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A Framework for the Evaluation of Quality of Dwellings

Anabela Gonçalves Correia de Paiva

A thesis submitted to the University of Bristol in accordance with the requirements for the degree of Doctor of Philosophy in the Faculty of Engineering, Department of Civil Engineering.

June 1995

Abstract

The house-building industry should evolve towards the production of dwellings of higher quality standards. Minimum standards are required to ensure that all new homes will be structurally sound, comfortable and have a long and reliable life. The notion of quality does not just concern the dwelling itself, but also the immediate and wider environment, namely the proximity of schools, shopping and leisure areas (theatres, cinemas, sport centres, playgrounds), accessibility (roads, railway lines, underground, buses) and views.

To achieve higher quality standards better design quality evaluation and inspection schemes are needed. In this thesis a new approach for the evaluation of the quality of dwelling designs named QDF (Quality Dwelling Framework) is proposed. In order to develop QDF a parallel between the form of a dwelling and the form of a human body is drawn. This is justified by the fact that the human body is a most sophisticated and highly developed form. The methodology behind QDF is the systems approach. In QDF, a dwelling is organised, in a hierarchical way, into systems, subsystems and components. Each of the elements in the hierarchy is both a system and a part of a larger system, i.e. a holon. Holons are modelled as software objects, in the sense of object-oriented programming.

QDF is an important contribution in the direction of raising dwelling quality standards (quality is used here in the sense of fitness for purpose). It provides a comprehensive framework to implement and develop different quality evaluation methods, adapted to different countries and cultures. No specific parameters are imposed for quality evaluation of each system, and so different quality evaluation schemes may be implemented. The parameters are dependent on several factors, namely: the climate, the habits of the users and the development of the construction industry in the relevant country. QDF is a generic framework, within which different evaluation methods can be implemented and adapted to different situations. It has been designed so that it can help all parties involved in the residential building industry, namely users, builders, architects, engineers, property developers, bankers, building societies, state agents and politicians, to agree upon quality standards tuned to the national or regional realities.

A strategy for the corroboration of QDF has been proposed, based on Popper's philosophy of scientific knowledge and on an extension of this theory proposed by Blockley in the context of risk analysis. QDF can only achieve a high degree of corroboration by testing it in practice in the long term, i.e. users will use the system, make decisions, live in a house; and then provide feedback as to whether the evaluation turned out to be dependable or true (i.e. decisions correspond with the facts). The process of evaluating QDF has been initiated by using a prototype system, developed in the programming environment KAPPA, to evaluate different dwelling designs as well as different alternative solutions for the same dwelling design. QDF is compared with product models of buildings, namely the RATAS product model and the AEC building systems model.

The QDF prototype system implements the quality evaluation for a thermal system (the metrics have been developed by Paiva and are based in the Portuguese thermal regulations), an electrical system (the metrics used are defined in the Qualitel method) and a close environment system (the metrics used are defined in the SEL method). The development and use of the prototype indicates that the complexity of modelling a dwelling in a comprehensive way calls for advanced computer techniques which provide high storage capacity and fast processing. As QDF is a naturally parallel system, this could be achieved in future by using parallel computer architectures, which are adequate for the developed model, based on the object-oriented paradigm.

To José Afonso and to my Parents

Acknowledgements

I am indebted to Professor David Blockley for his help and guidance in carrying out this research and in producing this thesis.

I would like to thank Professor Artur Bezelga for introducing me to the area of quality evaluation of dwellings and for his support and encouragement.

I am also indebted to Universidade de Trás-os-Montes e Alto Douro in the persons of the rector Professor Torres Pereira, my former head of department Professor Fernandes de Carvalho and my head of department at present Professor Carlos Couto for making this work possible.

I would like to thank my colleges in the Civil Engineering Systems Group for their support and friendship, in special David Platt for sorting out my computer problems and Bill Dester for his opinions and help with the English language.

Finally I would like to thank my colleges at Universidade de Trás-os-Montes e Alto Douro for their support, in special Maria Manuel for her friendship and encouragement in the hardest moments and Isabel for her friendship and help in organising the Civil Engineering Group.

This research was supported by Junta Nacional de Investigação Científica e Tecnológica, Lisboa, Portugal, under Grant number BD/1001/90-RM while the author was on leave from Universidade de Trás-os-Montes e Alto Douro, Vila Real, Portugal.

Declaration

This thesis, entitled "A Framework for the Evaluation of Quality of Dwellings", is submitted for the degree of Doctor of Philosophy, in the Faculty of Engineering, at the University of Bristol.

The research on which this thesis is based was carried out between October 1991 and June 1995 under the supervision of Professor D. I. Blockley. It is due entirely to the author except where otherwise acknowledged in the text and has not formed the basis of a submission for any other degree.

The views expressed in this thesis are those of the author and not of the University of Bristol.

Signed ...Anabela..Paiva...............

Date ....23/11/95..............................

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1. Introduction

1.1 Background and objectives

Quality evaluation is important for all parties involved in the design, production, distribution, sale, use and maintenance of a product. For users to get a certain quality standard, there is the need to define methods and metrics for the evaluation of quality.

The house-building industry should evolve towards the production of dwellings of higher quality standards. Of course minimum standards are required to ensure that all new homes, whatever they cost, will be structurally sound, comfortable and have a long and reliable life. However the notion of comfort does not just concerns the dwelling in itself, but also the immediate and wider environment, namely the proximity of schools, shopping and leisure areas (theatres, cinemas, sport centres, playgrounds), accessibility (roads, railway lines, underground, buses) and views.

In the UK, the National House Building Council has a quality inspection and warranty scheme with a very wide coverage (more than 98% of new dwellings built for sale), which is applied in the construction phase and takes manly into account structural aspects. According to Johnson (1991), the effect of this scheme upon the price of a new house is about 0.4% of the total cost of the home. This significantly indicates that this form of quality assurance in the building industry does not lead to greater costs.

To achieve higher quality standards better design quality evaluation and inspection schemes are needed. In this thesis a new technique for quality evaluation is applied to the design of new dwellings.

The main objectives of this thesis are:

- to identify and critically evaluate quality evaluation methods for dwellings,

- to identify and critically evaluate computer techniques and tools suitable for quality evaluation and implementation of an information system for dwellings,
- to identify and critically evaluate some recent developments in product modelling, for the building industry,
- to develop a quality evaluation framework for dwellings, based on a systems approach, that is suitable for computer implementation,
- to test the proposed framework by demonstrating a partial computer implementation,
- to critically evaluate the framework.

A Quality Dwelling Framework (QDF) has been developed. It is a conceptual model of design quality evaluation, that is suitable for computer implementation.

QDF defines the criteria for dwelling quality evaluation. A systems approach is used, in which the dwelling is divided into systems and subsystems, to the point where measurable parameters of quality are reached. No specific parameters are imposed for quality evaluation of each system, and so different quality evaluation schemes may be implemented. The parameters are dependent on several factors, namely: the climate, the habits of the users and the development of the construction industry in the relevant country. QDF is a generic method, from which different evaluation methods can be designed and adapted to different situations. For example if some criteria are not relevant in a certain context, they can be omitted.

In the scope of this thesis, a dwelling is a residential building or a part of a residential building which can be independently bought and sold, and that usually has individual utility supplies (water, electricity, gas).

QDF as well as taking into account the design of the dwelling also includes the characteristics of the environment.

1.2 Overview

An overview of the organisation of the thesis follows.

In Chapter 2 some methods for the evaluation of the quality of dwellings are reviewed and compared. They are: Qualitel (France), SEL (Switzerland), the Portuguese Method and NHBC recommendations (UK).

In Chapter 3 the object-oriented concepts, design methods and languages are presented and discussed. Their relevance for QDF is explained. The tool KAPPA-PC, which was chosen to experiment with QDF is introduced.

In Chapter 4 product modelling ideas are explained. Conceptual model languages and product modelling in the building industry are reviewed. The relevance of the object-oriented paradigm is discussed.

The Quality Dwelling Framework (QDF) is developed in Chapter 5. The methodology is presented based on a systems approach and using an analogy with a human body. The notions of classification, hierarchy and artefact are discussed. Finally, a summary is presented.

In Chapter 6 implementation decisions and strategies are explained. The design of the program is explained and object hierarchies are presented, both at a global level and at a detailed level.

A preliminary evaluation of QDF is made in Chapter 7. Test results are presented of the evaluation of various dwelling designs. A comparision between QDF and the Product Model approach is made.

Finally, future work and conclusions are presented in Chapter 8.

2. Methods for the evaluation of the quality of dwellings

2.1 Objectives

The objectives of this chapter are:

- to define quality,
- to present existing methods for the evaluation of quality of dwellings,
- to analyse in some detail these methods,
- to discuss and compare the methods.

2.2 Introduction

There are two important aspects related to the idea of quality:

- degree of excellence,
- fitness for purpose.

Quality as "degree of excellence" would mean that a dwelling of very high quality would have to be a palace or a mansion. This notion is not adequate for a quality professional, as noted by Arnold (Arnold 1995), because the intended use of the product is central to the notion of quality. This one can conceive a high quality semi-detached house.

There are many definitions of quality as "fitness for purpose". For example, the following definitions are from Merna (Merna 1995) and Arnold (Arnold 1995):

- Quality is the ability to meet market and customer expectations, needs and requirements.
- Quality means in conformance with user requirements.

- Quality means fitness for use.
- Quality is the supplying of goods that do not come back, to customers who do.
- Quality is the totality of features and characteristics of a product or service that bear on its ability to satisfy given needs.
- Quality is the composite of all of the attributes or characteristics including performance of an item or product.
- Quality is the total composite product and service characteristics of marketing, engineering, manufacturing and maintenance through which the product and service in use will meet the expectations of the customer.
- Quality is the conformance to standards that represent the product's or service's basic characteristic, and are based on customer needs and expectations.

All of these definitions relate quality to the idea of satisfaction of user requirements. Along this line, the definition given in the British Standard BS4778, as "the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs", is adopted in this work to define the quality of dwellings.

Harris and McCaffer (Harris 1995) note that "Quality management is now a major management function within construction companies". Unless a construction company can guarantee its clients a quality product it can now no longer compete effectively in the modern construction market." They refer four stages of evolution that led to the modern concept of quality:

- Inspection - process of checking that what is produced is what is required.
- Quality control - inspection of different stages in the development of products and services to ensure that they where being carried out to specified requirements. Usually quality control is done on a sampling basis dictated by statistical methods.
- Quality assurance - developed to ensure that specifications are constantly met. "Fit for purpose" and "right first time" are the principles of quality assurance.

- Total quality management - based on the philosophy of continually improving goods or services. A key factor is that everyone in a company should be involved and committed from the top to the bottom of the organisation.

The purpose of a dwelling may change with time and may include functionality, usability, safety, availability, reliability, maintainability as well as economic and environmental aspects.

There are many parties involved in the design, construction and use of dwellings. These parties have different end objectives examples of which follow:

- users - convenience, quality of life, cost,
- builders - construction, cost,
- architects - design, aesthetics, cost,
- engineers - structure, construction, cost,
- property developers - business, cost,
- bankers and building societies - finance,
- estate agents - transaction,
- politicians - funding, social aspects.

The objectives of these parties may sometimes lead to conflict. A dwelling is a complex system and the different parties referred above view it from different perspectives, giving different weights to the needs it is supposed to satisfy.

In this context, the concept of quality of dwellings has been changing. The technical evolution led to very high standards in the structural aspect and other aspects, namely the comfort that the house can give to the users, the functional versatility of the spaces and the environmental impact became more relevant.

Quality evaluation became important. In France the "Method Qualitel" and in Switzerland the "Method SEL" have been developed. These methods, the Portuguese Method and the recommendations of the NHBC in the United Kingdom will be reviewed in the following sections.

2.3 Method and Label Qualitel

As previously noted this is a French method to evaluate the quality of dwelling designs (houses and flats). After the latest update it is also suitable to evaluate the quality of student halls.

The method was created in 1974 by the "Association Qualitel", for helping users (buyers or tenants) to choose the best house to suit their needs. Since then this method has been updated several times. The improvements resulted mainly from the observations and suggestions of the users of the method and from the availability of new materials and new regulations.

Several groups form the administration board of the "Association Qualitel":

- professional organisations of builders,
- users (tenants and buyers) organisations,
- public sector bodies.

The principal aim of this method is to create an **objective information system** covering construction and economic qualities, some of which will only become manifest during use. This is important mainly:

- **to help the user** to make a conscious choice, providing trustable and objective information on the quality of design;
- **to help the design team** to evaluate the implications of their options, in an objective way;
- to provide a **guarantee to the developers of a coherent system of evaluation** that shows the efforts made to build a quality house.

The evaluation process is performed by the Qualitel examiners ("examinateur Qualitel"), who are quality evaluation experts of the "Association Qualitel" (250 in 1993).

The Qualitel method is applied to new dwellings, in the design phase. It may be used by the experts involved in the design of new dwellings as a way to evaluate the quality of usability, comfort and maintenance of their designs, which is recognised by other parties (developers, authorities, buyers, etc.).

The "Association Qualitel" has defined a set of **criteria**. Most of them relate to **functional** quality although others do concern the **costs of maintenance and exploitation**.

The latest version (7th version) of the Guide Qualitel, was produced by the "Association Qualitel" in 1993 (Qualitel 1993). The criteria used after this update are as follows:

1. finishes of the circulation areas in the common parts of the building,
2. possibility of installation of domestic equipment,
3. wall finishes in kitchens and bathrooms,
4. floor finishes,
5. plumbing,
6. electrical fittings,
7. protection against noise inside the building,
8. protection against noise outside the building,
9. thermal summer comfort,
10. costs of maintenance of facades and roofing,
11. estimated costs for heating and hot water,
12. access for the disabled,
13. other elements that account for the costs of exploitation and maintenance.

Each criterion is subdivided recursively into sub-criteria, in a tree like way. To get a rating for each criteria it is necessary to evaluate the sub-criteria at the bottom of the tree, which can be measured, described or referred to in an objective[1] way. The rating at a node is obtained from the ratings at the level below. The method used to combine the ratings is based on the opinion of experts and is presented in the form of look up tables.

The information for rating at the lowest level of the tree comes from the analysis of the plans and specifications. Some is obtained directly, reading the plans (e.g. dimensions of windows, orientation), other information is obtained by calculus (e.g. thermal and acoustic coefficients, temperatures), by experiment in laboratories (e.g. classification UPEC of the floor finishes), and from documentation of construction characteristics.

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[1] The word objective is used here in the sense proposed by Popper (1983, 1992) when referring to the world of *scientific knowledge* (world 3). As an engineer the author views the concept of *objectivity* in the light of Blockley (1980), as the ability to measure. So *objective* measurements are perceived in the same way in repeated experiments, by the same or different persons (inter-subjectivity).

The criteria are evaluated on a scale from 1 to 5, by the Qualitel examiners. Figure 1 shows the qualitative meaning of each rating, for functional quality and for costs of exploitation and maintenance. A mark of 3 in all criteria is equivalent to the dwelling having a technical quality level higher than the average of new constructions in France. To evaluate each criterion or sub-criterion two methods are more frequently used:

- direct categorisation,
- look up table categorisation.

rating	**functional quality**	**costs of exploitation and maintenance**
1	poor	expensive
2	medium	relatively expensive
3	good	relatively economic
4	very good	economic
5	excellent	very economic

Figure 1 - Qualitative meaning of Qualitel ratings.

In the first case the rating is obtained by analysing a value of a parameter and comparing it with a predetermined interval of variation for the parameter. Alternatively, there may be a description of the characteristics of a criterion that make it belong to a certain rating class.

A standard categorisation table is commonly used to obtain a criterion's rating, based on the ratings of its sub-criteria. An example is given in Figure 2. Here we can see that the rating for electrical fittings is obtained by reading the value situated in the position given by the row for "quantity and position of the electric equipment" and the column for "power". For example, if "quantity and position of the electric equipment" has rating 3 and "power" has rating 5, the rating for electrical fittings is 3.

It is important to notice that rating 5 for the electrical fittings is only obtained if both sub-criteria have rating 5. If a sub-criterion has rating 1, this implies rating 1 for the electrical fittings.

This may be not so strict in other cases, but Qualitel encourages a homogeneous level of quality. The quality level of each criterion is usually limited by the lowest rating of the sub-criteria, so that bad ratings are not balanced with good ones. This scheme is somewhat similar to the intersection of fuzzy sets. This will be referred to with more detail in section 2.8.

electrical fittings

		power		
		1	3	5
quantity and position of the electric equipment	1	1	1	1
	3	1	3	3
	5	1	4	5

Figure 2 - Example of look up table categorisation from the Qualitel method.

The results of the Method Qualitel are presented as a **quality profile**, "Indiquatel", with a rating for each criterion, so that the user can explore the available features. An example is given in Figure 3.

Based on the Qualitel method, the Association Qualitel defined a **"Label Qualitel"**, in 1985, that is awarded to the designs that are classified in criteria 5, 6, 7, 8, 9, 10 and 11 with at least rating 3. In 1990 three other labels were defined:

- **"Label Qualitel Confort Acoustique"**, related to criteria 7 and 8,
- **"Label Qualitel HPE"** (Haute Performance Energetique), related to criteria 11,
- **"Label Qualitel Accessibilité"**, related to criteria 12.

Figure 4 shows how these labels can be obtained.

criteria	**rating**				
	1	**2**	**3**	**4**	**5**
1-finishes of the circulation areas in the common parts			x		
2-possibility of installation of domestic equipment		x			
3-walls finishes in kitchens and bathrooms			x		
4-floors finishes				x	
5-plumbing				x	
6-electrical fittings				x	
7-protection against noise inside the building			x		
8-protection against noise outside the building			x		
9-thermal summer comfort				x	
10-costs of maintenance of facades and roofing					x
11-estimated costs for heating and hot water				x	
12-access for the disabled				x	
13-other elem. that account for the costs of expl. and maint.	descriptive summary (no rating)				

Figure 3 - Example of "Indiquatel", the quality profile from Qualitel.

Trelin (1991) emphasises that it is clearly in the interest of professionals in the construction industry in France to obtain a Qualitel label for their projects. It provides them with a strong sales presentation and the label guarantees the technical claims. It provides the buyer or the tenant with information supplied by an independent organisation about a wide range of designs. It gives the builder who obtains this "quality agreement" a distinct advantage over the competition.

Qualitel is not a normative method. Quality levels are always formulated in terms of requirements and so the method does not act as a brake on innovation, particularly where new materials and new building methods are concerned. The procedure followed in attributing a quality level is very open and guarantees a diversity of conception and design. A desired level of quality can usually be attained thanks to a wide range of technical solutions and designs.

In 1991 there were in France around 62,348 dwellings with the Qualitel Label. In 1993 this number has grown up to 147,888 dwellings. According to the latest numbers available, in 1994 this number should increase to over 200,000 dwellings. The number of designs analysed in 1993 was 58,138 and 51,308 were awarded the "Label Qualitel" (88%). This shows a significant improvement when compared to the 34.5% of successful applications in 1989.

criteria	**rating**				
	1	2	3	4	5
Protection against noise inside the building			Label Qualitel	Label Qual. Confort Acoust.	
Protection against noise outside the building					
Estimated costs for heating and hot water				Label Qualitel HPE ***	Label Qualitel HPE ****
Costs of maintenance of facade and roofing Plumbing Electrical fittings Thermal summer comfort					
Access for the disabled			Label Qualitel Access.		

Figure 4 - Labels Qualitel.

Qualitel certifies the design of the dwellings with the Label Qualitel. In order to verify the quality of this dwellings after construction, a sample of around 15% of the dwellings is inspected by Qualitel experts. They check whether the specification and recommendations of the design have actually been followed.

In this method the evaluation criteria are related solely to the dwelling, excluding the environment. The proximity of schools, shopping and leisure areas and accessibility (roads, railway lines, underground, buses) are not taken into account. The results of the application of the method are suitable for a home buyer in deciding the intrinsic qualities of the house. They are presented both as a global rating (various Qualitel labels) and a quality profile. The method is also useful for financial aspects, although it does not award a mark to the relation cost/quality. Structural aspects of the building are not taken into account. The scheme used for the combination of information will be critically discussed in section 2.8.

2.4 SEL

The Swiss method **SEL**, "Systeme d'Evaluation de Logements" (Housing Evaluation System), is the result of work that began back in the 60's. The development and application of SEL have assumed greater importance since the publication in 1975 of a law encouraging the construction and ownership of housing. As this law was also aimed at improving the quality of housing construction, it called for an instrument of quality evaluation for dwellings. SEL has since then been used to evaluate more than 10,000 dwelling designs in Switzerland. The method was designed to evaluate the quality of flats, as opposed to houses. Some of the criteria can also be applied to houses (e.g. criteria concerned with the dwelling in itself and the wide environment), while others are specific to flats (e.g. criteria concerning the close environment).

The main objective of SEL was to establish the relation between the quality and the cost of the dwelling, in order to assure an optimised utilisation of federal funds in subsidies for new housing.

SEL was developed by architects in the private sector and by planning and research institutes; it is co-ordinated by the "**Office Fédéral du Logement**". Testing and revision of the evaluation system took two years. The system is also an aid for other users and other application areas, according to Wiegand, Aellen and Keller (1986), as Figure 5 shows.

Users	Application areas
Authorities	Encouragement of the construction of dwellings with a better price/quality relation.
	Preparation of the specifications for bidding and evaluation of the results.
Builders	Preparation of the specifications for bidding and evaluation of the results.
	Definition of a quality standard.
	Comparison of residential building designs.
Architects	Design of dwellings.
	Management of the designs of residential buildings.
	Definition of the relation price/quality.

Figure 5 - Examples of applications areas for SEL.

The role of a housing evaluation system, according to the SEL developers, is to measure the degree of concordance between the characteristics of the dwelling and the needs of housing.

The most important guidelines for the development of the SEL method were the following (SEL 1988):

- the evaluation refers only to functional quality. Aesthetic questions are excluded;
- the resulting quality evaluations must be comparable. The classification of a dwelling as good or bad must not depend on the opinion of individual officials;
- the evaluation must not impose architectural uniformity. The system must allow different types of dwellings and buildings roughly the same chance to get a good "score";
- it is not enough to make sure that the minimal requirements are fulfilled. It should also be possible to measure the functional quality on a continuous scale from low to medium and high grades;
- the subject under evaluation is moderately priced dwellings. The evaluation criteria must always take this fact into account;
- there should not be any rigid price limitations. Higher costs should be allowed for high-quality dwellings;

- the success of the evaluation should be measured by its capacity to reflect the wishes and long-term needs of the users of housing.

The technical quality of housing construction imposed by the building regulations in Switzerland is high. So the SEL developers, in order to simplify the method, decided to establish a **minimum set of conditions** for a dwelling to be accepted for evaluation:

- minimum net habitable space,
- dwelling and room sizes,
- equipment of the kitchen and sanitary spaces,
- acoustic and thermal insulation,
- adaptation (in certain cases) of the dwelling to the needs of elderly and disabled people.

The evaluation criteria are divided in three groups:

- the dwelling, W1 (Figure 6),
- the immediate surroundings of the dwelling, W2 (Figure 7),
- the availability and quality of services in the wider environment, W3 (Figure 8).

Each criterion is given a rating between 0 and 4, that indicates the degree of satisfaction of the criterion. Rating 0 corresponds to minimal satisfaction of the criterion and rating 4 corresponds to good satisfaction of the criterion.

To evaluate each criterion one of the following methods is used:

- direct categorisation,
- transformation function, Figure 9.

In the first case, a description of the characteristics of a criterion is used to decide to which rating class it belongs.

In the second case, a transformation function is defined. An example is given in Figure 9, which is used to evaluate the criterion "sun lighting of shared spaces and outside spaces". The objective is to ensure that regular sunlight, especially during winter and afternoons, is obtained through appropriate orientation in the shared and outside spaces.

Fitness to be furnished	
	area of individual spaces
	area of common spaces
	area of outdoor extensions
	area of kitchen
	area of bathrooms
	area of circulation spaces
	area of storage
	width of individual spaces
	width of common spaces
	width of outdoor extensions
	width of kitchen
	width of bathrooms
	width of hall
	walls free for furniture in individual spaces
	walls free for furniture in common spaces
	walls free for furniture in kitchen
	walls free for furniture in circulation spaces
Communications	
	hall - kitchen functional link
	hall - WC functional link
	hall - common spaces functional link
	hall - individual spaces functional link
	individual spaces - bathrooms functional link
	kitchen - living room functional link
	functional links to outside extensions
Possibility of changes	
	division of individual spaces
	division of common spaces
	movable dividing panels
	partition walls
	change in the area of the dwelling
Physiological and functional requirements	
	sanitary fittings
	outdoor plantations
	living-room windows
	kitchen windows
	bathroom windows
	sun exposure of individual spaces
	sun exposure of common spaces and outdoor extensions
	sound insulation of contiguous spaces
	sound insulation inside of the dwelling

Figure 6 - Criteria for the dwelling (W1).

Possibility of choice	
	choice regarding dwellings in the same building
	choice regarding dwellings in the same environment
Circulations	
	car parking
	entrance of the building
	distribution of spaces in the building
	access to the building
Building equipment	
	outside storage places
	bicycle parking places
	laundry and drying places
	multi-purpose common facilities
outside equipment	
	toddlers playground
	children playground
	vegetable gardens and animal breeding

Figure 7 - Criteria for the immediate surroundings of the dwelling (W2).

Immediate surroundings equipment	
	leisure opportunities
	equipped play field
	non equipped play field
	public park
	public swimming-pool
	public forest
	foot paths
	public lakes and streams
Community equipment	
	village and county centre
	regional centre
Education, social services and public transports	
	nursery
	primary school
	county educational establishments
	social services equipment
	distance to next bus stop

Figure 8 - Criteria for the wider environment (W3).

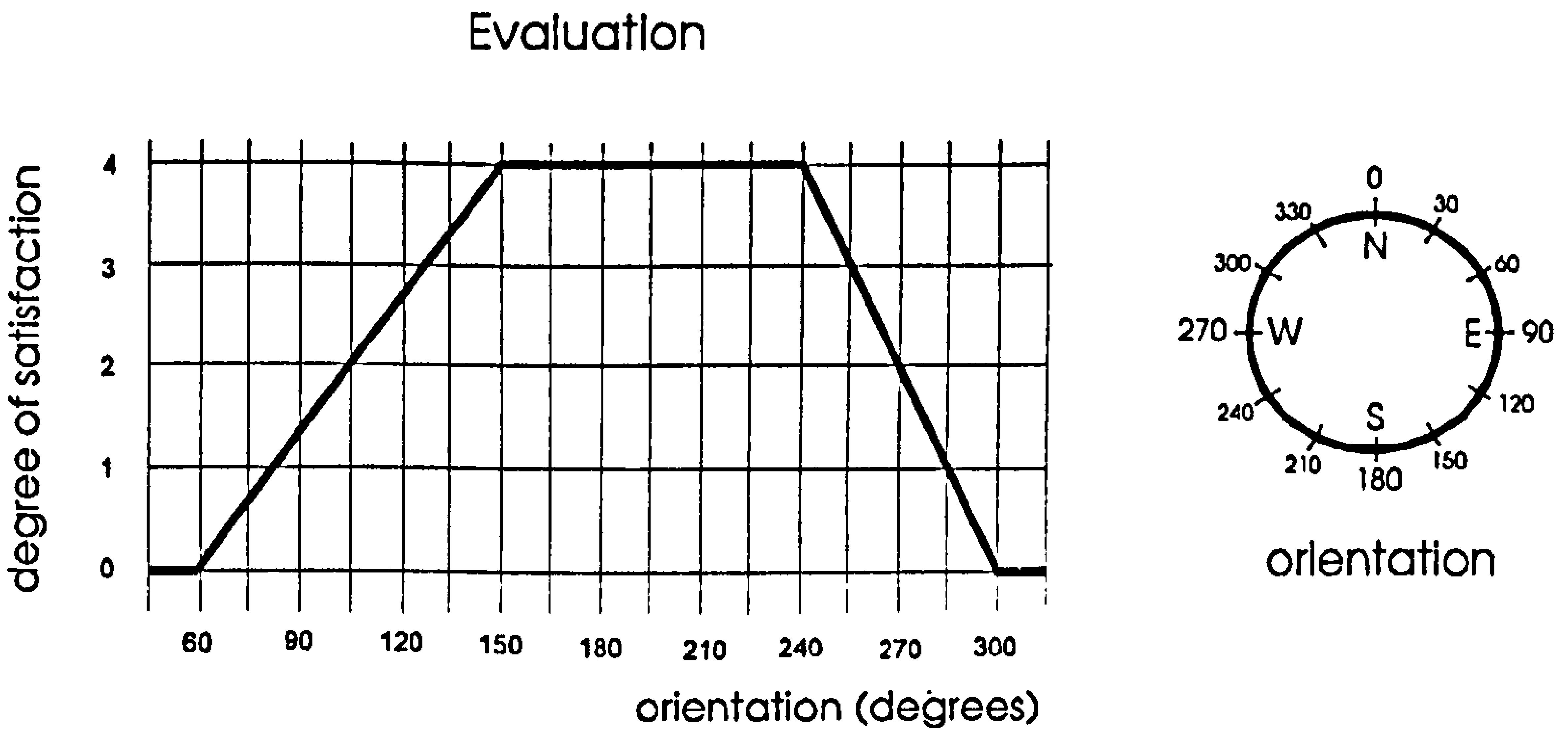

Figure 9 - Example of a transformation function.

The directives given to measure this criterion are transcribed below:

"The orientation of the living room and outside space are measured to calculate the average degree of satisfaction. The orientation of the living room is measured as perpendicular to the plane of the window. In the case of windows facing various directions, the most favourable orientation is taken into consideration provided that the surface area of such windows equals at least 10% of the net surface area of the room. In the case of outside spaces, the dominant orientation of the external space attached to the leaving area is measured."

For example, a dwelling with a living-room with orientation 180° (south) and an outside space with orientation 270° (west), would get for each one of this spaces respectively a degree of satisfaction 4 and 2. The rating for the criterion is the average of the two sub-criteria referred to above (4+2)/2=3.

To each criterion a weighting coefficient is assigned, according to importance.

The results of the method are a **quality profile** with the ratings of the 66 criteria and an **overall quotation** named the **use-value** of the dwelling, **VU**. This is obtained as follows:

$$VU = \Sigma n_i p_i$$

where

n_i - rating of the criteria,

p_i - weight coefficient (these coefficients are re-examined periodically).

The quality score of a construction design is only one aspect of its evaluation. Higher construction costs are permitted in the case of high quality dwellings, as improvement of the quality of dwellings is the desire and legislative obligation of the "Office Fédéral du Logement" (Swiss Federal Office of Housing). In the SEL method the relation between quality and cost is also measured, as a function of the cost, and the ratings obtained in the categories W1 (the dwelling) and W2 (the immediate surroundings of the dwelling).

The "Office Fédéral du Logement" fixes the acceptable levels for the cost of construction on the basis of this degree of quality in parallel with the evolution of the unit construction costs in Switzerland. An example is shown in Figure 10. The value W3 (wider environment of the dwelling), together with other factors, is used to verify the suitability of the land cost.

The writers of SEL developed the following tools, in order to simplify the application of the method:

- catalogue of minimum standards,
- classification of the size of the dwelling,
- catalogue of the evaluation criteria,
- documents for the synthesis of the use-value,
- table for examining the suitability of construction costs.

The SEL method has been used to evaluate more than 10,000 dwellings, till 1988 (SEL 1988). More recent statistics could not be obtained.

This method evaluates aspects related to the dwelling itself as well as to the close and wide environment. The proximity of schools, shopping, leisure areas and accessibility (roads, railway lines, underground, buses) are important factors. This method was created to help financiers decide if a dwelling is mortgageable and so a rating is given to the relation cost/quality. It is also useful for home buyers and builders. The results are presented globally as a use-value, but partial results can also be analysed. SEL does not evaluate aspects related with the structure of the building. The scheme used for the combination of information will be critically discussed in section 2.8.

PPH	Corresponding number of rooms excluding kitchen, bathroom and toilet	Use-Value total points W1+W2	level of quality	Rental unit	Owner-occupied unit	one family house
1	1 - 1 1/2	no points	sufficient	100,000	110,000	
			good	125,000	125,000	
			excellent	150,000	165,000	
2	2 - 2 1/2	880	sufficient	125,000	135,000	
		1,100	good	150,000	165,000	
		1,320	excellent	175,000	200,000	
3	3 - 3 1/2	930	sufficient	150,000	165,000	
		1,310	good	175,000	200,000	
		1,680	excellent	200,000	220,000	
4	3 1/2 - 4 1/2	1,000	sufficient	175,000	200,000	250,000
		1,450	good	200,000	220,000	300,000
		1,850	excellent	220,000	240,000	325,000
5	4 1/2 - 5 1/2	1,000	sufficient	200,000	200,000	300,000
		1,450	good	220,000	240,000	325,000
		1,850	excellent	240,.000	265,000	350,000
6	4 1/2 - 6	1,000	sufficient	200,000	240,000	325,000
		1,450	good	240,000	265,000	350,000
		1,850	excellent	260,000	285,000	370,000
7	5 1/2 -7	1,000	sufficient	240,000	265,000	350,000
		1,450	good	265,000	285.000	370,000
		1,850	excellent	280,000	305,000	390,000
8	5 1/2 - 8	1,000	sufficient	260,000	285,000	370,000
		1,450	good	280,000	305,000	390,000
		1,850	excellent	300,000	325,000	410,000

Legend: PPH - number of persons per household.

Figure 10 - Acceptable total construction costs (Swiss francs).

2.5 Portuguese method

In 1988 the **AICCOPN** (Associação dos Industriais de Construção Civil e Obras Públicas do Norte) asked two Portuguese Universities, **FEUP** (Faculdade de Engenharia da Universidade do Porto) and **UTL/IST** (Universidade Técnica de Lisboa/Instituto Superior Técnico), to develop a method to evaluate the quality of dwellings. The method is still unfinished, but a significant amount of work has been done.

The method is based on previous work developed in Portugal in this field, namely by Gomes (1971), Cabrita and Paiva (1981), MHOP (1981), Paiva (1985), MOPTC (1987), Bezelga and Neto (1986) and Costa (1986). It is also based on the Qualitel and SEL methods.

The **objectives** of the method are (Abrantes, Bezelga, Costa e Macedo, 1988):

- evaluation of the quality of dwellings through a quality profile,
- evaluation of the quality of dwellings through a global rating,
- simplicity of use, so that it can be applied with moderated costs to a large quantity of dwellings,
- objectivity,
- to be applicable in a wide range of dwellings, namely to houses and flats,
- to follow Portuguese regulations,
- to be designed in such a way to enable the method to evolve.

The **criteria** used for the evaluation process should be as follows:

- independent of each other,
- easy to measure,
- adapted to the Portuguese building real estate.

The draft of the method uses 23 criteria, divided in three groups (Figure 11):

- A- **architectural** aspects,
- B- **construction** quality,
- C- **maintenance** costs and durability.

Each criterion is subdivided into sub-criteria, in a tree like way. In order to obtain the rating for a criterion the ratings of the sub-criteria are combined.

It is still to be decided if the method will take into account the environment of the dwelling or if it will consider only the dwelling itself.

Due to the early development phase of this method, there is not enough information available for a critical view to be presented in this thesis.

2.6 Quality evaluation in the UK

2.6.1 Review

This section gives a brief overview of work developed in the UK concerning the evaluation of the quality of dwellings.

A - Architectural quality

- 1 - Dwelling spaces
  - 1.1. Spaces
    - 1.1.1. common room
    - 1.1.2. bedrooms
    - 1.1.3. kitchen
    - 1.1.4. bathrooms and WC
    - 1.1.5. other spaces
  - 1.2. Relation between spaces
  - 1.3. Flexibility and adaptability
- 2 - Common spaces

B - Construction Quality

3 - Construction elements	3 - Habitability requirements
3.1. Primary elements	3.1. Watertightness
3.1.1. external walls	3.2. Ventilation and smoke exhaust
3.1.2. internal walls	3.3. Thermal winter comfort
3.1.3. floors and roofs	3.4. Thermal summer comfort
3.2. Secondary elements	3.5. External noise
3.2.1. internal openings	3.6. Internal noise
3.2.2. external openings	3.7 Visual comfort

- 4 - Finishes
  - 4.1. Finishes of the dwelling
  - 4.2. External finishes
- 5 - Dwelling equipment
  - 5.1. Kitchen and laundry equipment
  - 5.2. Sanitary fittings
- 6 - Services
  - 6.1. Water supply and sewerage
  - 6.2. Electrical fittings
  - 6.3. Lifts
  - 6.4. Others

C - Deferred costs and durability

Figure 11 - Portuguese method criteria.

The shortage of houses in 1917 and the lack of regulations of standards for dwellings led to a situation where construction quality standards were very low. A committee, under the chairmanship of Sir John Tudor Walters, was appointed "to consider the questions of building construction in connection with the provision of dwellings for the working classes ... and report upon methods of securing economy and despatch in the provision of such dwellings" (Shaw 1991). This committee produced a report, known as **Tudor Walters Report**.

The report recommended that every housing scheme should be prepared by a competent architect, the aim being to obtain the best value for building cost. Plans for dwellings should indicate for example furniture and swinging of the doors.

Other requirements concerned the minimal areas, the layout of the house (number and position of rooms, position of the sink and sanitary fittings) and some economic aspects (e.g. the house should have a simple rectangular form, a simplified roof and painted woodwork should be avoided externally).

After the second world war another committee was appointed to solve the problems of the lack of housing. Another report was produced known as **Dudley Report**, named after the committee chairman, the Earl of Dudley.

Some of the recommendations are listed below:

- All local authorities should employ trained architects for their housing schemes.
- Thermal insulation should be considered under roof tiles and for protection of water tanks and pipes from frost.
- Sound insulation was recommended with cavity wall construction.

Other recommendations were given concerning the type and position of the housing equipment.

Later, in 1961, the government set up a another committee "to consider design and equipment applicable to family dwellings and other forms of residential accommodation, whether provided by public authorities or private enterprise, and to make recommendations". The primary task was to consider standards of internal design. The outcome was a report, known as **Parker Morris Report**. For the first time the idea that a house should be adaptable to different needs was expressed as "a national necessity". The report also emphasises the importance of good heating: "a house without good heating is a house built to standards of a bygone age" and it defines heating requirements for the ground floor.

In 1983 a report was published jointly by the Institute of Housing and The Royal Institute of British Architects, entitled "Homes of the Future". This report updates the

Parker Morris Report and introduces new standards. Heating of the whole house, accessibility for the disabled and flexible housing designs are recommended.

More recently Shaw (1991) proposed weighting factors for a list of housing design features. The features were based on:

- content analysis of relevant literature, such as government reports, official publications, articles in journals and books,
- analysis of perceptions of occupiers concerning their requirements, expectations and attitudes towards specific aspects of design.

The weighting factors were based on a survey of a group of architects and quantity surveyors. Figure 12 (from Shaw 1991, pp. 871) shows some of the features and corresponding weighting factors.

feature	factor
maximise sunlight and natural lighting	5.4
kitchen: cupboards not directly over cooker	5.4
kitchen: cooker not below a window	5.4
main bedroom (BR): to take a double or twin beds	5.4
weather stripping windows and external doors	5.4
space for child's pram/buggy	3.2
letter plates with draught flaps and hoods	3.2
hand rails grippable by child's hand	3.2
TV aerial socket, living room	3.2
baths not placed under windows	3.2
non-slip floor finish, bathroom	3.2
roof space storage, sealed trap, ladder, light	3.2
adequate number of shelves in storage cupboards	3.2
double electric sockets instead of single	3.2
sockets on opposite walls	3.2
paving at G.F. windows to facilitate cleaning	3.2
plain rectangular form	0.2
dinning space combined with hall	0.2
two single BRs divided by folding doors	0.2

Figure 12 - Range of design features and factors (source Shaw 1991).

The criteria established by Shaw could be used for the evaluation of the design of a house.

2.6.2 The NHBC

The National House Building Council (NHBC) was founded over 50 years ago and has been, since then, the consumer protection body of the private house-building industry in the UK (Johnson 1991). In 1951 only 4% of the new homes were protected by the scheme. In 1963 this percentage increased to 26%. Now over 98% of the houses built for sale in the UK are covered by the NHBC warranty.

The NHBC is governed by a Council, nominated by groups who are interested in improving the quality of new homes, including building societies, consumers, architects, surveyors, town planners, trade unions, lawyers and house builders.

The wide coverage of the NHBC scheme nowadays is due to the fact that it has been transformed from a builder's association into a wider organisation. The government and the financial entities recommend that only homes covered with the NHBC warranty should be mortgageable.

This warranty is known as NHBC Buildmark. The NHBC Buildmark is an agreement between the builder, the NHBC and each home buyer. It provides insurance to safeguard deposits lost through the builders insolvency or to put right defects which prevent the issue of a ten year warranty. The ten year warranty is an insurance against major damage due to a defect in the structure and against any defect in the drainage system.

In order to get the NHBC warranty, the builder must be a member of the institution and follow a set of recommendations. The main items considered by these recommendations are listed in Figure 13. To make sure that the recommendations are followed, a NHBC inspector is sent to the site every three weeks without warning. The builder is obliged to correct any defects detected by the inspectors.

The NHBC maintains a National Register of House-Builders, with over 27,000 members. To become a member the builder has to show good technical ability.

The claims received by the NHBC are analysed in order to improve quality standards. Also the site problems identified by the inspectors are an important source of information. This data is used to make new recommendations and new technical publications to help the builders and designers avoid the detected problems. Figure 14 shows a flowchart of the method used to process this information.

NHBC recommendations
Foundations
Concrete superstructure
Brickwork superstructure
Carpentry
Roof coverings
Construction of flat roofs
Joinery
Glazing
Services
Wall and ceiling finishes
Floor finishes
Painting
Garages
Drainage
Drives and paths
Retaining and boundary walls

Figure 13 - NHBC recommendations.

It is important to emphasise that the NHBC does not define a method to evaluate housing designs, but defines a set of recommendations for designers and builders to follow when constructing new dwellings to minimum quality standards.

The NHBC has a comprehensive set of publications, covering all aspects of the design and construction process (NHBC 1984-1991).

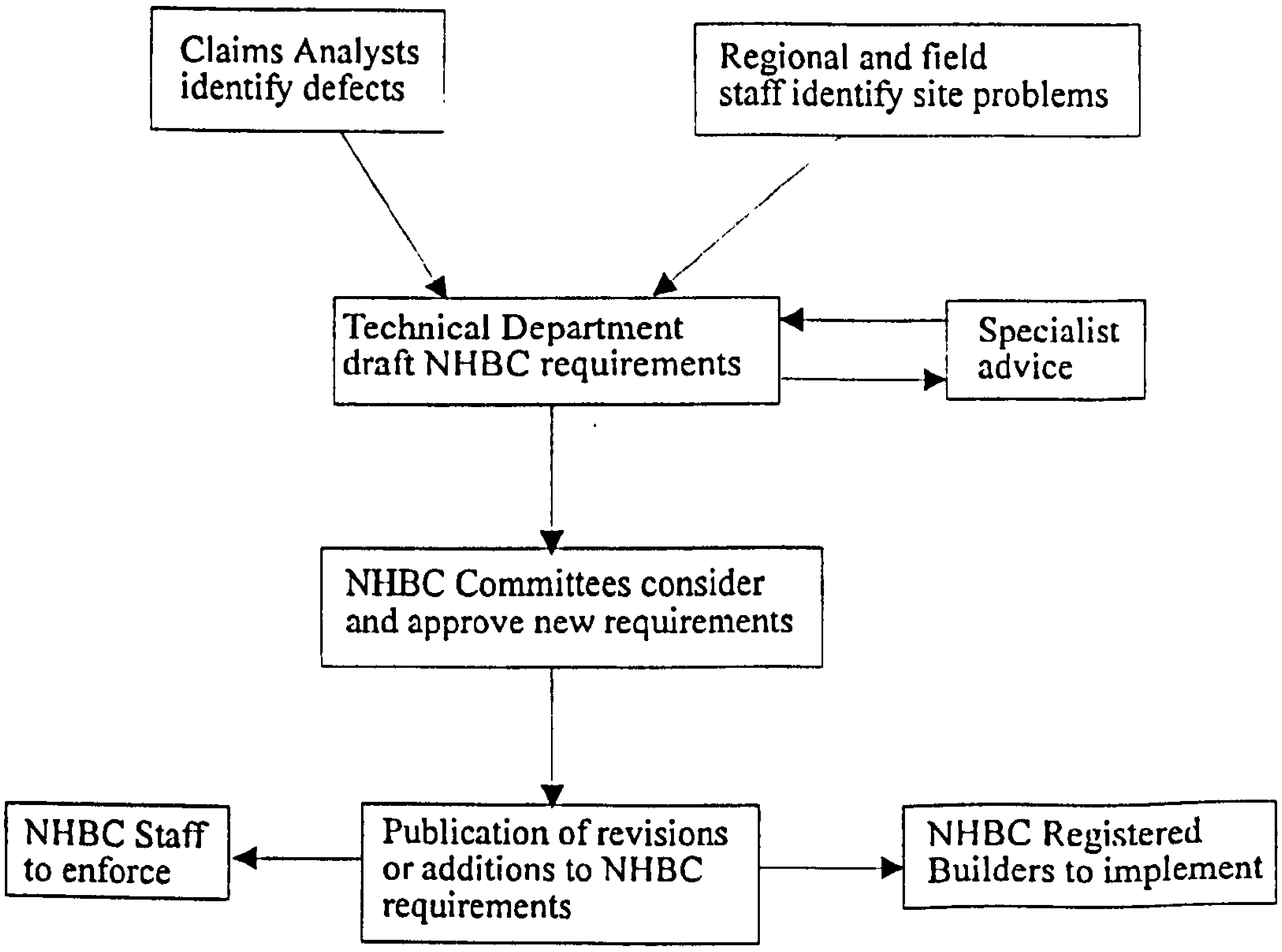

Figure 14 - Claims and problems analysis.

2.7 Discussion of the methods

The methods presented in the previous sections are compared and evaluated in this section.

A set of criteria are needed in order to evaluate these methods. These criteria can be identified from the characteristics of a good dwelling.

The quality standard of a dwelling is defined here as the degree of satisfaction of the needs of the users. So, the results obtained when applying a method should be in accordance with the users opinion.

The user expects that a dwelling will have a good performance during its lifetime. This can usually be achieved if the dwelling has been well designed and constructed. So an evaluation method should take into account the life-cycle of the dwelling (design, construction, life and demolition).

The user will also appreciate some form of guarantee, to protect him against any faults.

Another important aspect of an evaluation method is that it should not inhibit evolution of any development. The method should not act as a brake on innovation, but evolve and allow for new technical solutions and social needs.

The method should be adaptable. The results must be tested with the users and experts opinion.

A simplified scheme of this procedure is shown in Figure 15.

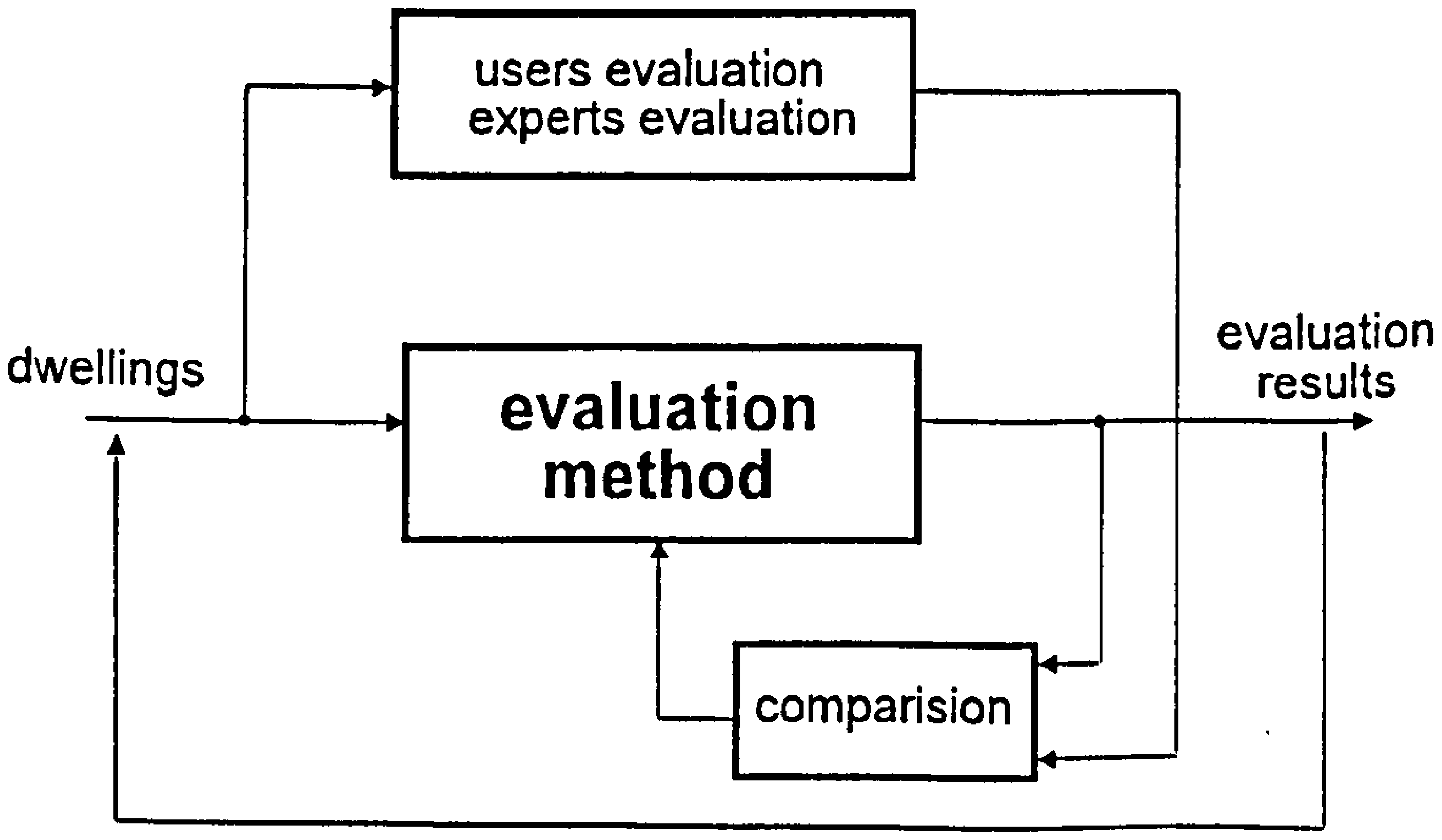

Figure 15 - The evaluation loop.

To satisfy the needs of the users an evaluation method should include a range of aspects including for example technical aspects (e.g. structural aspect), environmental aspects and the versatility of the spaces.

The method should be able to compare different dwellings or alternative designs for the same dwelling.

The rating of a dwelling should be given by an overall measure, which may be a single mark and/or a quality profile. The quality profile gives the user a better indication of the weaknesses and strengths of the dwelling and therefore a better decision aid.

A comparison table of the methods Qualitel, SEL and NHBC is shown in Figure 16. The Portuguese method was not considered in this comparision because it is still in an immature development phase.

	Qualitel	**SEL**	**NHBC**
Application of the method	147,888 dwellings (till 1993)	10,000 dwellings (till 1988)	more than 98% of new dwellings built in UK (in 1991)
Design evaluation	Yes	Yes	No
Construction evaluation	Yes (by sampling)	No	Yes
Environment Evaluation	No	Yes	No
Versatility of the spaces evaluation	No	Yes	No
Overall quotation	Yes	Yes	Yes
Quality profile	Yes	Yes	No
Relative measure of the quality	Yes	Yes	No
Provides some form of guarantee	No	No	Yes

Figure 16 - Comparison of the methods.

It is clear from Figure 16 that these methods complement each other. None of them is very broad, because each one only considers the aspects that are important in the context in which they have been developed.

As mentioned before, the French method Qualitel is used to evaluate the design of dwellings. The evaluation criteria are related solely to the dwelling, excluding the environment. The proximity of schools, shopping and leisure areas and accessibility (roads, railway lines, underground, buses) are not taken into account. The results of the application of the method are suitable for a home buyer in deciding the intrinsic qualities of the house. They are presented both as a global rating (various Qualitel labels) and a quality profile. The method is also useful for financial aspects, although it does not award a mark to the relation cost/quality. Structural aspects of the building are not taken into account.

As referred before, the Swiss method SEL is used, like Qualitel, to evaluate the design of dwellings. It evaluates aspects related to the dwelling itself as well as to the close and wide environment. Unlike in Qualitel, the proximity of schools, shopping and leisure areas and accessibility (roads, railway lines, underground, buses) are important factors. This method was created to help financiers decide if a dwelling is mortgageable, and so a rating is awarded to the relation cost/quality. It is also useful for home buyers and builders. The results are presented globally as a use-value, but partial results can also be analysed. Like Qualitel, this method does not evaluate aspects related with the structure of the building.

The Portuguese method is based on the Qualitel and SEL methods. It is being adapted to a Portuguese reality and analyses the dwelling itself. It is still to be decided whether the environment will be taken into account.

Quality evaluation in the UK has a completely different approach. It is concerned with the quality of the construction process, and gives less emphasis to the design phase. The NHBC inspects building sites periodically and ensures that they are being built in accordance with a comprehensive set of recommendations. If the dwelling meets the minimum standards, it is awarded the NHBC Buildmark. The result is relevant to financiers, builders and home-buyers. It does not give a relative measure of quality. It evaluates almost all aspects related to the construction process, but it neglects the environment and, to some extent, the comfort that the dwelling may give to the users.

2.8 Schemes for the combination of information

In this section the schemes used to combine information in the referred methods will be briefly analysed and compared with existing schemes (e.g. fuzzy reasoning).

There are two important aspects of quality evaluation methods where information is combined:

- How to obtain the rating of a criteria, from the ratings of sub-criteria.
- How to combine information from experts and users, in order to fine tune the methods.

In the Qualitel method the scheme used to obtain the rating for a criterion from the ratings of its sub-criteria is usually based on look-up tables (e.g. Figure 2), which are a form of matrix relation. The way the ratings of the sub-criteria are combined varies. In the example of Figure 2 if the sub-criteria have ratings 1 and 3, then the criteria has rating 1. In the example of Figure 17 ratings 1 and 3 (for sub-criteria circulation finishes and hall finishes, respectively) imply rating 2 for the criteria (finishes of the circulation areas in the common parts). No systematic way of combining the ratings for the sub-criteria is used and the ratings of the sub-criteria are assumed to be precise, without taking into account uncertainty or confidence in the estimates. Furthermore, concepts are assumed mutually exclusive when they are sometimes strongly interrelated.

finishes of the circulation areas in the common parts

		hall finishes					
		none	1	2	3	4	5
circulation finishes	1	1	1	1	2	2	3
	2	2	1	2	2	3	3
	3	3	1	2	3	3	4
	4	4	1	2	3	4	5
	5	5	1	2	4	5	5

Figure 17 - Example of combination of ratings of sub-criteria in Qualitel method.

Similar comments can be made about the SEL method. A weighted sum is used to combine the ratings of the sub-criteria in order to obtain a global mark for each sub-set of criteria (W1, W2 and W3, referred to in section 2.4).

There are no attempts at systematising the combination of information from experts and users known to the author. NHBC has a scheme to analyse defects and site problems (see Figure 14), but there is no mathematical basis. Qualitel and SEL had several updates, in order to respond to technical and social changes, but again no mathematical model has been used to systematise the process of combining information from experts and users.

In summary, the ways in which information is combined in existing dwelling quality evaluation methods are simple and based on common sense.

In the opinion of the author, several reasons justify the approach used in these methods:

- The need for a simple solution, to make the method easy to understand and to use:
- The need to handle the complexity and variability of dwelling construction (although some pre-fabricated elements are used, there is a strong workmanship component).
- The need to include geographical (climatic) and social influence on the notion of quality of a dwelling. This leads to a set of criteria which are applicable only within a limited country or region.
- The lack of techniques for quality evaluation of dwellings.
- The fact that a long period of time is necessary to establish the performance of a material or a constructive solution.

Fuzzy set theory is a mathematical tool to deal with information which can be vague or ambivalent (Zadeh 1965, 1988; Blockley 1980). It is much closer in spirit to human thinking and natural language than traditional bivalent logical systems, providing an effective means of capturing the approximate and inexact nature of our perception of the real world.

In traditional crisp sets an element of the universe of discourse, say a, belongs or does not belong to the set, say A, i.e. $a \in A$ or $a \notin A$.

When using fuzzy sets, a membership function μ is defined which establishes the degree of membership of an element a to a fuzzy set A. The membership function measures to what extent an element belongs to a set. The example of hot water illustrates the idea (see Figure 18). In a given context (e.g. bath water) this notion could be exemplified by the upper graph of Figure 18: at 80°C water is usually considered to be hot. On the other hand, water at 40°C is usually accepted as not hot. Somewhere in between, opinions are not so consistent. Natural language allows some imprecision or *fuzziness*, like quite hot, not very hot and fairly hot. The degree of membership can be interpreted (Baldwin 1979) as the support for a given assertion. In the above example, it can be seen as the percentage of people that would consider a water at a certain temperature to be hot. If water at 60°C is considered hot by 63 people over 100, then the membership function should take the value 0.63 at 60°C (see Figure 18).

Operations on fuzzy sets have been defined in order to model human reasoning. As an example, it is worth noting that the intersection of fuzzy sets may be pointwise defined as the minimum of the membership function. Using as an example the functions shown in Figure 18, which illustrate the concepts of hot water and water safe temperature in a given context, the intersection of the corresponding fuzzy sets would represent the concept of water temperature that is simultaneously hot and safe. The resulting membership function is shown in Figure 19. This is equivalent to the rule that emerges from the fact that bad ratings should not be balanced with good ones when evaluating a criterion[2] (quality should be homogeneous). The data of Figure 2 is analogous to that of a fuzzy relation, since the minimum of the two values is usually taken as the rating of the criterion (exception made to ratings 3 and 5 which imply rating 4 instead of 3).

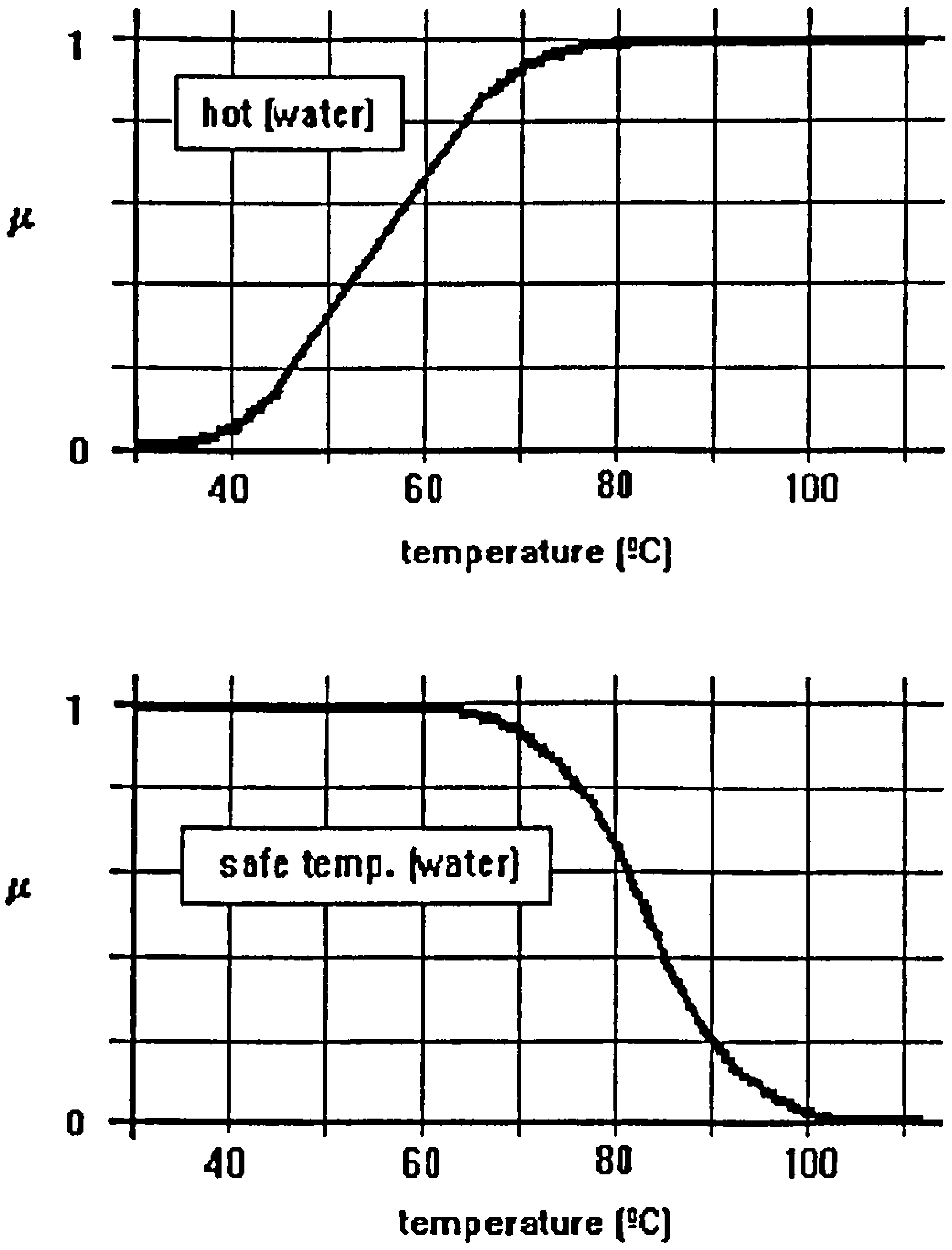

Figure 18 - Examples of membership functions of fuzzy sets.

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[2] In the case of the example both fuzzy sets are defined relatively to the same variable (water temperature). If two fuzzy sets are defined by their membership functions $\mu_A(x)$ and $\mu_B(y)$ relatively to two different variables $x \in A$ and $y \in B$, then their intersection (fuzzy cross product) may be defined in AxB space as

$$\mu_{AxB}(x,y) = [\, \mu_A(x) \wedge \mu_B(y)].$$

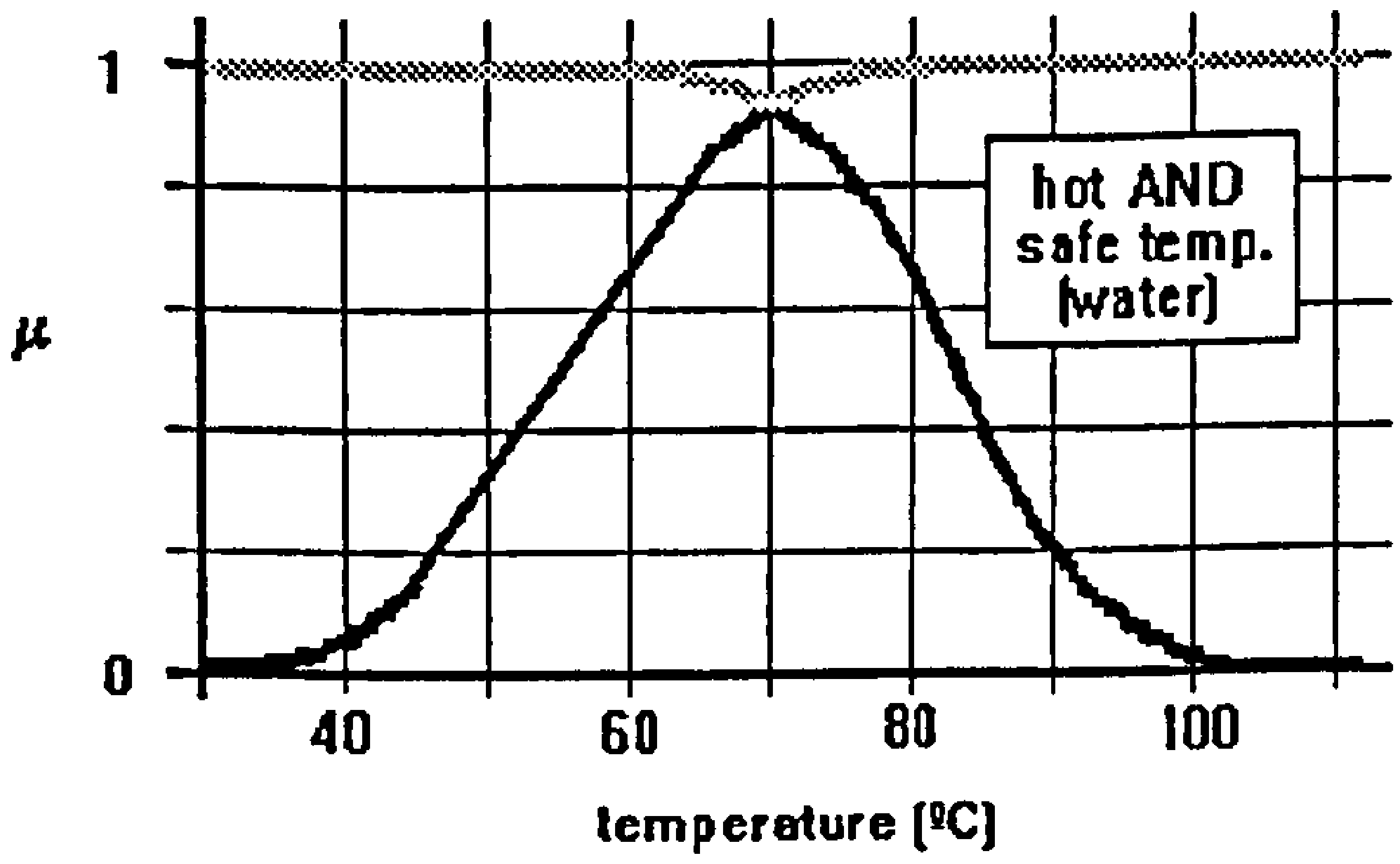


Figure 19 - The intersection of the fuzzy sets in Figure 19.

However these fuzzy set operations imply a total dependence between the sets which may not be the case. A much more general algebra is available through the use of interval probability theory (Cui and Blockley 1990).

2.9 Summary

Quality has been defined as fitness for purpose.

The schemes for quality evaluation in France, Switzerland, Portugal and United Kingdom have been presented, compared and discussed. None of these methods is fully comprehensive: SEL and Qualitel are adequate to evaluate the quality of dwelling designs, while the approach taken in the UK by NHBC is to supervise the construction process. Even so they are a valuable contribution to the improvement of quality and provide a basis for the development of a more comprehensive scheme.

The analysis of these methods helped in identifying some important aspects of quality evaluation, which were relevant to the design of QDF:

- the aspects to be evaluated,
- the evaluation criteria for each method,
- the evaluation procedures to produce a partial or global rating.

3. The object-oriented paradigm

3.1 Objectives

The objectives of this chapter are:

- to define the characteristic features of a computer system suitable for modelling complex artefacts, more specifically dwellings,
- to show that OOP is adequate for this task,
- to present some important object-oriented concepts,
- to introduce modelling concepts and the graphical notation that will be used to develop a QDF prototype,
- to review and compare some object-oriented languages and present the tool chosen to develop a QDF prototype.

3.2 Introduction

Modelling a complex artefact like a dwelling requires for a systematic approach. In order to implement a model on a computer, the solution requires appropriate computer modelling techniques and tools.

A brief analysis of some of the important aspects to be taken into account when choosing a computer modelling framework follows.

As languages gain more functionality and expressive power, more attention needs to be devoted to software engineering issues. How should a software system be designed and implemented? Meyer (1988) defines five key aspects of software quality, that he calls external quality factors. They are important for software users:

- **Correctness** is the ability of software products to perform exactly their tasks, as defined by the requirements and specification.
- **Robustness** is the ability of software systems to function even in abnormal conditions.
- **Extendability** is the ease with which software products may be adapted to changes of specifications.
- **Reusability** is the ability of software products to be reused, in whole or in part, for new applications.
- **Compatibility** is the ease with which software products may be combined with others.

The referred qualities may seem obvious or not relevant. Experience proves that small software systems are usually easy to implement and maintain. This does not apply to large software systems (e.g. the model of a dwelling), which call for different strategies to design and maintain them (solutions used for small programs are usually not scalable), i.e. how should software systems be built in order to achieve the qualities listed above? Different authors have different opinions about the solution for this problem. Nevertheless, there is a common belief that in order to improve on software quality software has to be **modular**.

Modularity has been the key concept to engineering practice. Software engineering is now entering a stage of development where this concept becomes very important. Cox (1990) expresses the view that software construction has to abandon the stage where "everything in the software domain is unique, composed of modules and routines that have never been seen before and will never be seen again". Software production has to enter another stage, where programmers will assemble new systems from libraries of reusable software modules. That is what happened in the industrial revolution: hand-crafted artefacts entirely made by one person were substituted by artefacts assembled from parts produced separately by specialised workers. **Modularity** is the key issue: it simplifies production and maintenance. Cox thinks that a software industrial revolution will occur as a solution to the actual software crisis. Large software systems are too costly, of insufficient quality and their development is very difficult to manage.

Meyer (1988) agrees that the solution is based in **modularity**. He defines five criteria that help evaluate design methods with respect to modularity:

- **Modular decomposability**: the method helps in the decomposition of a new problem into subproblems.
- **Modular composability**: the method favours the production of software elements which may be freely combined with each other to produce new systems.
- **Modular understandability**: the method helps produce modules that can be separately understood by a human reader.
- **Modular continuity**: the design method is such that a small change in a problem specification implies changes in a module or a few modules of the designed system, rather than in the architecture of the system.
- **Modular protection**: the method yields architectures in which the effect of an abnormal condition occurring at run time in a module will be confined to that module (or will propagate to a few neighbouring modules only).

Object-oriented design methods meet these criteria. To ensure proper modularity at the implementation level Meyer (1988) defines the following software internal quality factors, that are key issues in ensuring that external factors are satisfied:

- **Linguistic modular units**: modules must correspond to syntactic units in the language used.
- **Few interfaces**: every module should communicate with as few others as possible.
- **Small interfaces (weak coupling)**: if any two modules communicate at all, they should exchange as little information as possible.
- **Explicit interfaces**: whenever two modules communicate, this should be obvious from the text of at least one of them.
- **Information hiding**: all information about a module should be private to the module unless it is specifically declared public.
- **Modules should be both open and closed**: modules should be open for extension, they should be closed in the sense that every module should have a well defined and stable interface (information hiding).

It is worth noting that Meyer gives strong emphasis to software engineering issues. In his view language support is essential in order to achieve better software quality. In this thesis the view that language support for the object-oriented paradigm is important is adopted. However it is thought that modelling and design concepts are the basics behind an object-oriented system. Adequate language support is important, by making implementation easier and more robust.

The key idea is modularity. Object-oriented modelling, design and implementation techniques are modern techniques for improving software quality, by providing a framework where software modularity is natural.

Object-oriented became a buzzword that implies the meaning "good" when referring to a software system. What does object-oriented mean? A loose definition is given by Rumbaugh (1991): "the term object-oriented means that we organise software as a collection of discrete objects that incorporate both data structure and behaviour". Rumbaugh focus his attention on object-oriented modelling and design. Implementation issues, namely language features that support object-oriented concepts, are desirable but not essential: "implementation of an object-oriented design is easiest using an object-oriented language. [...]. Even when an non-object-oriented language must be used, an object-oriented design is beneficial. Object-oriented concepts can be mapped into non-object-oriented language constructs.". The issue is the expressiveness of the language, because all programming languages are eventually converted to machine language.

As previously noted Meyer (1988) gives strong emphasis to language support for object-oriented concepts. He defines seven requirements for a system to be object-oriented:

- **Object-based modular structure**: systems are modularised on the basis of their data structures.
- **Data abstraction**: objects should be described as implementations of abstract data types (classes).
- **Automatic memory management**: unused objects should be deallocated by the underlying language system, without programmer intervention.
- **Classes**: every non-simple type is a module, and every high-level module is a type.
- **Inheritance**: a class may be defined as an extension or restriction of another.

- **Polymorphism and dynamic binding**: program entities should be permitted to refer to objects of more than one class, and operations should be permitted to have different realisations in different classes.
- **Multiple and repeated inheritance**: it should be possible to declare a class as heir to more than one class, and more than once to the same class.

Meyer developed the Eiffel programming language, that verifies these seven requirements. His view seems too restrictive as it would even exclude Smalltalk from being object-oriented. Languages and systems that are frequently said to be object-oriented do not usually have all these features, or support them only to a certain degree.

Wegner (1990) seems to have a more realistic approach. He divides the object-oriented paradigm into subparadigms, with respect to the language support for object-oriented concepts. Languages are classified in three classes (Figure 20):

- **object-based languages**: the class of all languages that support objects,
- **class-based languages**: the subclass that requires all objects to belong to a class,
- **object-oriented languages**: the subclass that requires classes to support inheritance.

This view is less restrictive than Meyer's, and is adopted in this thesis. It classifies as object-oriented not only languages like Simula, Smalltalk and Eiffel, but also C++, and other extensions to traditional procedure-oriented languages.

How should modularity be achieved? Object-oriented design methods provide an answer to this question. Some key object-oriented concepts will be briefly explained in the following sections.

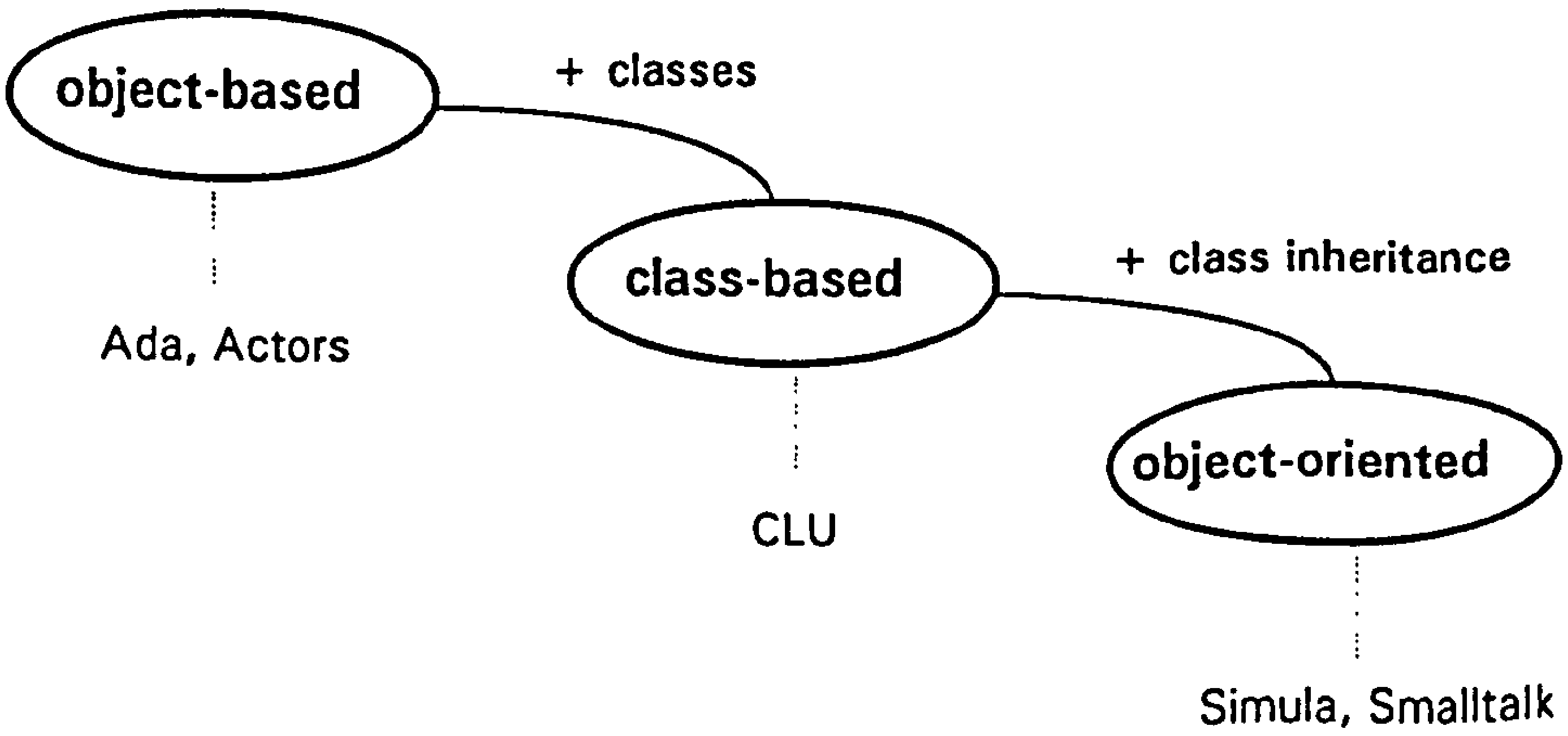


Figure 20 - Subparadigms of the object-oriented paradigm (source Wegner, 1990).

3.3 Object-oriented concepts

3.3.1 Objects

The central concept behind the object-oriented approach is the **object**.

Rumbaugh et al. (1991) define an object "as a concept, abstraction or thing, with crisp boundaries and meaning for the problem at hand".

According to Wegner (1990) an object is "a collection of operations that share a state". This state, embodied by some data structure, should be externally accessible only by the interface functions, usually called **methods**.

Examples of objects for a building contractor may be dwellings, customers, employees and prices. A dwelling object may have as data, its **attributes**, number of rooms, area and type (e.g. flat or house). This data is private to the object and can only be accessed by calling its methods. For example, in order to know the number of rooms of the dwelling a **message** should be sent that would invoke the corresponding method which returns the number of rooms.

The methods of an object define its **behaviour**.

The set of methods that can be externally invoked is known as the **interface** of the object. So, the interface defines the type of messages to which the object will respond.

Each object in an object-oriented system has a unique **identity**. "Two apples with the same colour, shape and texture are still individual apples, a person can eat one and then eat the other" (Rumbaugh et al. 1991).

The object-oriented paradigm narrows the gap between the data structures and the functions that manipulate them. It is possible with objects to represent both **passive** and **active** entities, as well as **static** and **dynamic** ones. These capabilities give to the object-oriented approach the capability to model some application domains in a natural way. This applies to artefact modelling in general and more specifically to the modelling of dwellings.

3.3.2 Encapsulation or data hiding

The ability to combine in a single entity, the object, both the data (**attributes**) and the procedures that manipulate that data (**methods**) is usually known as **encapsulation or data hiding**.

Cox (1986) claims that encapsulation is the foundation for the object-oriented approach, shifting emphasis from coding techniques to packaging.

The data structures in one object should only be externally accessed through the interface methods. This means that, even if the need arises to change the way the information is represented inside the object, the clients of the object will still be able to use the interface with no apparent difference. All the actions in a "pure" object-oriented environment come from the exchange of messages between objects.

From the user point of view, an object is a black box. This makes it possible to build applications that are easier to maintain and modify because they are easier to understand. Objects can be seen in a client/server way; each object is able to offer it's clients a number of services and is responsible for them (Wirfs-Brock, 1989).

3.3.3 Classes and instances

In most object-oriented systems objects are organised in object classes and object instances. Object classes are templates. Objects instances are created from these templates.

An object class is an abstraction, that defines the attributes and behaviour of the members of the class, representing a group of similar things. An object instance represents a single thing.

The class **houses** represents the skeleton from which the object instances representing **specific houses** will be created.

Some object-based systems are classless. In such systems all objects are object instances.

3.3.4 Abstraction

By organising objects into classes the object-oriented paradigm has a greater ability to abstract problems. According to Rumbaugh et al. (1991) "abstraction gives modelling the power and ability to generalise from a few specific cases to a host of similar cases".

Also code reuse comes from abstraction. Operations are written once per class for all objects of the class to use.

3.3.5 Inheritance

Inheritance makes it possible to derive a class from another class. A class will have the functionality of the class it has been derived from (its superclass) with the possibility of some aspects being changed. Using inheritance it is easier to extend a class, making a subclass to which the details that are missing will be added.

Inheritance is used in object-oriented systems to develop class hierarchies.

A class hierarchy captures "**a kind of**" relationship: a residential building is a **kind of** building. This type of relationship is usually used in **classification.**

Inheritance can be single or multiple. Single inheritance implies that a class only inherits from another class (its superclass). Multiple inheritance enables a class to inherit from more than one superclass. Figure 21 shows an example: a load bearing wall is both a kind of structural element and a kind of containment element.

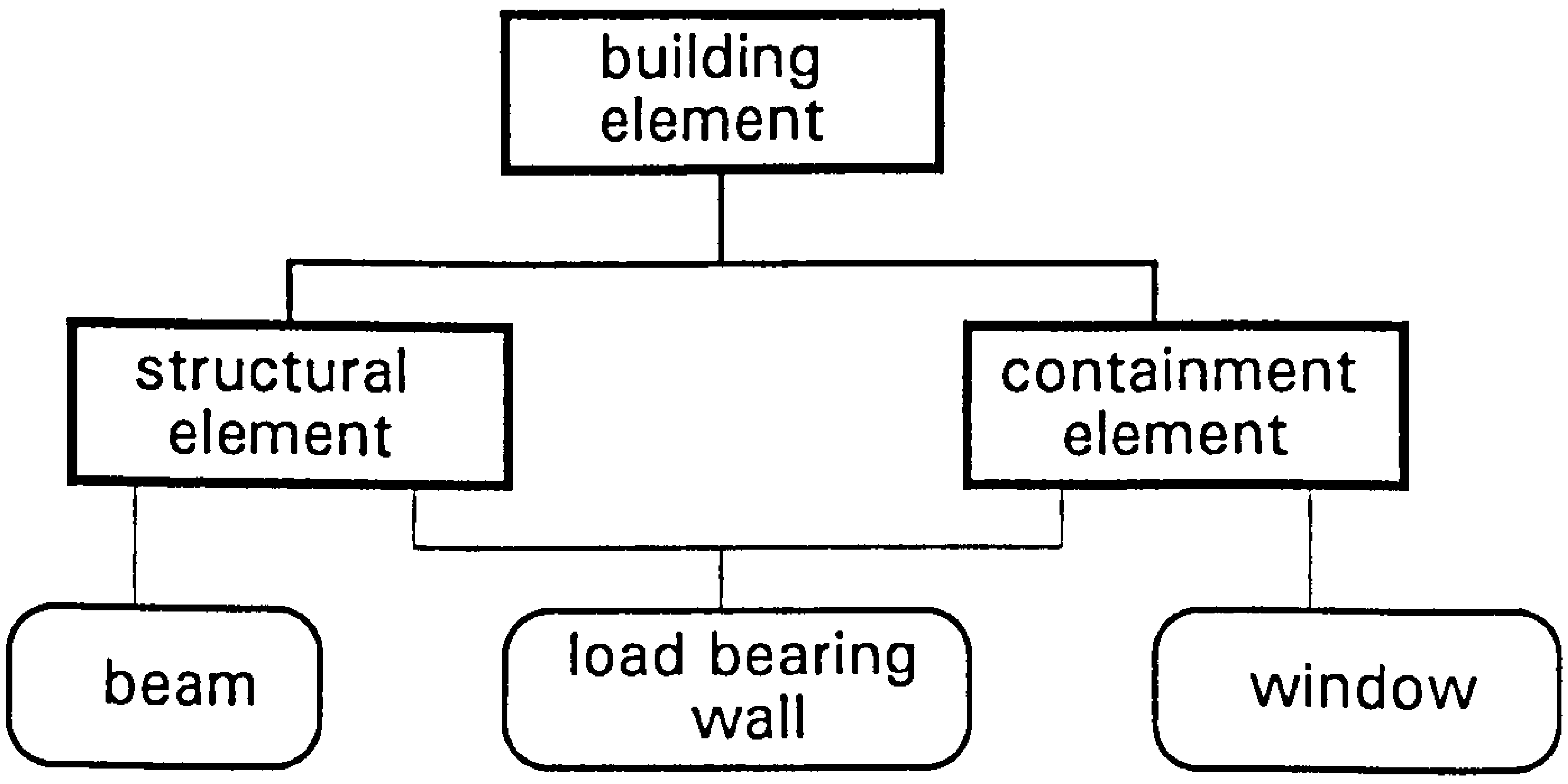


Figure 21 - Examples of single and multiple inheritance.

Inheritance can also be repeated if it is possible to inherit more than once from the same class (Meyer, 1988).

Some classless systems do not use inheritance. They use instead a language mechanism called delegation, in which objects are viewed as prototypes that delegate their behaviour to related objects.

3.3.6 Polymorphism

Polymorphism enables the system to use common names for the same kind of operations on different objects. Let's take the usual example of a class "shape", having as subclasses, also called derived classes, "triangle" and "quadrilateral". If the classes "triangle" and "quadrilateral" both have methods to move their positions, it makes sense that the methods will have the same name for objects of both classes. The programmer will only need to remember the name "move", for example, and use it whenever it needs to move one shape. The identification of the method that should actually be called when the message "move" is sent can be made at compile time or at run time. In the last case, the program can state that a shape should be moved, but only when the program runs, and depending on the actual data, will it be decided which method should in fact be used. This technique is called **late or dynamic binding**. Using polymorphism it is possible to reduce the number of identifiers in one application, reducing what is sometimes called the **surface area** of the application (Cox, 1986).

3.3.7 Links and associations

According to Rambaugh et al. (1991), "links and associations are the means for establishing relationships among objects and classes".

A **link** represents a connection between object instances. A house *belongs to* a person.

An **association** describes a group of links with common structure. "An association describes a set of potential links in the same way that a class describes a set of potential objects" (Rambaugh et al. 1991).

When developing a hierarchy different aspects of the relationships between component objects may be taken. Some of the aspects are:

- **"A kind of"** or **"is a"**: an object of a certain level is a **kind of** the object at the level above - e.g. a building is a kind of construction and a residential building is a kind of a building.
- **"A component of"** or **"a part of"**: the objects of a certain level are the components of one of the objects of the level above - e.g. a building is composed of columns, beams, walls, slabs, etc..
- **"A function of"**: the objects at a certain level are the functions of an object at a level above - e.g. the function of the skeleton is to act as a framework, to protect the internal organs.

As previously noted, **a kind of** relations are related to **classification** and are captured by inheritance.

Another important form of association is **aggregation**. It represents **"a part of"** or **"a component of"** relationship.

Sometimes the aspects **"a kind of"** and **"a component of"** lead to the same hierarchy. This is sometimes misleading. For example, a mammal is a kind of animal and the set of animals has as a component the set of all mammals.

Associations should be modelled as classes and links as instances. This approach leads to models that are more flexible and easier to understand. For example, the association **works-for** can be established between a **person** and a **company**. **Salary** and **job-title** should be attributes of the association works-for, instead of being attributes, for instance, of class person. If a person works for more than one company this would oblige class person to have salary and job-title attributes for each company. This is not a good design decision, because it will make class person dependent on the number of companies someone works for.

When an association is defined between two classes, roles are attached to each end of the association. In the works-for association mentioned earlier a person assumes the role of employee with respect to a company; a company assumes the role of employer with respect to a person. A role can be viewed as a collection of responsibilities with consistent objectives (Platt 1993, 1994).

3.4 Modelling and design

The object-oriented approach to software development (analysis, design and implementation), benefits from a synergetic effect. Some of the key features of object-oriented systems are present in other approaches, but the fact that they can be combined together results in a better use of each of them.

In order to benefit from the potential of object-oriented techniques, attention has to be paid to the various steps involved in the development of a software system:

- analysis - development of a conceptual model,
- design - development of a software model,
- implementation - development of a program code model.

Figure 22, from Dilon (1993), shows these steps. By analysing, abstracting and representing the real world a conceptual model is constructed. The model only takes into account the aspects that are relevant to the problem to be solved. In the next stage the conceptual model is adapted to a model suitable for computer implementation (a software model). In the last stage the software model is mapped into a programming language.

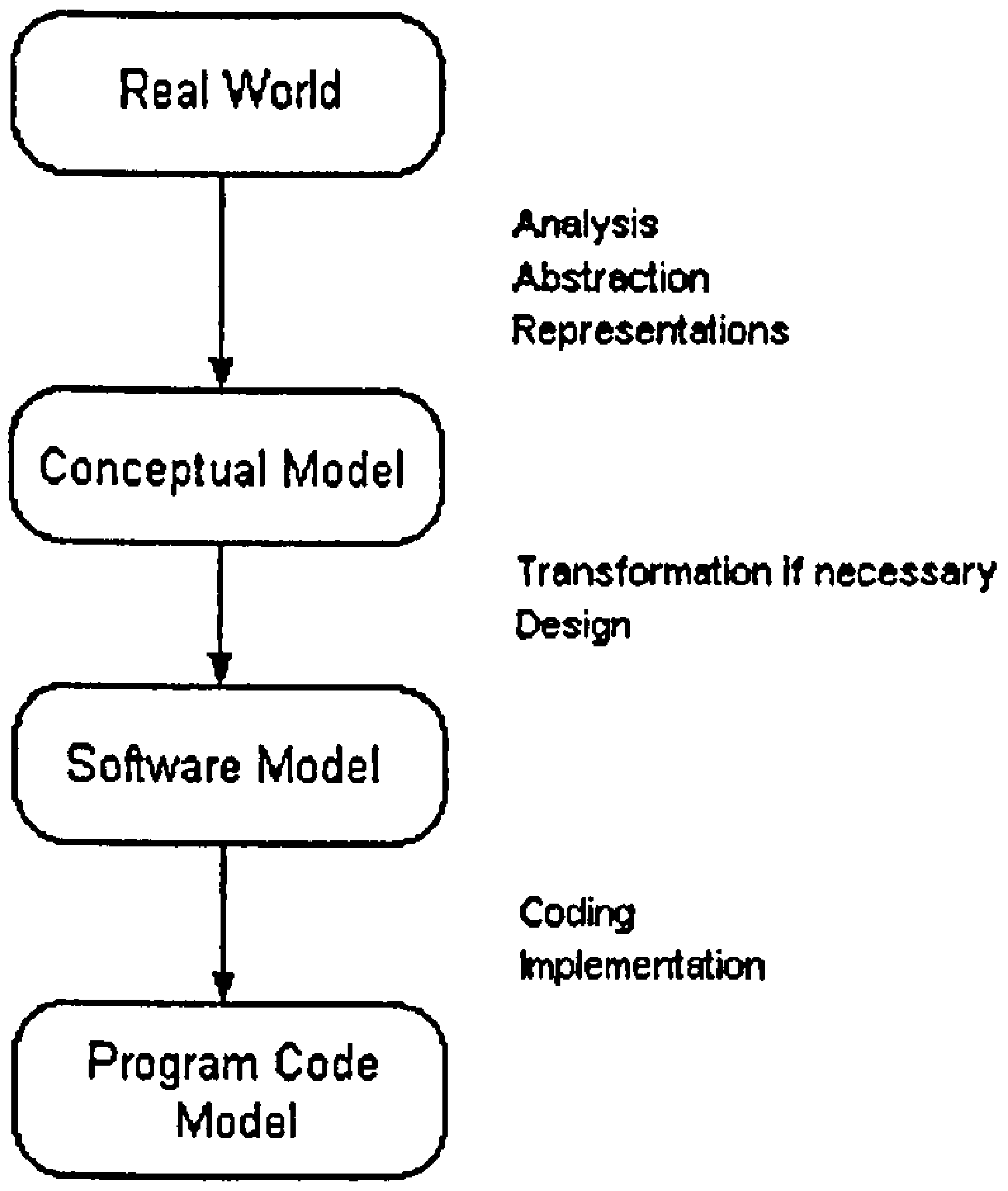


Figure 22 - Analysis, design and implementation of a software system (source Dilon 1993).

A graphical notation is usually useful in the analysis and design phases. The graphical notation proposed by Rambaugh et al. (1991) has been adopted in this thesis.

Figure 23 shows the notation for classes and instances. Class **Dwelling** may has as attributes **owner** (string) and **number of rooms** (integer). One instance of class **Dwelling** may be a flat with 2 rooms and owned by Joe Dexter.

The complete graphical notation of a class is shown in Figure 24. Attributes and methods are listed in separate sections. In the example class **Dwelling** has two methods: **change-owner** which takes a string (the new owner) as parameter and does not return anything; and **get-age** which takes no parameter and returns an integer (the age of the dwelling).

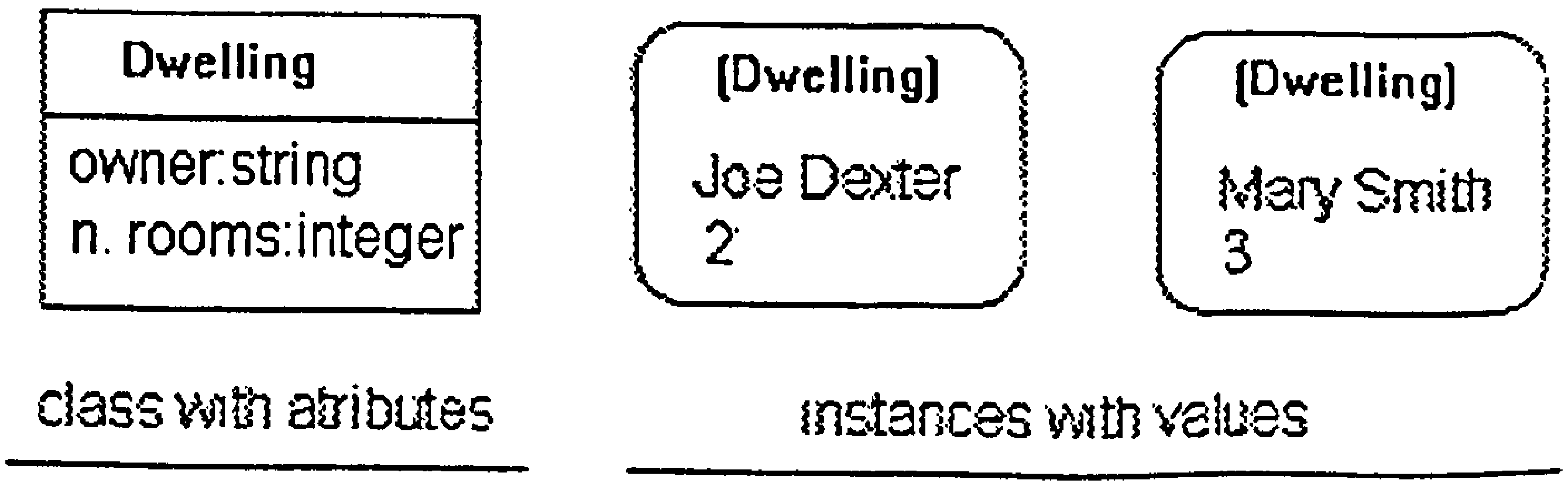


Figure 23 - Notation for classes and instances.

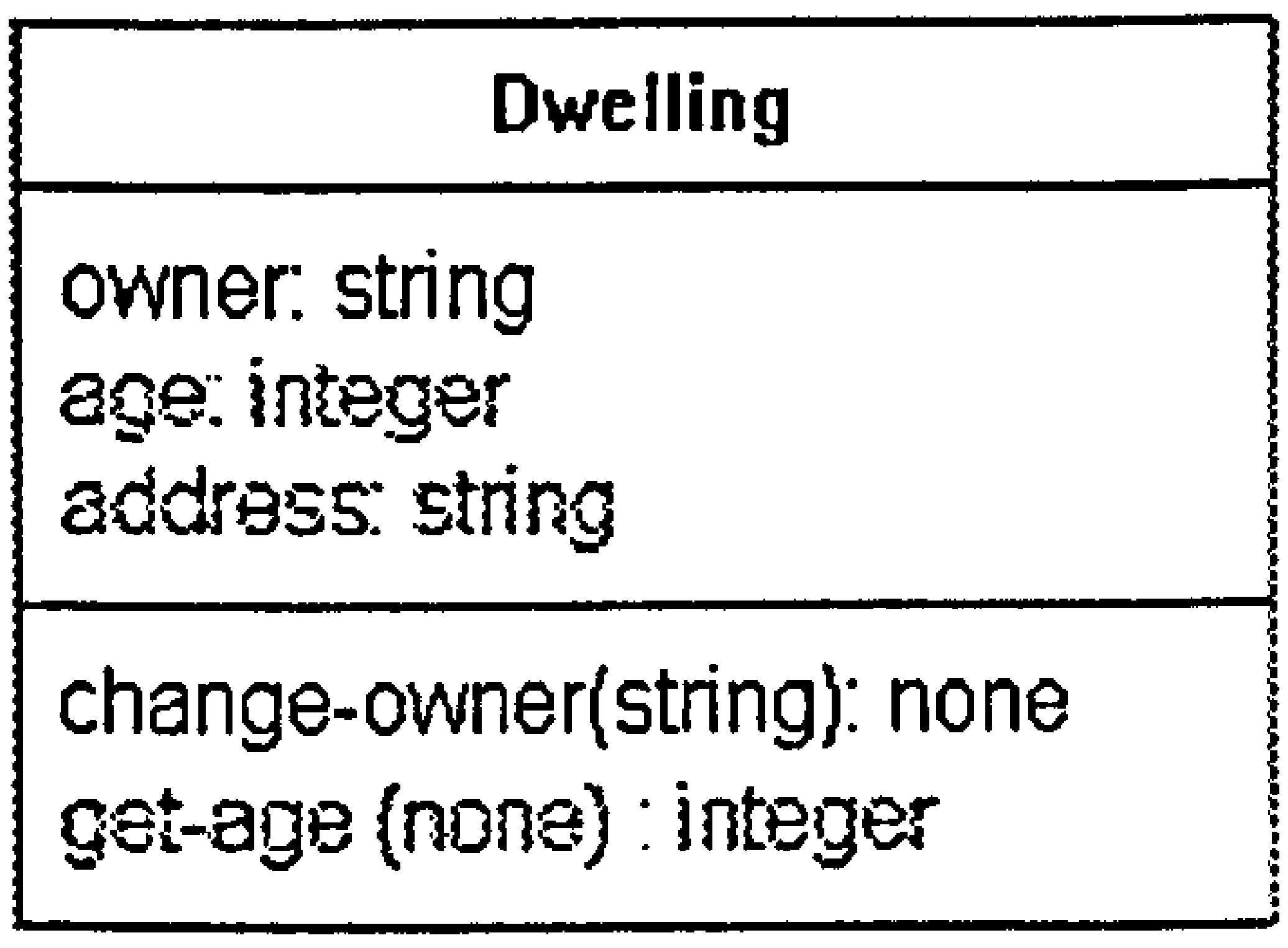


Figure 24 - Notation for class with attributes and methods.

Figure 25 shows the graphical notation for associations and links. The association has-owner is defined between classes **Dwelling** and **Person** and is written over or above the line representing the association. The cardinality of the association may be also shown: a **Dwelling** has one or more (1+) owners and a **Person** owns zero or more (•) dwellings. The symbol for zero or one is an open circle (o). A link relates two instances. A Person named Mary Smith owns a flat. Another Person named Joe Dexter owns a semi-detached house.

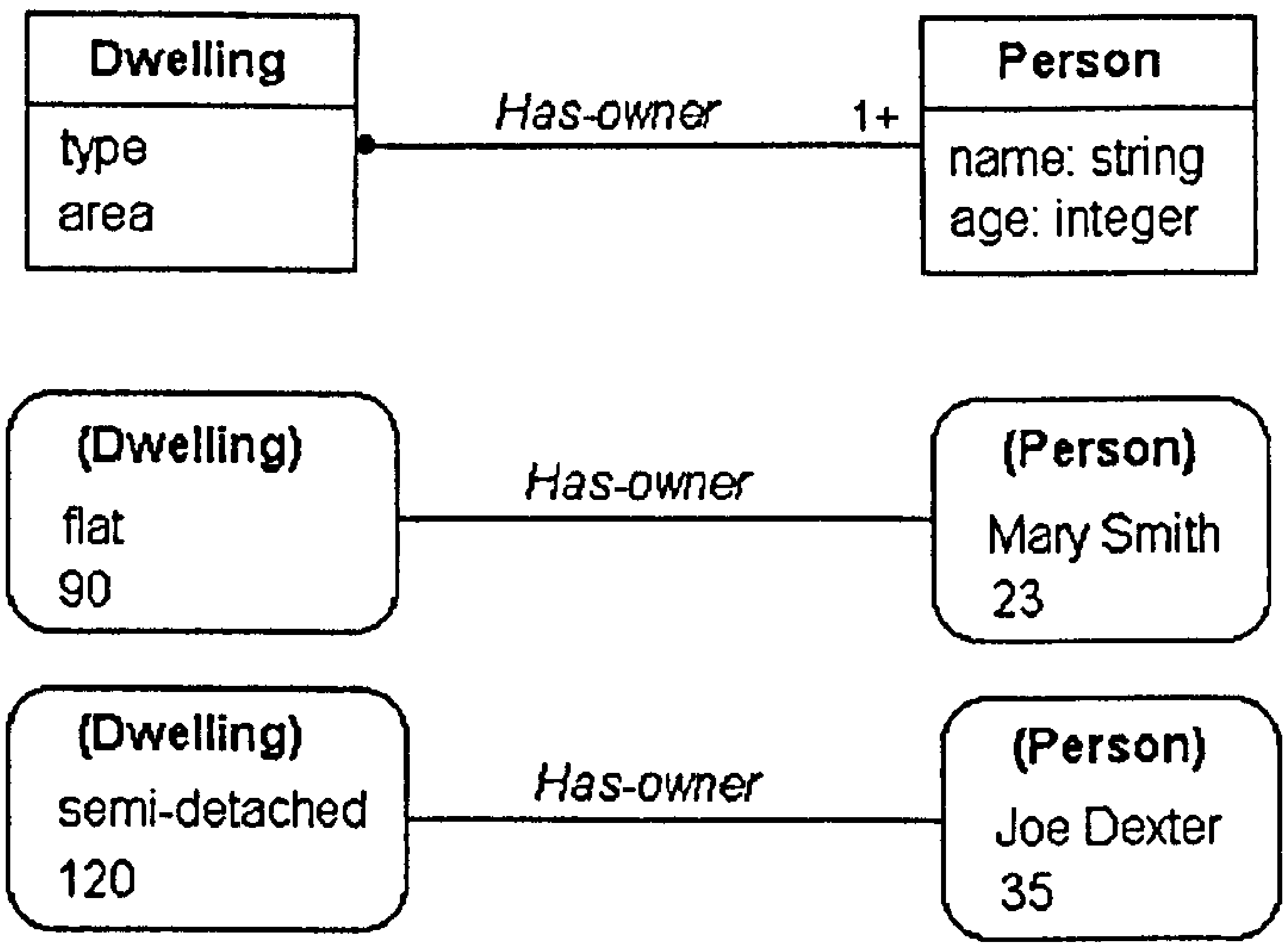


Figure 25 - Notation for associations and links.

Associations should be modelled as classes and links as instances. In this way associations may have attributes and methods. Figure 26 shows an example for the association **works-for** between classes **Person** and **Company**. The attributes considered in this association are salary and **job-title**.

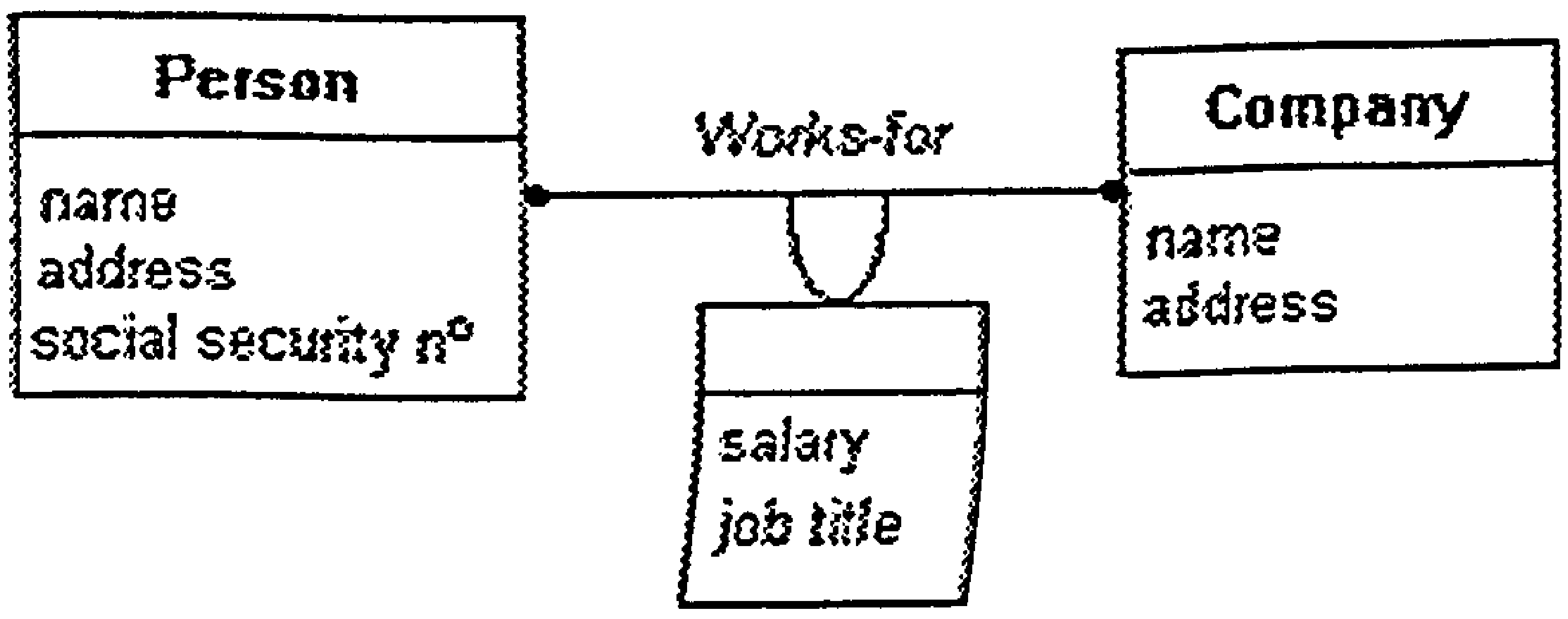


Figure 26 - Association with attributes.

Figure 27 shows the graphical notation for role names. The role names are listed in the appropriate end of the association. In this example a person plays the role of an employee and a company plays the role of an employer.

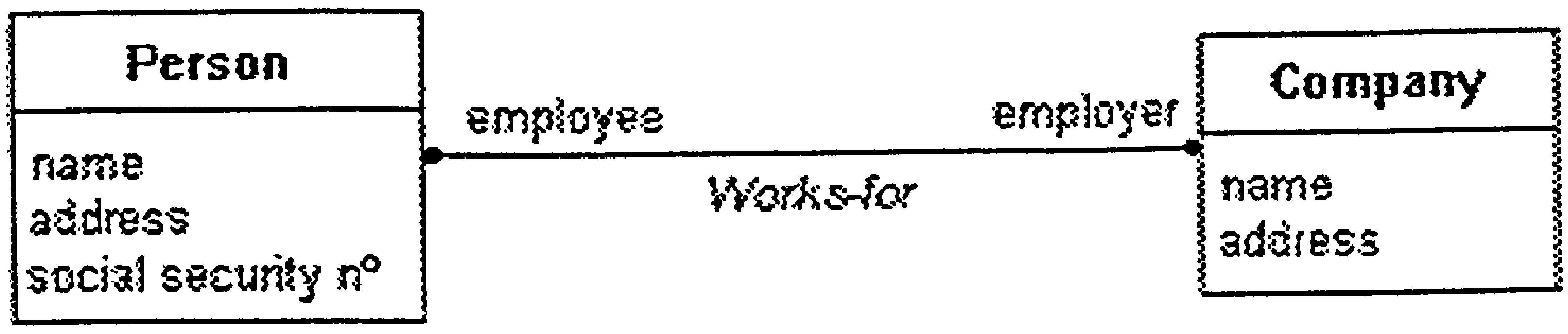


Figure 27 - Role names.

The symbols for a-kind-of and a-component-of are shown respectively in Figure 28 and Figure 29.

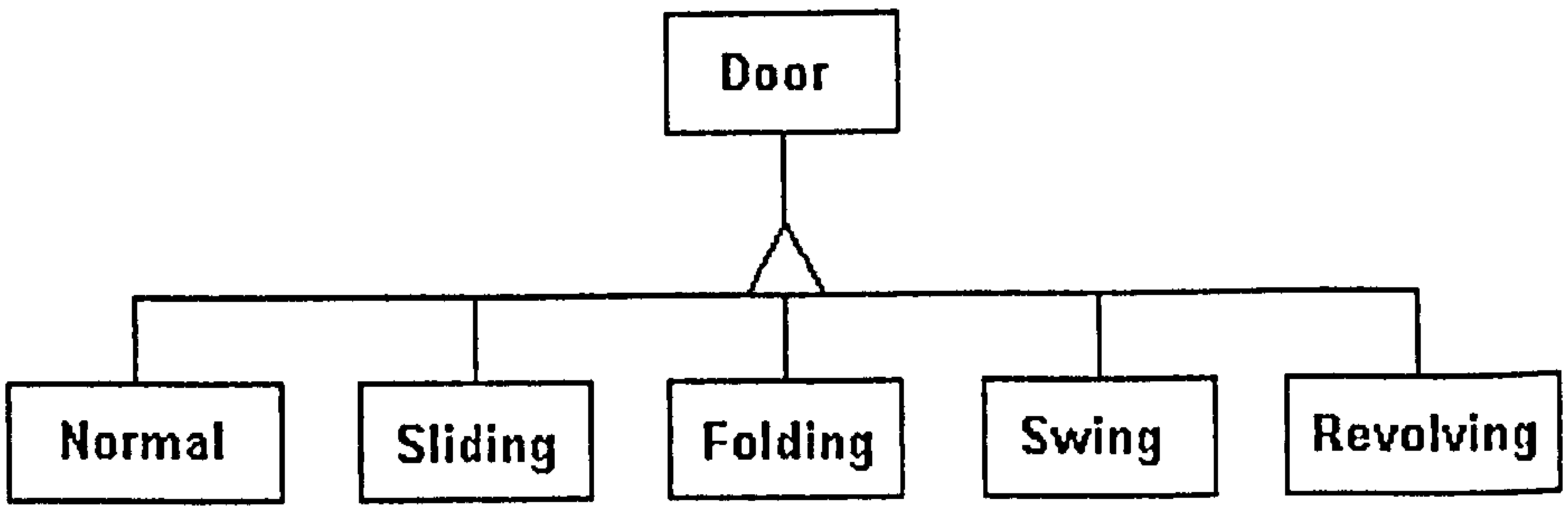


Figure 28 - A kind of hierarchy (inheritance).

3.5 Object-oriented languages

According to Booch (1994) there are currently more than 100 object-based or object-oriented languages. The first object-oriented language was Simula, a language for describing systems and develop simulations. Simula introduced the idea of writing programs that use the vocabulary of their problem domain, together with encapsulation and inheritance.

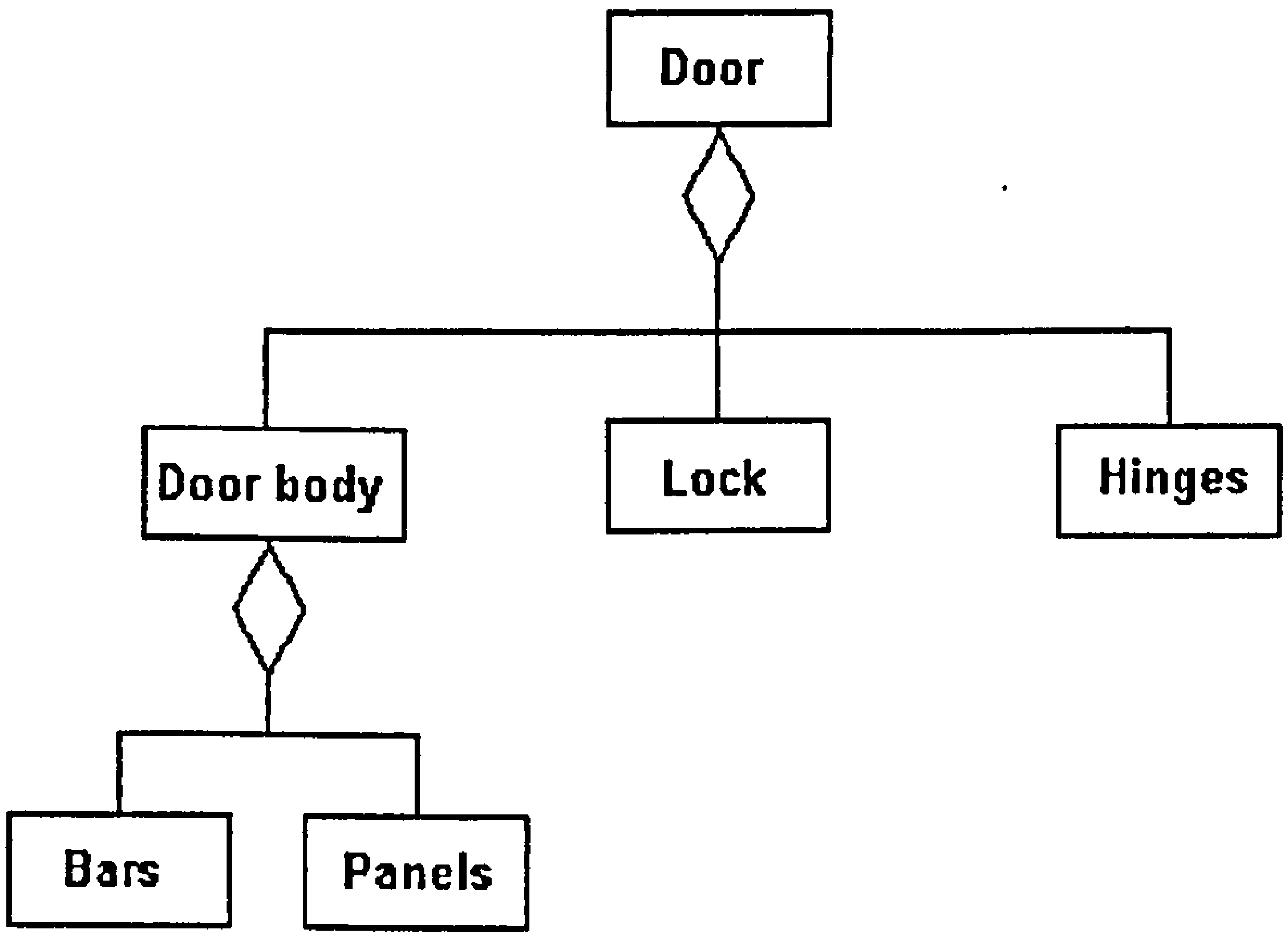


Figure 29 - A component of hierarchy (aggregation).

Figure 30, derived from Booch (1994), shows the genealogy of the more important object-oriented languages. Smalltalk and Eiffel are "pure" object-oriented languages, design to fully support this paradigm, while C++ and Object Pascal are extensions of procedural programming languages, with support for object-oriented concepts.

It is very difficult to mix different programming paradigms in the same system (Wegner 1990). The object-oriented paradigm, because objects support modularity in a natural way, is especially well suited to multiparadigm approaches and has been used in developing such tools. KAPPA is a programming environment, developed by Intellicorp, Inc., that has been used to experiment with the framework developed in this thesis. KAPPA supports the object-oriented programming paradigm, as well as rule-based reasoning. It includes an object-oriented language named KAL.

Figure 31, derived from Booch (1994), shows a comparison of several object-oriented languages, including KAL.

An introduction to KAPPA is presented in the following section.

3.6 KAPPA

The information presented here is based in the KAPPA-PC manuals (1992), Joseph (1991) and Lydiard (1990).

KAPPA-PC is written in the C programming language and runs under Microsoft Windows for IBM compatible micro-computers. It is a strongly object-oriented system and provides a wide range of tools for constructing and using applications.

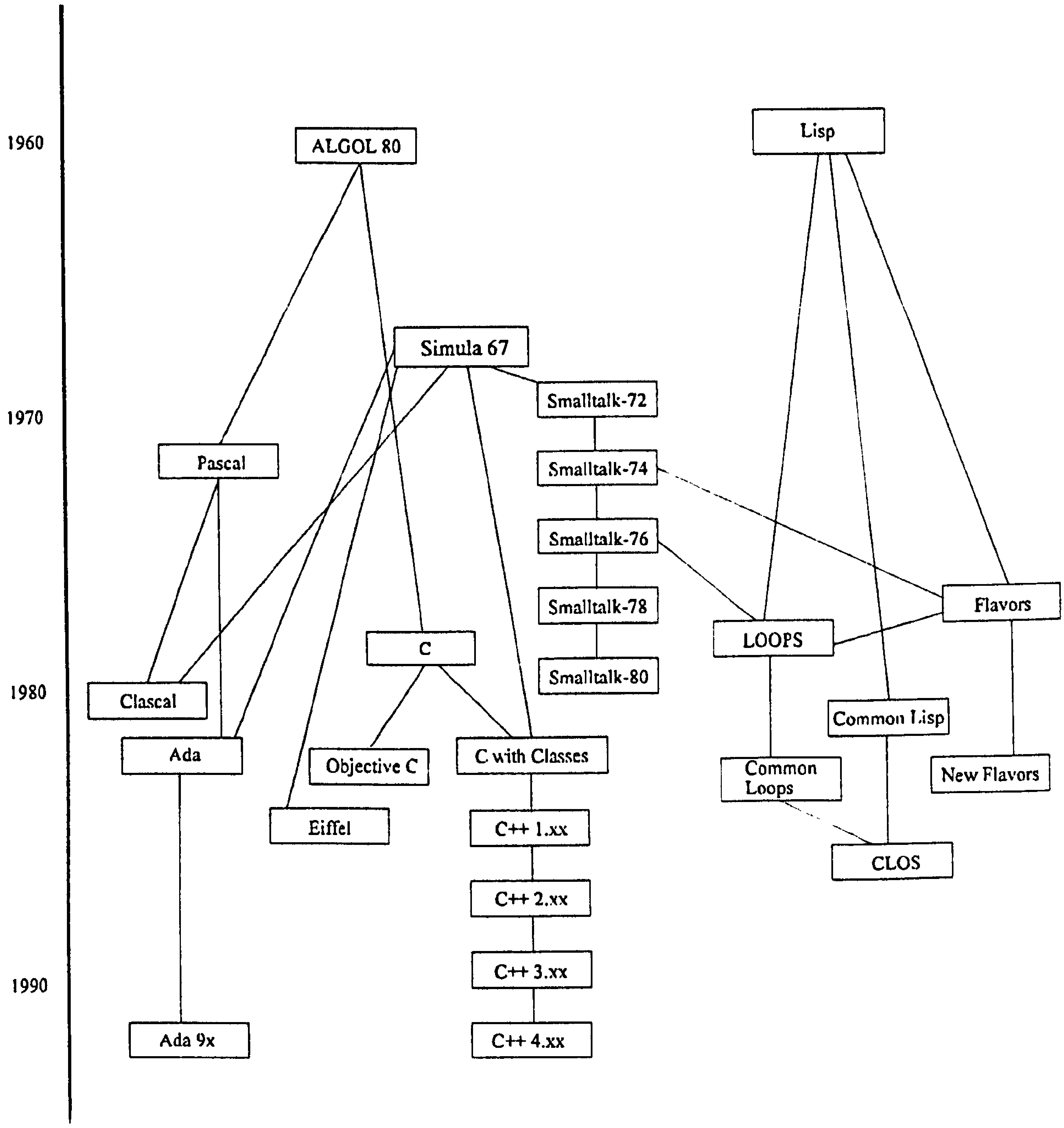


Figure 30 - Genealogy of object-based languages (source Booch 1994).

The components of a domain are represented by objects. Objects are organised into classes, subclasses and instances, using inheritance (single). Object attributes are called slots. The slots of a parent are inherited by its children (subclasses and instances). Each slot can have a value that is inherited by default. For the value not to be inherited the slot must be made local at the required level. A slot can contain a single value or multiple values of type text, number, Boolean or reference to another object.

Characteristics		Language						
		Small-talk	Object Pascal	C++	CLOS	Ada	Eiffel	KAL
Abstraction	Instance variables	yes	yes	yes	yes	yes	yes	yes
	Instance methods	yes	yes	yes	yes	yes	yes	yes
	Class Variables	yes	no	yes	yes	no	no	yes
	Class Methods	yes	no	yes	yes	no	no	yes
Encapsulation	Of variables	private	public	public, protected, private	reader, writer, accuser	public, private	private	public
	Of methods	public	public	public, protected, private	public	public, private	public, private	public
Modularity	Kinds of modules	none	unit	file	package	package	unit	none
Hierarchy	Inheritance	single	single	multiple	multiple	no, part of Ada9x	multiple	single
	Generic units	no	no	yes	no	yes	yes	no
	Metaclasses	yes	no	no	yes	no	no	yes
Typing	Strongly typed	no	yes	yes	optional	yes	yes	no
	Polymorphism	yes, single	yes, single	yes, single	yes, multiple	no, part of Ada9x	yes	yes
Persistence	Persistent objects	no	no	no	no	no	no	yes

Figure 31 - Comparison of object-oriented languages.

Objects can have methods which define their behaviour. KAPPA-PC contains some special methods called monitors that are attached to a slot. There are four types of monitors:

- If Needed - the method is executed whenever the value of the slot is requested and it has no value.
- When Accessed - the method is executed when the slot is accessed.
- Before Change - the method is executed just before a new value is assigned to the slot.
- After Change - the method is executed just after a new value is assigned to the slot.

Objects inherit methods in a similar way that they inherit slots. Methods can also be made local at a certain level. All the objects in the hierarchy below the level at which the method has been made local inherit the new method.

Methods can be used to change the state of the application, generally by:

- changing slots values in an object;

- sending messages, either to the same object or to other objects,
- activating other facilities of the KAPPA-PC system, such as rule based reasoning or data access,
- activating other applications.

Objects, slots, methods, rules and images can be created using the developer's interface or the KAL language. Methods, functions and rules have the same syntax. The interface is very user-friendly (see Figure 32), but the KAL language provides a more effective way of developing an application.

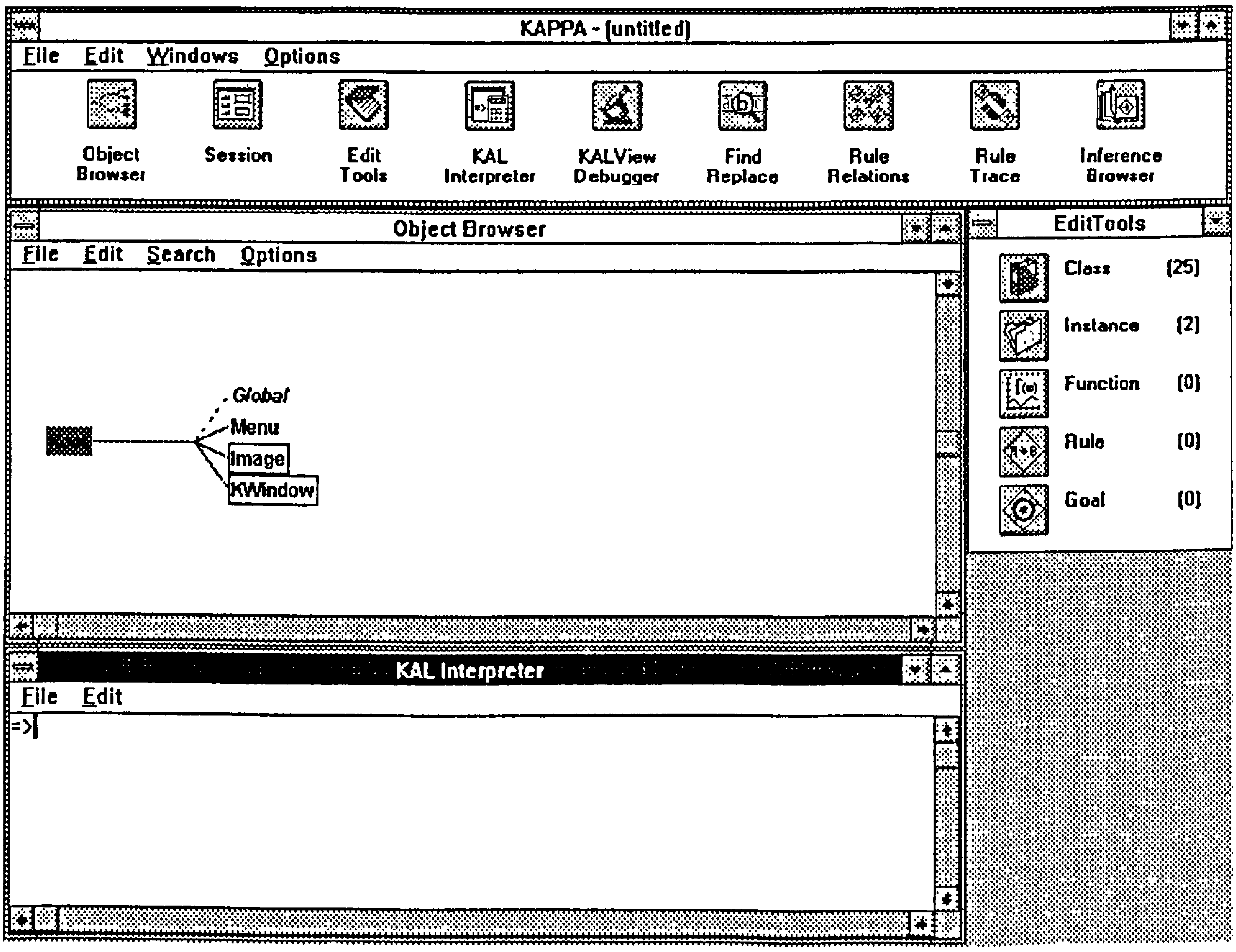


Figure 32 - Example of KAPPA main menu.

KAPPA objects are persistent, which makes it possible to save all objects of an application in the state they are and load and proceed with the application later.

The KAL language does not have strong typing. Automatic conversion is performed between different types, when possible.

As mentioned before KAPPA-PC allows rule based reasoning. The rules use the **If...Then** format and are not implemented as objects. It is possible to reason using forward chaining or backward chaining, but this must be decided "a priori" and not during the process of reasoning. Forward chaining proceeds from premises towards conclusions. It is touched off by the entry of a new fact. Using backward chaining it is necessary to begin asking the inference engine whether a certain fact can be established. The objective is to find a rule whose conclusion matches this question or goal. Backward chaining proceeds from conclusions to premises. This is more commonly used.

Forward chaining is most appropriate when it makes sense to enter new facts and find their consequences. This is the case of simulation. Backward chaining is most appropriated when specific information is needed. This is the case of diagnosis.

The following reasons influenced the decision of choosing KAPPA for experimenting with QDF:

- To be object-oriented.
- To have persistent objects.
- To be an integrated development system, not only a programming language.
- To have good interfacing facilities with Microsoft Windows and with the C programming language.
- To have the possibility of being used for procedural programming as well as for declarative (rule based) programming.
- To have good facilities to develop a user-friendly interface.
- To be very user-friendly.
- To be relatively simple to learn.
- To be available for more than one platform (Windows and UNIX).
- To be a mature tool and have a well organised user group (KAPPA User's Group).

KAPPA has been used to experiment with object-oriented programming and to implement the prototype described in this work. It is powerful, flexible and very user-friendly. Its major weaknesses are the lack of robustness (it crashes when the size of the program becomes large - a solution based in a manual swapping mechanism has been implemented, but at the cost of extra development time) and the poor performance of the debugging facilities.

3.7 Relevance of OOP in modelling complex products

It is difficult to model a complex product using a simple model. The model developed in this thesis for modelling dwellings, QDF, is complex and calls for an adequate methodology in order to make it suitable for computer implementation. Although only a computer prototype of QDF has been implemented, a comprehensive methodology has been developed to allow for a real scale system to be implemented in the future.

It is usual in engineering practice to divide a complex problem in simpler subproblems in order to make it easier to solve. This is the key idea behind modularity in software engineering, which is behind the success of the object-oriented approach to software development. Object-oriented methodologies, centred around software objects which are responsible for the services they offer to their clients, provide a convenient way to build and maintain modular programs, as it has been shown in the previous sections. QDF was developed having modularity in mind and following an object-oriented methodology.

Important aspects of this approach are:

- composition - a dwelling is a complex system recursively composed of subsystems and elements (composition hierarchies, which are based in **a-part-of** relations),
- inheritance - each element of the dwelling is modelled as an instance of a class, with characteristic attributes and behaviour; classes are organised in hierarchies (classification hierarchies, which are based in **a-kind-of** relations).

To develop and present these hierarchies the graphical notation defined by Rambaugh was used.

Other aspects of the object-oriented approach to software development, although not so important in themselves, are important components of an object-oriented system. As with any system, the emergent properties of an object-oriented system result from the interactions between its components and go beyond the individual properties of the components (the object-oriented approach to software development is a systems approach). This is the essential property of a systems approach to modelling as distinct from the reductionist approach. There is no other approach to software development known to the author which can model the extremely complex relations and interactions of the elements of a complex system like a dwelling in a satisfactory way for computer implementation.

3.8 Summary

In this chapter the characteristic features of a computer system suitable for modelling dwellings have been presented, in order to chose a programming methodology. The object-oriented approach to software development (analysis, design and implementation) has been shown to be adequate for this task. Important object-oriented modelling concepts and the graphical notation that will be used to develop a QDF prototype have been presented. A brief comparision of some object-oriented languages, including KAPPA-PC, the tool used to develop a QDF prototype, has been made. Finally, the importance of object-oriented concepts to model complex products is referred and its influence in the development of QDF is analysed.

4. Product modelling

4.1 Objectives

The objectives of this chapter are:

- to present the definition and ideas behind current approaches to product modelling,
- to refer some attempts at product modelling,
- to refer the STandard for the Exchange of Product model data, STEP,
- to present some examples of product modelling related to buildings,
- to relate product modelling with the object-oriented programming paradigm and to QDF.

4.2 Introduction

Product data model according to Björk and Wix (1991) is a conceptual description of a product, capable of structuring all the information necessary for the design, manufacture and use of the product.

A conceptual model consists of a collection of entities, together with their attributes and relationships with other entities. An entity (or object) can be a class or an instance of uniquely identifiable things, events or notions (Danner, 1988). Product models are a sub set of conceptual models: they specifically describe artefacts that are tangible (Dias 1993a, 1993b, 1994).

The idea of creating a product data model appeared when the industries began to realise that it was difficult to exchange information between the different application programs and CAD systems they used to design their products.

Attempts have been made to exchange this information using digital techniques. The first two main options for such integration were:

- to use the same CAD system throughout the design and manufacturing process and to agree on the distribution of information on layers,
- to use bilateral translation programs or neutral transfer formats for the conversion of CAD drawing files between different programs.

IGES (Initial Graphics Exchange Specifications) was the first attempt at defining a neutral format for the exchange of basic graphic and some simple geometric data. It has been developed in the USA and the first version appeared in 1979. The development has continued throughout the years and it is used world-wide with varying levels of success in a variety of industries.

IGES is a very general specification. In parallel more research aiming to more specific needs was developed. Other standards appeared, namely:

- SET (Standard d'Exchange et Transfer) developed in France for the aerospace industry and now used in joint European aerospace projects,
- VDA-FS developed by the German automotive industry for the transfer of surface model data,
- PDDI (Product Data Definition Interface) project carried out for the USA Air Force,
- AutoCAD DXF (Data Exchange Format),
- BEC, a CAD Data Transfer Standard developed in Finland for the concrete industry.

Nowadays the use of computers in the industry is very generalised not only using design programs, as in CAD, but also using word processors, spreadsheets, etc. to store information related to the production and usage of a product. So the data formats referred above proved to be insufficient in the long run.

The aim of product modelling is to define a framework for storing in the computer all the information related to a product in an integrated way, so that whenever necessary that information will be available to produce any kind of document (e.g. a drawing, a calculation or a text document), instead of having different documents for different kinds of output, with unnecessary redundancy of information. Figure 33 (from Björk 1989), gives an idea of the complexity of the problem.

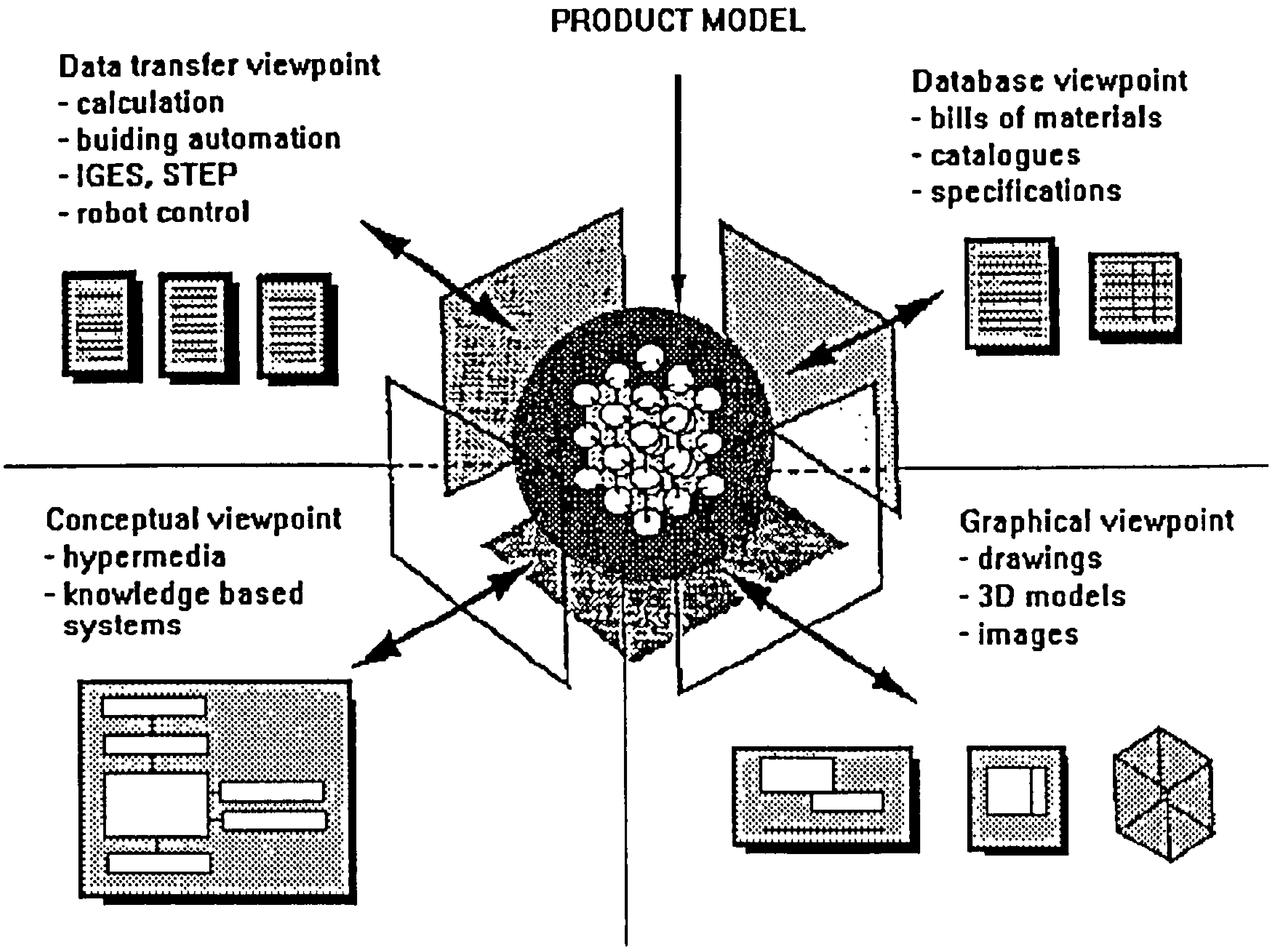


Figure 33 - The complexity of product modelling (source Björk 1989).

A product data model can be viewed as a common language for the description of a particular type of product or as a more complex and complete form of a traditional classification system, rather than as a single database.

According Björk and Wix (1991) a product data model should fulfil the following criteria:

- the model should be comprehensive. It should be capable of containing all kinds of data,
- the model should cover the information created during all stages of the design and manufacturing process,
- the model should not contain redundant data,
- the structure of output documents should be independent of the product model,
- the product model standard should only specify what information is contained in the product model. It should not specify how this information is physically stored in computers.

Following this idea and previous efforts, a world-wide project with the objective of creating an international standard for data exchange emerged. It was named STEP, STandard for the Exchange of Product model data.

4.3 STEP

4.3.1 Overview

Both in USA and Europe people felt the need of a standard that would be applicable in future CIM (Computer Integrated Manufacturing) systems. It was clear that the capability of exchanging basic graphic data and some simple geometric data was not enough for this kind of systems. A new standard should at least cope with the exchange of non-graphic data and three dimensional geometric data (Boyle 1992).

In order to solve these needs the Product Data Exchange Specifications (PDES) appeared in the US, with a final report in 1986. At the same time a similar effort was made in Europe through the International Standards Organisation (ISO) who commenced the development of the STandard for Exchange of Product model data (STEP) in 1984.

These projects were very similar. As a consequence of this they have been developed in collaboration under the secretariat of the US National Institute of Standards and Technology, but they remained separate until 1990. Then all the US activities were merged into STEP.

As STEP becomes the world-wide standard for data exchange many countries became either members or observers of this project, as shown in Figure 34 (Smith and Wellington 1992).

The development of STEP has taken around 8 years. This is due to the fact that it seeks to be a standard for a technology which remains largely undeveloped, namely advanced CAD/CAM/CIM and Product Modelling Systems, and also because many different countries, with different viewpoints and priorities are involved.

STEP aims to provide the framework both for specific and general information transfer. As the project is very large several working groups and projects were created to produce the different parts that will constitute it.

Members	**Observers**
Australia	Algeria
Belgium	Bulgaria
Brazil	China
Canada	Czechoslovakia
France	Denmark
Germany	Finland
Hungary	Poland
Italy	South Korea
Japan	Spain
Netherlands	
Norway	
Russia	
Sweden	
Switzerland	
United Kingdom	
United States	

Figure 34 - Members and observers of STEP.

The following areas have been studied:

- topology / geometry,
- structures,
- layered electrical products,
- materials,
- AEC (Architecture, Engineering and Construction) models.

According to Turner (1989) and Warthen (1989) in the development of STEP a three layer approach has been used. Different committees perform the tasks of each layer:

- **application layer** - each product of each discipline is described in writing and modelled using a formal graphic notation. The ones usually used are IDEF1X, NIAM or EXPRESS-G,
- **logical layer** - entities are extracted and it is determined which are unique to the discipline and which are general, or can be applied to two or more disciplines, the model is integrated or merged with other models for basic capabilities,
- **physical layer** - the integrated model is converted into a more computer like text based data definition language called EXPRESS, then a committee will determine the appropriate file format which will become the neutral file.

The modelling of a product begins with a universe of discourse, that is a native language description of the product, which describes the relevant objects of the product model and the relationships and constraints between them. From the universe of discourse a **conceptual model** of the product is created. This is a graphic based model and the languages IDEF1X, NIAM or EXPRESS-G are usually used to describe it (Turner 1989). A brief review of these languages is presented in the section 4.3.2.

A software tool to convert a NIAM diagram to an EXPRESS schema, called NESSIE (NIAM to Express Schema: Software Interface and Environment) has been developed by Kendall (1993). Using this tool the introduction of data becomes much easier. It allows also the division of large schemas, that are difficult to draw and manipulate, into logical sub-units that can be entered separately and organised in a hierarchy of inter-referencing sub-systems. To manage them there are facilities to aid navigation when going from sub-system to sub-system and also when travelling around in a single sub-system. A demonstration version for Microsoft Windows (IBM-PC) has been already released (NESSIE V1.0), which was used to produce the NIAM diagram shown in Figure 37, as well as the EXPRESS code of Figure 39. NESSIE main screen after designing the diagram of the example referred above is shown in Figure 35.

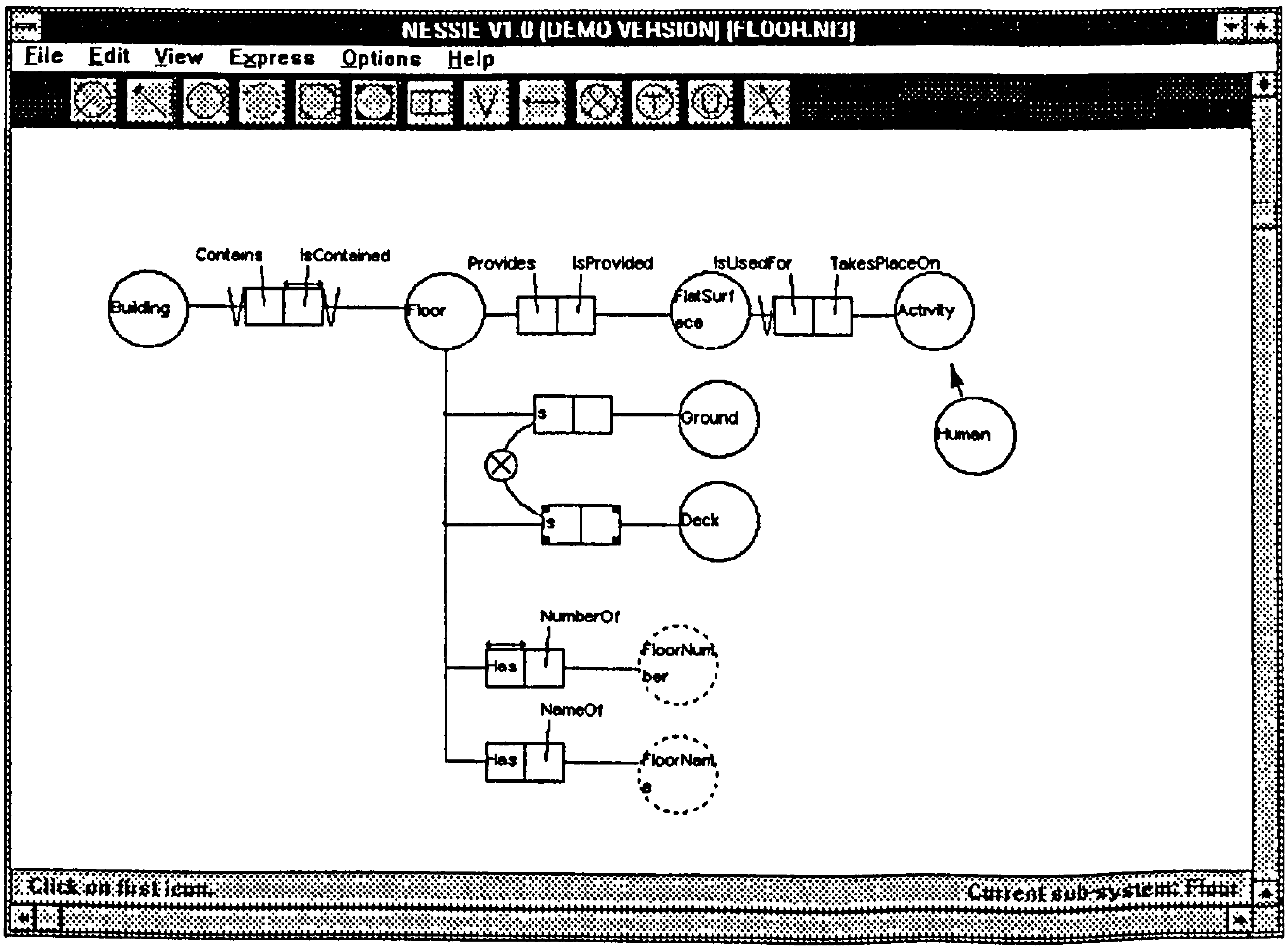


Figure 35 - NESSIE main screen.

4.3.2 Conceptual model languages

4.3.2.1 NIAM

NIAM (Nijssen Information Analysis Method) is one of the graphical languages used in STEP to create the graphic models (Williams 1989, Björk and Wix 1991).

Its basic data structures resemble the sentences of classical logic. The basic data construct is the concept. As shown in Figure 36, concepts are represented by circles and they can be either objects (NOLOT) or attributes (LOT). NOLOT concepts are represented by solid circles, while LOT concepts are represented by dashed circles. Relationships between the concepts are represented by subdivided rectangles. A description of the relationship is written inside or outside the rectangle. This notation is similar to natural language. It is also possible to define concepts as subtypes of other concepts, so inheritance of the properties of the supertype by the subtype is allowed. NIAM supports the representation of constraints between relationships and on subtype membership, as exemplified in Figure 36. In Figure 37 the notation used to represent the same relation is different in the cases of Floor/Deck and Floor/Ground, due to NESSIE notational restrictions.

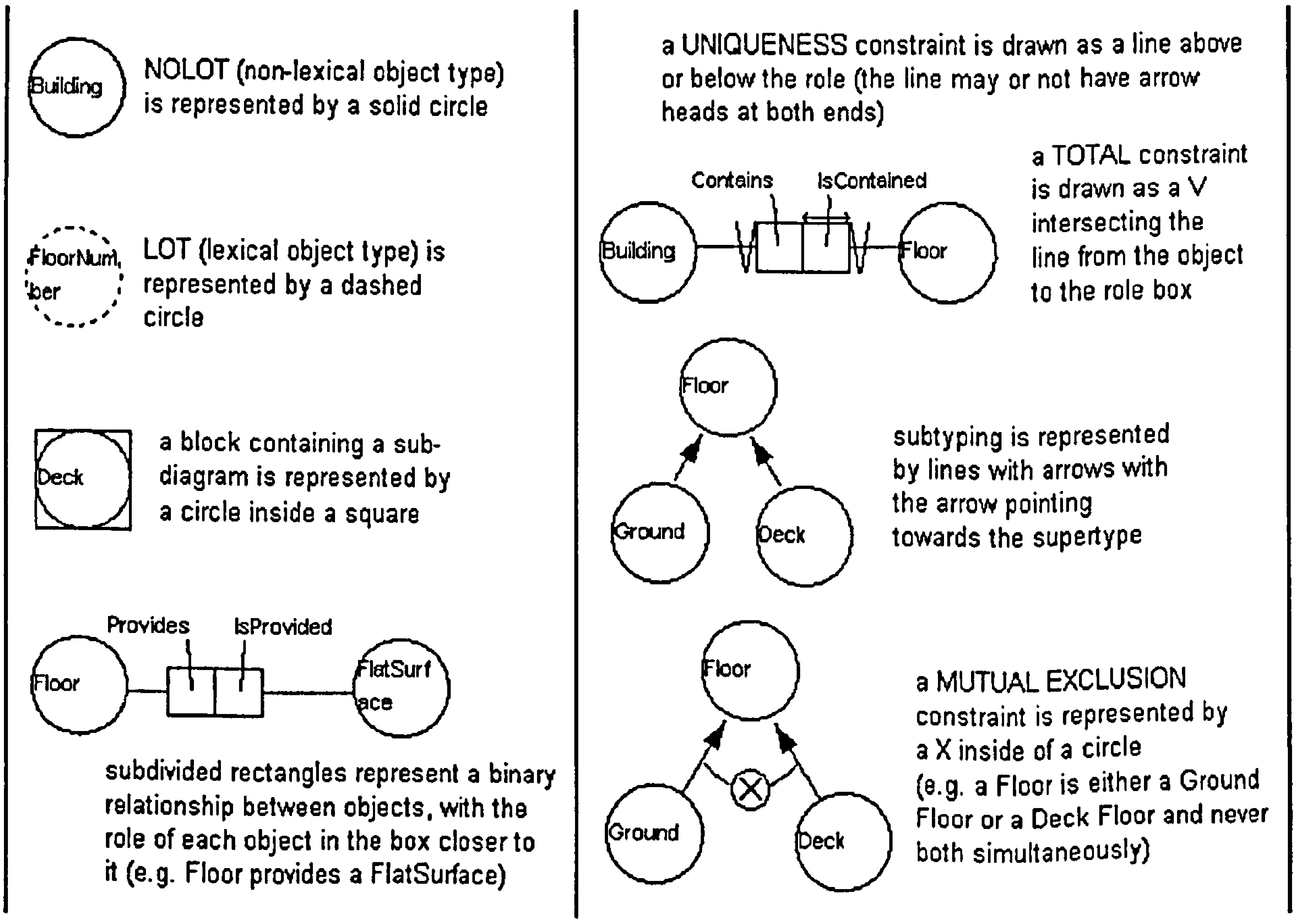


Figure 36 - NIAM symbols.

The understanding of NIAM diagrams can be difficult since they can become large. In order to help solving this problem, NESSIE allows for hierarchies of systems to be developed.

An example of a NIAM diagram is shown in Figure 37. As mentioned before, it was produced using NESSIE V1.0 (Kendal 1993). It shows the following concepts: Building, Floor, FlatSurface, Activity, Human (Activity), Ground, Deck, FloorNumber and FloorName. Some relationships are expressed between these concepts.

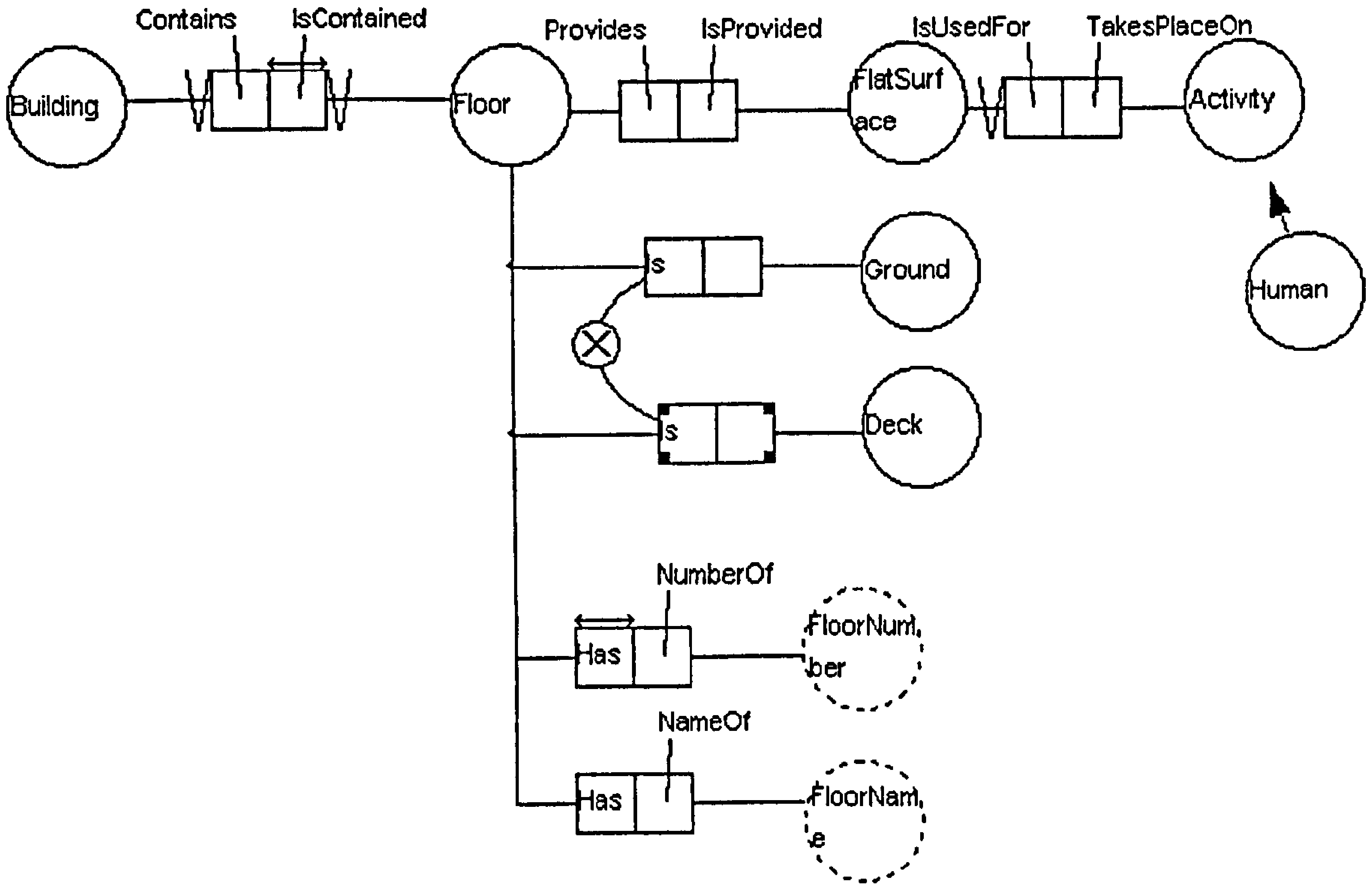


Figure 37 - A NIAM diagram produced with NESSIE V1.0.

A relation without constraints is defined between Floor and FlatSurface: "Floor Provides a FlatSurface", while "a FlatSurface IsProvided by a Floor". The relationship IsUsedFor between FlatSurface and Activity has a TOTAL constraint, which means that a member of FlatSurface plays the role IsUsedFor with one or more members of Activity. The relationship IsContained between Floor and Building has a UNIQUENESS constraint (as well as a TOTAL one). The UNIQUENESS constraint means that each member of Floor plays role IsContained with zero or more members of Building (combined with the TOTAL constraint it implies that one Floor IsContained in one Building).

4.3.2.2 IDEF1X

IDEF1X is another of the graphical languages used in STEP (Williams 1989, Björk and Wix 1991).

An example diagram using the same entities of Figure 37 is shown in Figure 38. The basic elements are objects, relationships between objects and attributes of objects. The objects are represented by rectangles and named with nouns (e.g. Building, Floor). The relationships are represented by lines and named with verbs (e.g. Contains, Provides). The attributes are represented by named fields within the rectangles (e.g. Floor-Number, Floor-Name). Sub-types are represented by boxes with rounded corners (e.g. Ground, Deck). Objects and attributes are clearly separate and the diagrams are easy to read.

Attributes have to be single-valued. Otherwise they are considered as objects.

The relationships between objects can be one of the following:

- **existency dependency relation** - the child object can exist only if the parent object exists,
- **subclass-superclass relationship** - the subclass inherits the attributes of the superclass. They form large hierarchies,
- **free relation** - the cardinality of the relationship is n x m. This type of relationship is only allowed in the early stages of the modelling work, because this cannot be implemented in a straightforward fashion in relational databases. At a later stage they should be transformed in n x 1 and 1 x m relationships.

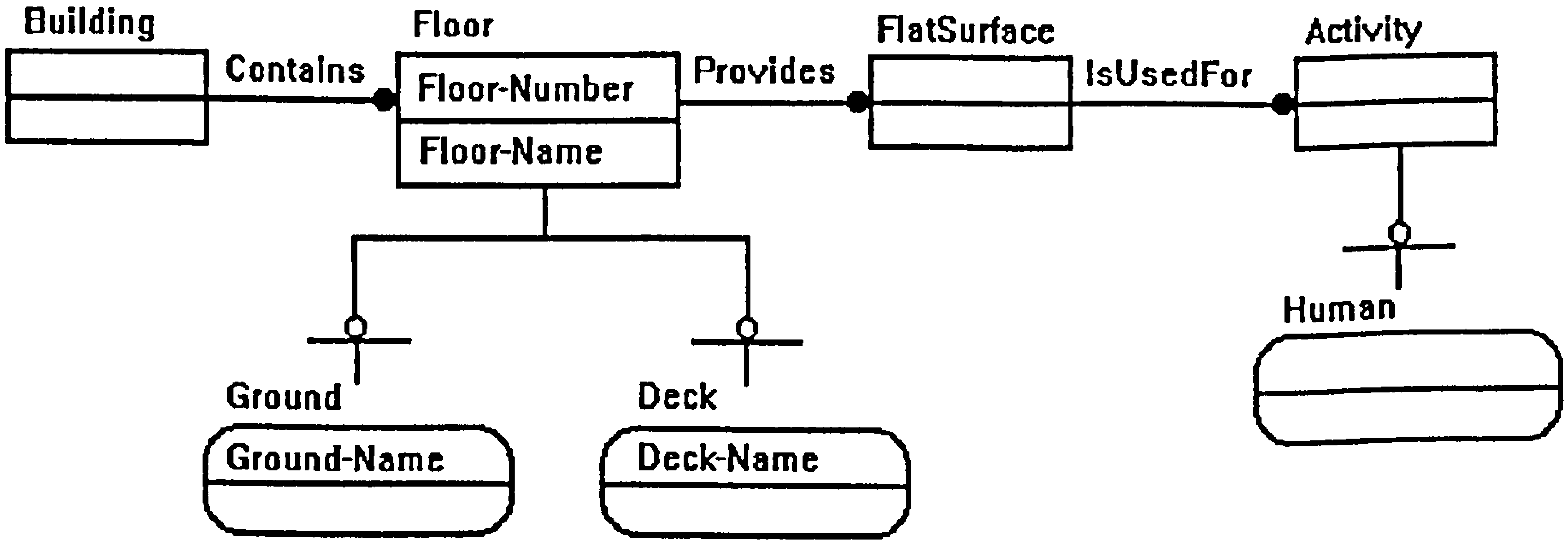


Figure 38 - IDEF1X diagram.

4.3.2.3 EXPRESS

EXPRESS (Williams 1989, Björk and Wix 1991, Björk 1992) is a formal data definition language that can be directly understood by a computer, which is not the case with the other languages previously described.

This language has been specially designed for the development of product data conceptual models. EXPRESS is a very good tool but not the most appropriate choice in the early stages of model development, since it lacks a graphical user interface. That is the reason for the use of NIAM and IDEF1X. In principle these languages can be translated to EXPRESS (NESSIE translates NIAM into EXPRESS, as mentioned before). The four main aims of EXPRESS are:

- to model the concepts of the problem area,
- to define the constraints which apply to these,
- to define the operations which can be carried out on these,
- to present the model in a way which the computer can understand.

The central concept is the entity. Entities can be viewed both in an abstract level or by explicitly declaring its attributes. It is also possible to create rules, that can be local or global. A rule is local if is included in the definition of a single entity and only refers others attributes of the same entity. A rule is global if refers attributes of other entities, in this case it must be declared separately from the entity definitions themselves. EXPRESS also allows the definition of operations on the attributes in the form of functions or procedures. The NIAM example presented in section 4.3.2.1 (Figure 37) translates into EXPRESS as shown in Figure 39.

4.3.2.4 EXPRESS-G

This is the more recent graphical language used in STEP and was specifically designed to support a subset of the EXPRESS language.

The entities are represented by rectangles with the name of the entity inside (See Figure 40). Attribute relationships between entities are represented by lines. Thick lines are used to represent supertypes-subtypes relationships, the subtype end being indicated by a small circle on the line (Björk 1992).

An example diagram using the same entities of Figure 37 is shown in Figure 40.

```
(* FLOOR.EXP    Created Sat  20-05-95                    *)
(*                                        *)
(* Express Schema automatically generated by the              *)
(* NIAM to Express Schema; Software Interface and Environment.  *)
(*                  NESSIE              *)
(* Developed by John Kendall at                      *)
(*          The South Bank University,              *)
(*          Borough Road,                   *)
(*          London                      *)
(* E-Mail: KENDALJ@UK.AC.SBU.VAX                          *)

SCHEMA FLOOR;

 TYPE
   Floor = SELECT(Ground, Deck) ;
 END_TYPE ;

 ENTITY Building;
   Contains       : Floor;
 UNIQUE
   Contains;
 END_ENTITY;

 ENTITY FlatSurface;
   IsUsedFor      : Activity;
 END_ENTITY;

 ENTITY Activity
   SUPERTYPE OF (Human);
 END_ENTITY;

 ENTITY Human
   SUBTYPE OF (Activity);
 END_ENTITY;

 ENTITY Ground;
 END_ENTITY;

 ENTITY Deck;
 END_ENTITY;

END_SCHEMA ;
```

Figure 39 - Translation of the NIAM schema of Figure 37 to EXPRESS.

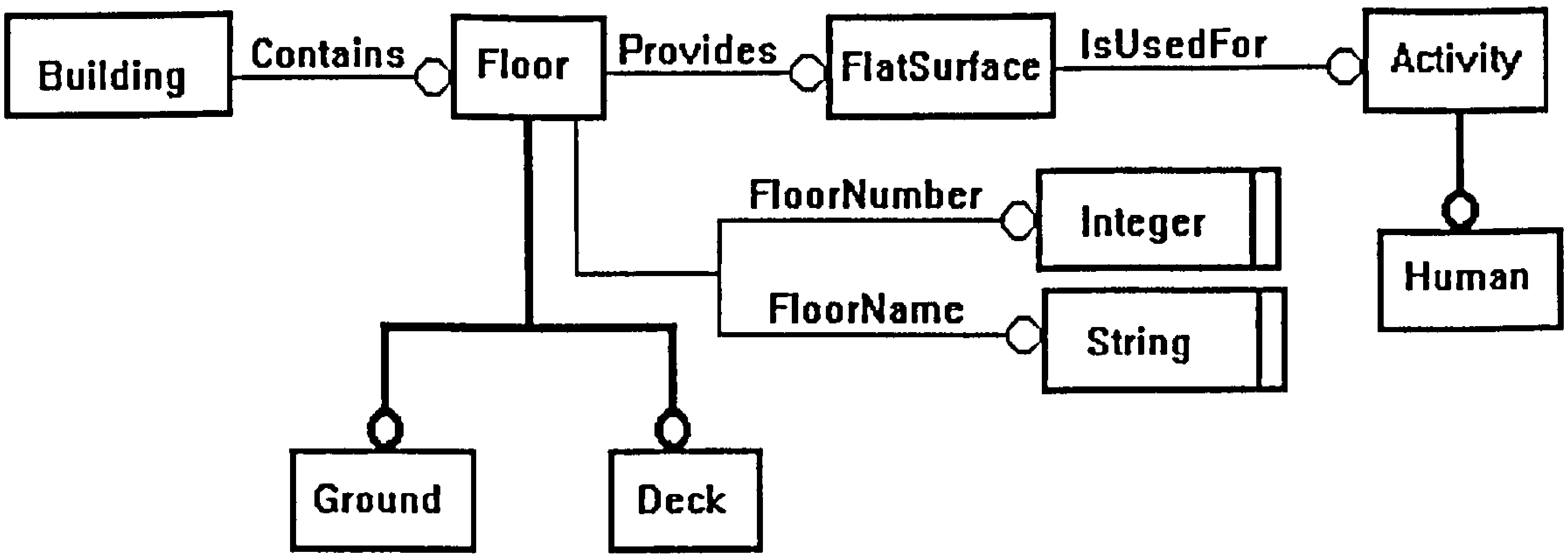


Figure 40 - An EXPRESS-G diagram.

4.4 Product modelling in the building industry

4.4.1 Introduction

According to Watson and Boyle (1993) "potentially we could have a product model for a complete building, more realistically, its scope could simply address the structural sub-system".

Also Wright et al. (1992) have a similar opinion: "we are used to dealing with specialised product models and doing mental mappings to other product models. A quantity surveyor may think of a brick wall in terms of the cost per unit area, a contractor may think of it in terms of work schedule and materials, while a thermal modeller may only consider it as a layer with thermal properties, each view point leads to quite different representations".

These authors agree that for a building it is unrealistic to have all the information that characterises the building for all applications over its life-cycle. There is no absolute level of completeness. The completeness described by Smith (1992) and Gielingh (1990) is only true for a closed system and it is always possible to find applications will require data which is not contained within such a comprehensive or global product model.

Wright et al. (1992) define three types of mapping between product models and applications (Figure 41, from Wright et al. 1992):

- **one to one** - represents the present situation for most applications, where each program has a unique data set or product model and no data to be shared between applications (except through translations),

- **one to many** - represents the global product model approach, where a single, all-encompassing product model can serve all applications directly,
- **hierarchy of mappings** - represents a hierarchical approach, where specialised product models can be derived from more general ones to serve one or more applications with substantially common data requirements. In describing the hierarchy, some data is left out, while others may be modified to suit the applications (e.g. surface areas may be derived from and replace vertex geometry in a specialised product model for a cluster of applications which only use surface areas).

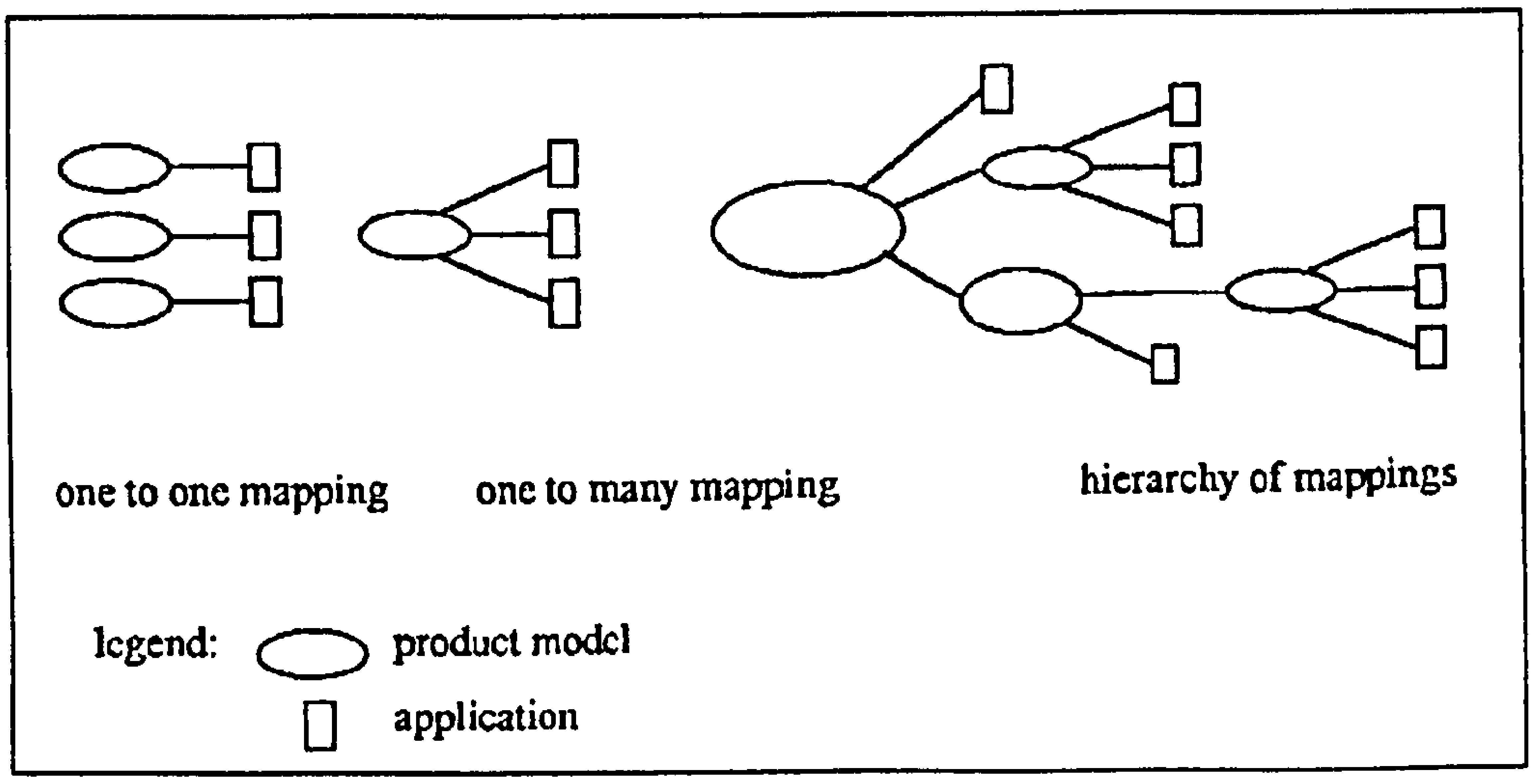


Figure 41 - Mappings between product models and applications (source Wright et al. 1992).

The hierarchy of mappings is a compromise between the other two mappings and seems to be a more realistic approach for modelling complex products as buildings. The attempts to model a building that will be referred in the following sections were based on the one to many mapping. For the moment only some general ideas and partial prototypes of how to model a building have been developed, so this approach is appropriate, only when implementing more complex systems hierarchies of mappings will be needed.

Three important models related with the building will be described in the following sections.

- the RATAS product model,
- AEC STEP related models: the General AEC Reference Model (GARM) and the AEC building systems model.

4.4.2 The RATAS product model

The RATAS product model has been developed in Finland since 1987. Its aim has been to develop a national Finnish system for computer-aided design in the construction industry.

This model describes a building symbolically using objects, the relationships between the objects and attributes. The detailed definition of objects classes, attributes and relationships types remains to be done (Björk and Pentilla 1989, Björk 1992). There is not any other published work on this line known to the author.

At the moment an abstraction hierarchy with five levels was developed (see Figure 42, from Björk 1992). The five levels are:

- **building** - this object contains attributes about the site, the climate, the total size of the building, the construction cost or the type of the building,
- **system** - these objects contain general information about the systems that together constitute a building. All the spaces in a building form one system. All load-bearing building components too form one system. There are also several technical systems in a modern building (heating, power, communication networks, etc.).
- **subsystem** - using subsystem objects the designer can subdivide the above systems into functional parts (for instance floor, hospital ward). Several part overlapping subsystem objects can constitute the same system objects through **part of** relationships. Objects from the part level are in turn part of the subsystem objects.
- **part** - the vast majority of objects in the product model belong to the part level. Part level objects are most usually tangible physical objects such as building elements or technical devices. The part level object space is a very important class of objects.
- **detail** - many part level objects may be further subdivided into detail level objects (for instance a window into its constituent parts). In principle, the product model also covers the information structures on this level. In practice, such information can often reside in the general data bases provided by construction material manufacturers, etc. rather than in the data base describing a particular building under design.

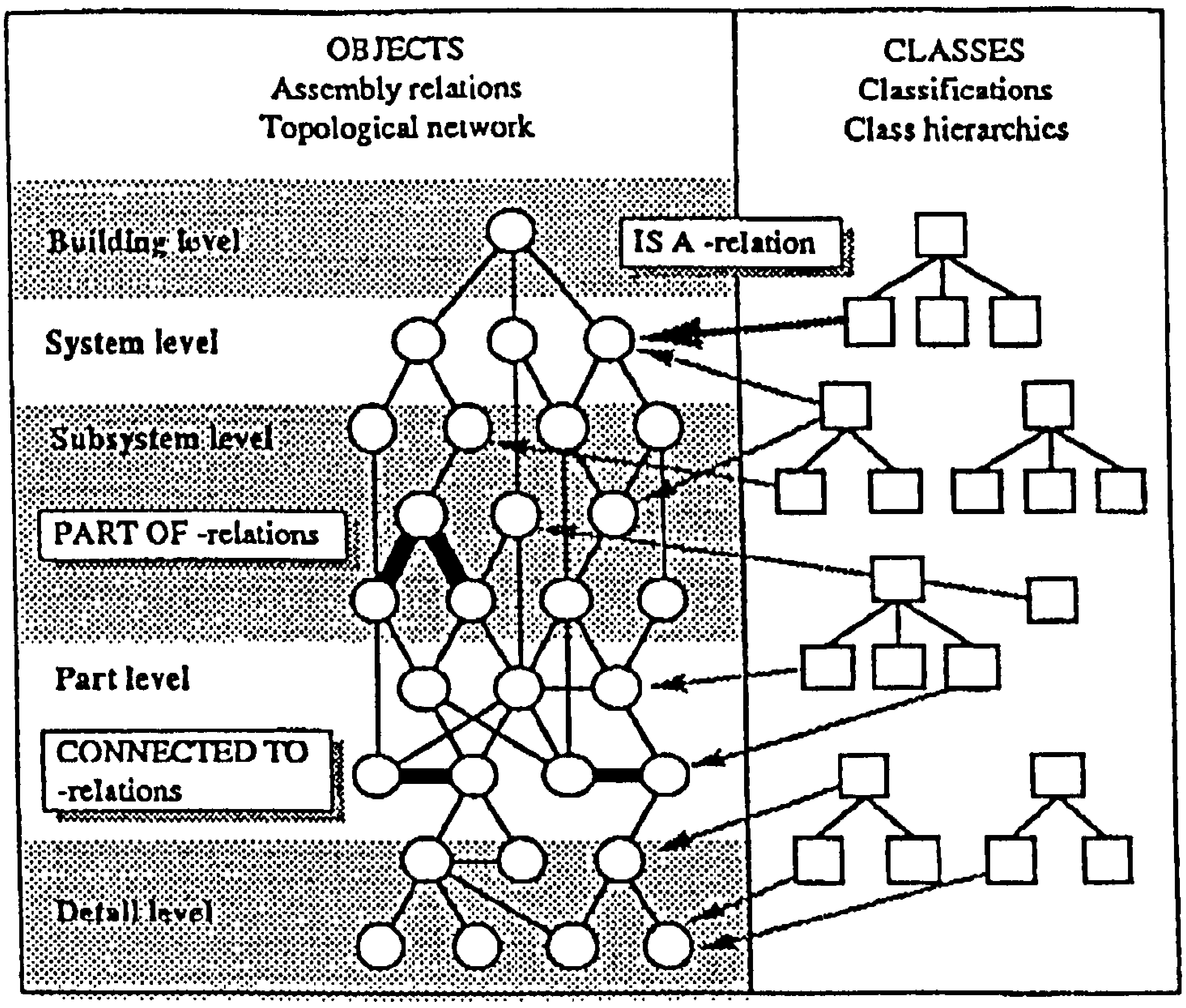


Figure 42 - Decomposition hierarchy in the RATAS-model (source Björk 1992).

The objects of the different levels are related using the relationship **a part of** (aggregation). Also the relationship **connected to** is used in this model. This relation is used more frequently for the lower abstraction levels (parts and details), and usually connects objects of the same level. The relationship **a kind of** (here called **is a**) is used as usual to relate objects classes and its object instances.

After the definition of the framework of the model some prototypes have been developed to test and illustrate the ideas. They are (Björk and Pentilla 1991):

- a relational database prototype,
- an hypermedia prototype,
- a relational database prototype with hypermedia user interface,
- a relational database and CAD prototype.

The main aim of the first prototype was to show the benefits of the relational database approach in allowing the users of the information the ability to produce a large variety of output documents according to their particular needs. The developers of this prototype assume that the problems of entering the information into the database have been solved.

The second prototype aims to provide a conceptual user interface to the building product model. An hypermedia tool was used to organise the building information. Figure 43 (from Björk 1989) shows a further development of the abstraction hierarchy of the RATAS model, used for developing this prototype.

The third prototype is a mixture of the two first ones. It is based on storing the information on a relational database but viewing the information through a user interface created with a hypermedia program.

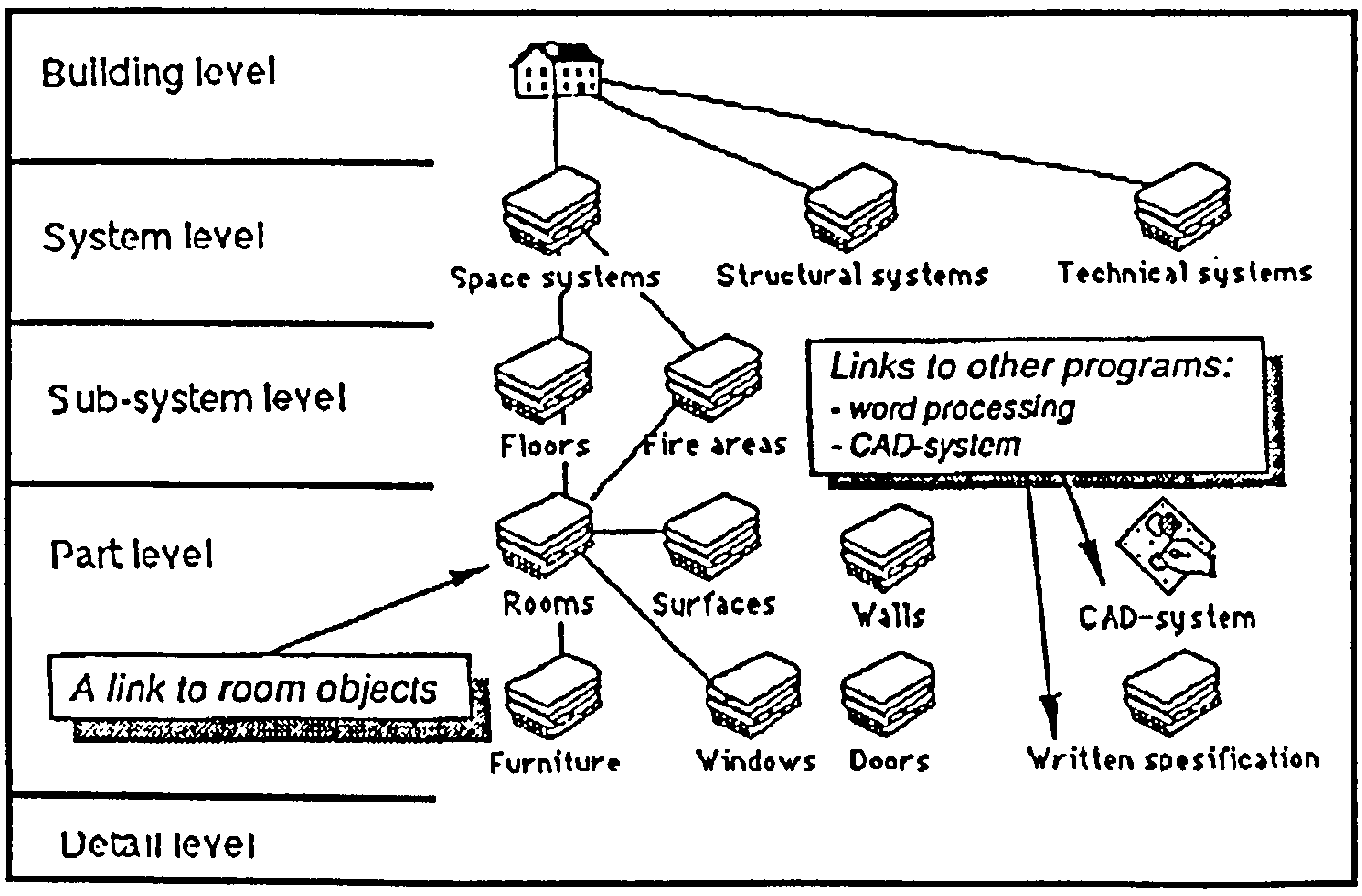


Figure 43 - A conceptual overall view of the RATAS building product model (source Björk 1989).

The fourth prototype specifically addresses the problem of data entry in a form more suited to a designer's way of working. This prototype has been developed as a part of the third phase of the RATAS project. The basic aim has been to define the object classes, attributes and relationships types needed for information transfer from the designers to the contractors.

Limited resources were available for going ahead with the RATAS model and the prototypes. Therefore some key issues and restrictions were imposed for the later definition of a full product model and for the development of commercial software based on such a standard (Björk and Pentilla 1989). The main restrictions and issues were:

- the researchers should concentrate on the modelling of buildings, not on programming work. The programming language used to develop the prototypes should not be, when possible, a basic programming language but databases, CAD systems, expert systems, etc.,

- instead of building one large prototype several small ones should be built as a start, using different types of software and later on integrate them,
- the modelling of geometrical shape and location data should be developed because work is already being done both by CAD commercial companies and the developers of the STEP standard. The prototypes being developed should be left open, in the sense that they could later be integrated with other software namely the one developed by STEP,
- the interaction between the design process and the product model will not be a concern of developers of the RATAS model.

4.4.3 AEC STEP related models

4.4.3.1 Overview

The ability to store data in a neutral form is an important requirement in the Architecture, Engineering and Construction (AEC) universe (Warthen 1989). So the appearance of STEP was a big improvement in helping the exchange of information between different CAD systems and the exchange of three dimensional, non-graphic and non-geometric data in the form of specifications, materials, analysis data, etc.

The modelling of products under the STEP project has been attempted in the areas shown in Figure 44 (from Gielingh, 1988): AEC (Architecture, Engineering and Construction), Mechanical and Electrical/Electronical.

The approach taken is based in a generalisation/specification hierarchy. Four layers have been defined:

- General STEP layer - contains entities which are general for all types of industry.
- Industry-type layer - contains entities which are specific to one of the three classes of industry (AEC, Mechanical and Electrical/Electronical), but general to each of these areas.
- Product type layer - contains entities which are more specific of each industry product type. For AEC four product types have been defined: Architecture, Civil, Plant and Shipbuilding.

- Non-STEP layer - can be used for additional national standards, company standards and others.

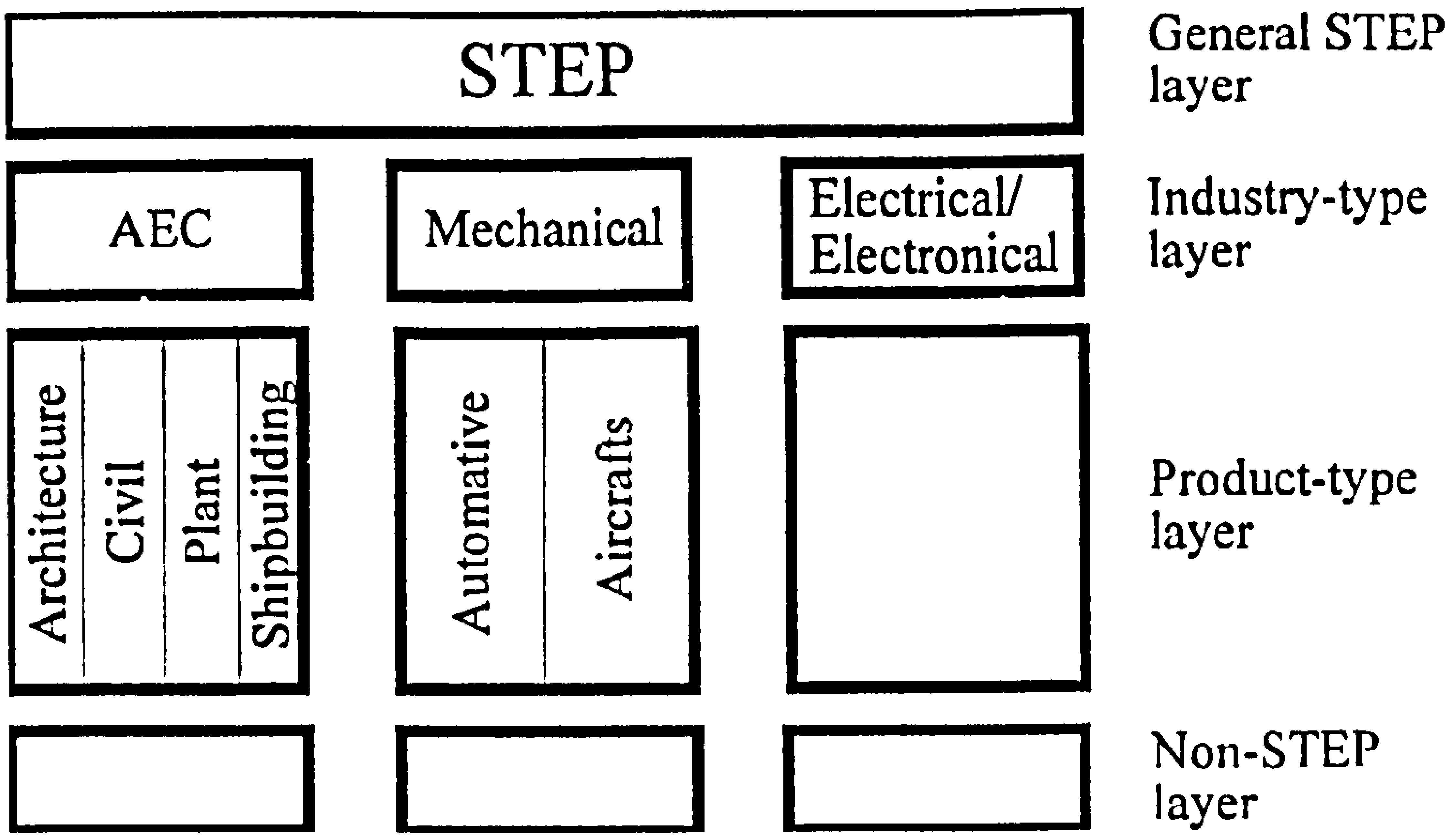


Figure 44 - Four layers to specify product definition data (source Gielingh 1988).

Two models will be analysed in the following sections, the General AEC Reference Model (GARM) and the AEC Building Systems Model.

GARM belongs to the industry-type layer. It is an abstract high level data model, which is supposed to be general enough to serve the needs of all AEC application areas (Gielingh 1988).

The AEC Building Systems Model belongs to the product-type layer. Instead of a complete product, the model represents high level general building concepts.

4.4.3.2 The General AEC Reference Model (GARM)

GARM was originally developed by the Institute of Building Materials and Structures (IBBC) of the Dutch Organisation for Applied Science Research (TNO) in 1986. It was further developed within the AEC committee of ISO STEP/PDES that suggested the inclusion of GARM in the STEP version 1 in 1989.

The model was originally focused on the modelling of buildings, building systems and building elements but has been generalised such that it could serve also the needs of other products-types. GARM has evolved in the direction of modelling generic AEC entities. It has to be extended with data-structures for specific product-types. This can be done by defining sub-types of some GARM entities for each application area (Architecture, Civil, Plant and Shipbuilding).

For some time GARM has been seen as a candidate planning model for STEP. GARM is not global enough to serve this goal. A Planing Model for STEP has been defined, which is based on the following abstractions (Gielingh 1990):

- Generalisation /specialisation - modelled by **a-kind-of** associations. Generic entities defined in the general STEP layer are specialised in the AEC layer and further refined in the application layers.
- Aggregation / decomposition - modelled by **a-part-of** associations. A building is divided into systems, components and features.
- Characterisation - modelled by **is-aspect-of** or **is-characteristic-of** associations.
- Life-Cycle - modelled by **is-in-stage** associations. Different stages have been defined (requirements, design, planning, etc.).

Figure 45 (from Gielingh 1990) shows the three fundamental abstractions which define Product Model Definition Space.

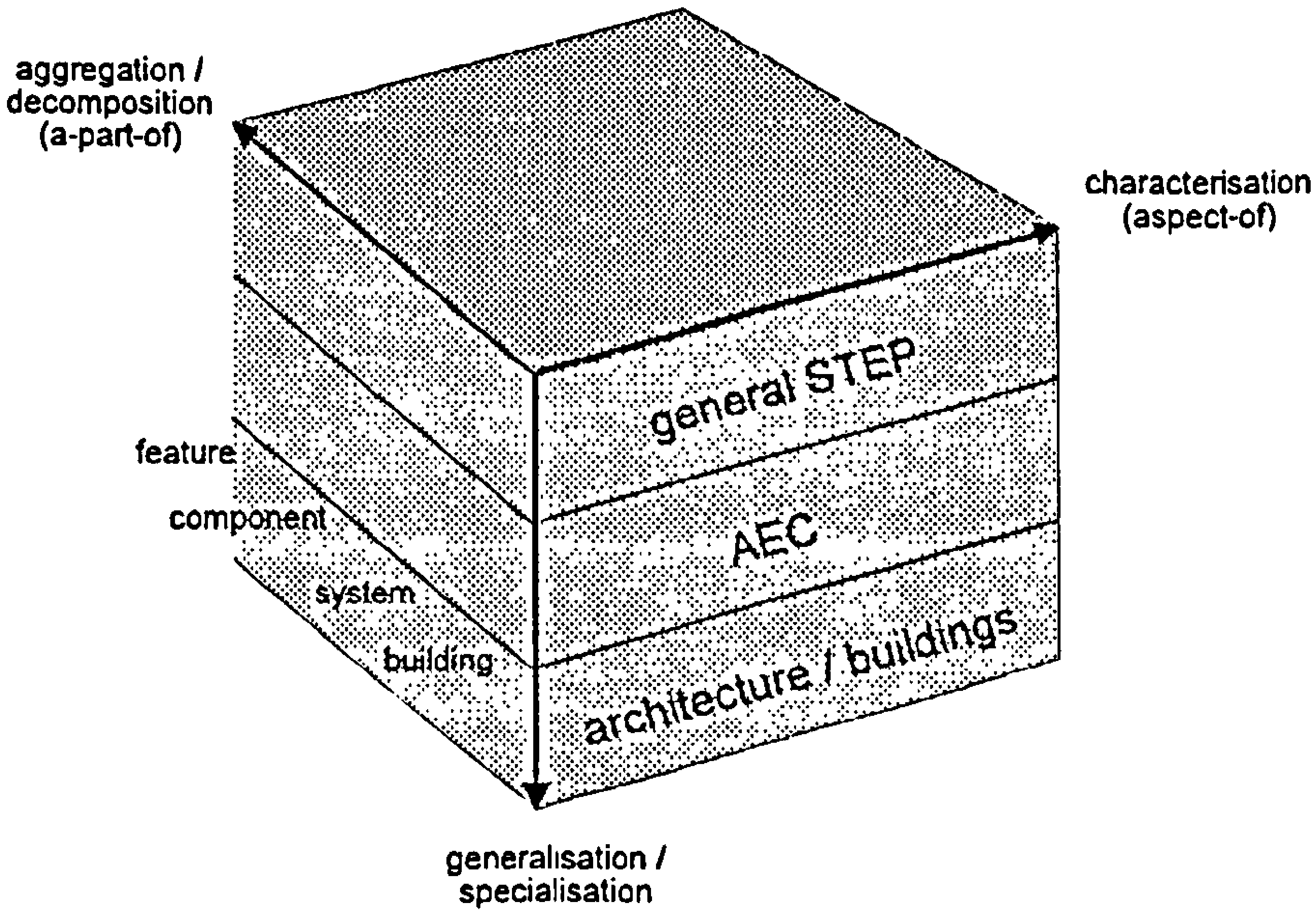


Figure 45 - Three fundamental abstractions which define Product Model Definition Space (source Gielingh 1990).

GARM adopts the abstractions defined in the Product Model Definition Space at a more specialised level.

GARM is based on the idea that product information is represented in its basic units PDU's (Product Definition Units). A PDU is a generic entity which represents a product or a part of a product. It can be the whole product, or the sub-systems, elements, components, parts or features of a product.

A PDU has characteristics which refer to certain aspects of the product, as shown in Figure 46 (derived from Gielingh 1990). Each characteristic is related to an aspect, such as stability, fire safety and economy. Characteristics vary during the various stages of product life-cycle and can be divided at a coarse level in required, expected (analysis and simulation) and measured (when the product physically exists).

The different stages of a product life-cycle are further refined in GARM as shown in Figure 47 (from Gielingh 1990). PDU sub-types are also defined which correspond to these stages. The sub-types, Functional Unit (FU) and Technical Solution (TS) will be further analysed.

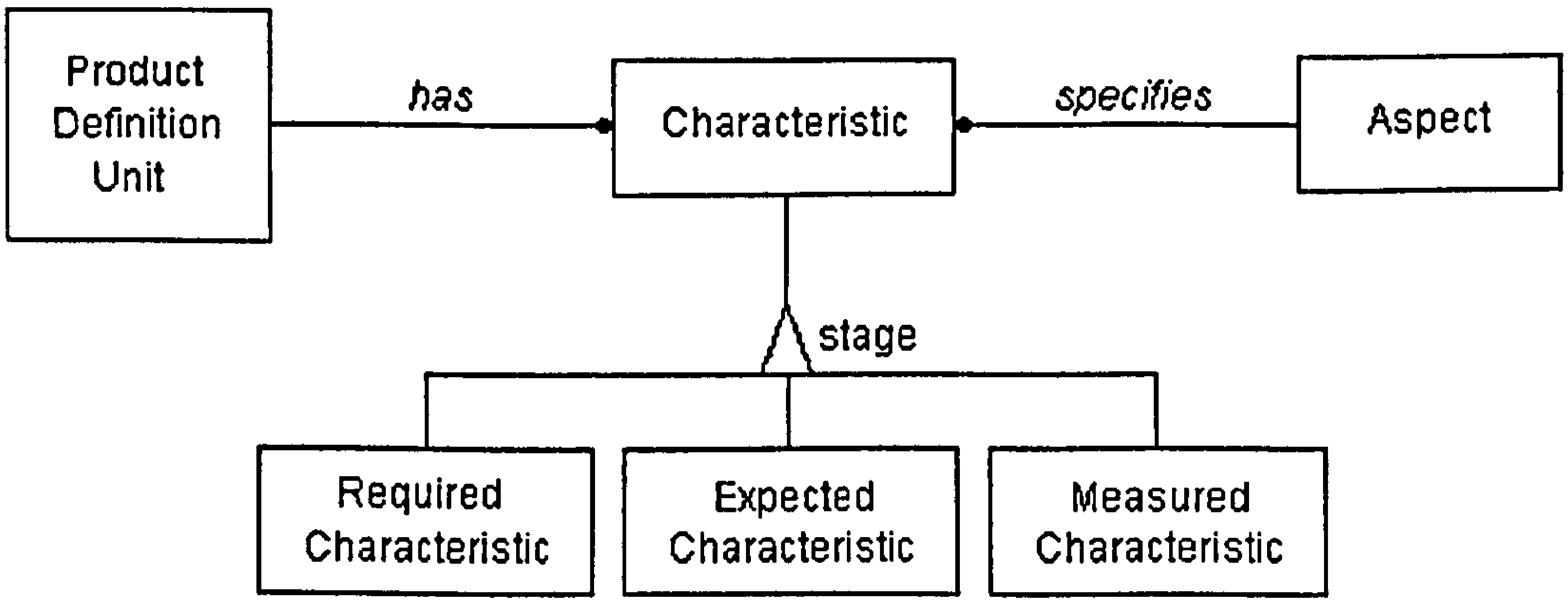


Figure 46 - Product Definition Unit (PDU) (source Gielingh 1990).

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

Figure 47 - Stages in the products life cycle and respective PDU subtypes (source Gielingh 1990).

A Functional Unit is the "collector" of all the requirements for the PDU. A Technical Solution is the "answer" to the problem or the product that fulfils the requirements of the Functional Unit.

Figure 48 (from Gielingh 1990) shows the relation between a Functional Unit and a Technical Solution. Several Technical Solutions may exist which fulfil the requirements of a Functional Unit. Only one of them will eventually be selected. A Technical Solution may be decomposed again in a set of Functional Units.

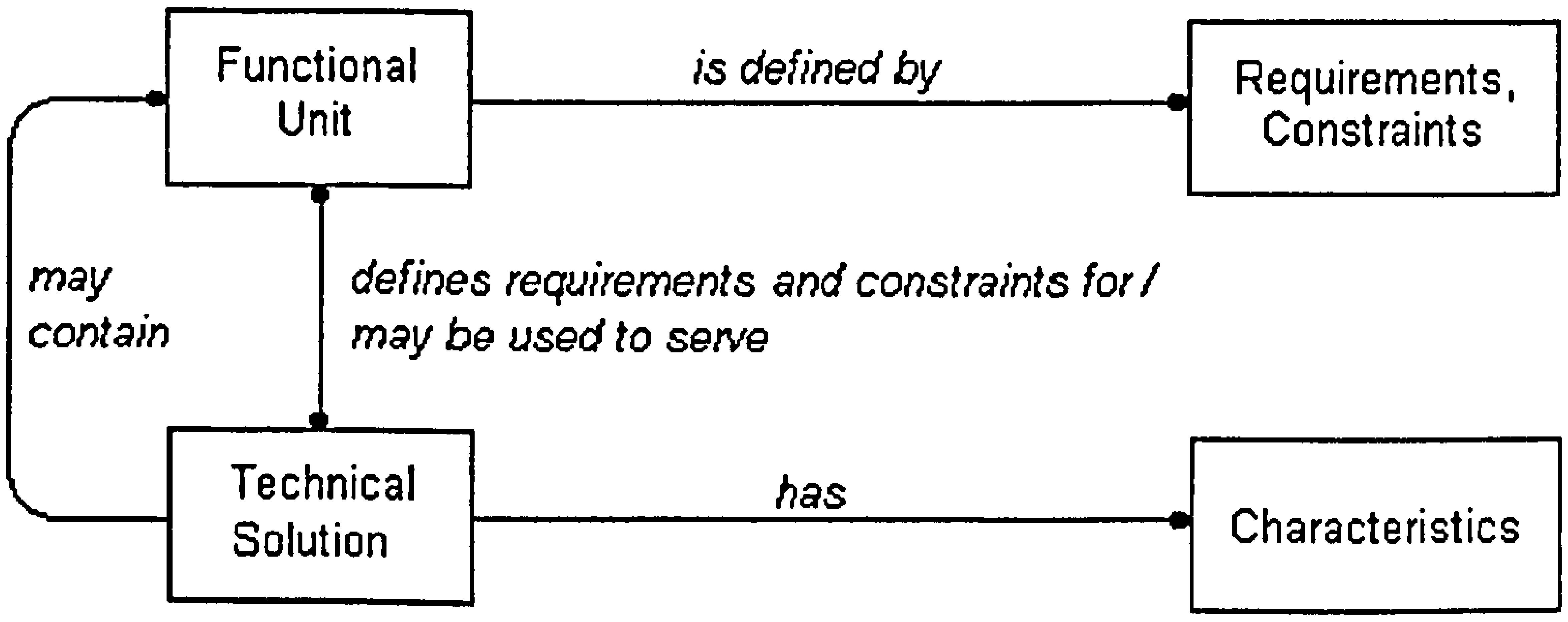


Figure 48 - The relation between a Functional Unit and a Technical Solution (source Gielingh 1990).

Figure 49 shows an example of a decomposition of a central heating system in a tree structure of Functional Units and respective Technical Solutions. A central heating system (FU) has a set of requirements which can be answered by several Technical Solutions, proposed by different vendors of central heating equipment. In the example the ROCA central heating system has been chosen. This system is decomposed in several Functional Units, which have again one or more Technical Solutions.

The "real-world" is very complex. The developers of GARM felt that too many interactions would have to be considered when modelling "real world" situations. This would make it very difficult to maintain the consistency of a model. Rules have been defined that restrict the communication between Functional Unites which do not belong to the same Technical Solution.

4.4.3.3 The AEC building systems model

This model is being developed by the University of Michigan, within the STEP project. It is concerned with the modelling of building systems and site systems. It shows the decomposition of the building and site systems into sub-systems, the connection of these systems and sub-systems and the classification of building systems and components (Turner et al. 1989, 1990a, 1990b, 1990c, 1990d).

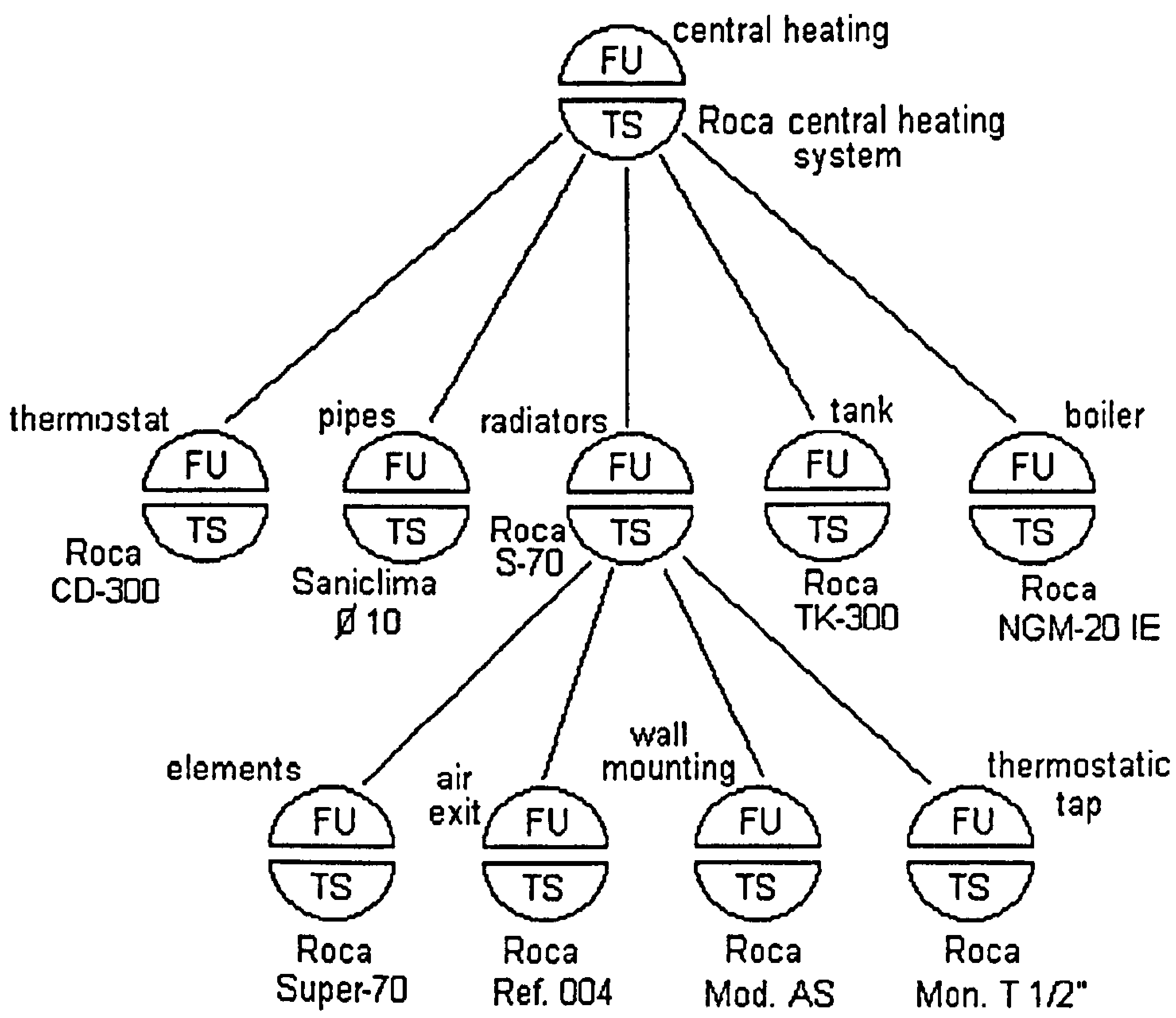


Figure 49 - Example of the decomposition of a central heating system.

The approach taken uses a formal description of a building in the NIAM graphical language. Figures 50 to 55 have been derived from Turner (1989, 1990a). The NIAM diagrams have been translated to the notation presented in the previous chapter. There are notations used in NIAM which do not have an equivalent notation, but the loss of information is not relevant to the understanding of the subject.

The basic concept used to develop the model is the object. A universe is composed of a collection of objects, each object can have one or more properties and can be decomposed into zero or more objects (but not into itself). It must have one and only one identifier and may have zero or one object name to make it viable in a database (Turner 1992).

An AEC building project is one in which at least one building is built in one single site. The model considers the building and the site on which it rests to be of equal importance: one complements the other, one cannot be designed without knowledge of the other, each generates its own type of data. The first one is the internal environment of a building project and the second one is the external environment.

In this model both the building and the site are characterised as having one or more properties (some of the possible properties are shown) and one or more systems as shown in Figures 50 and 51.

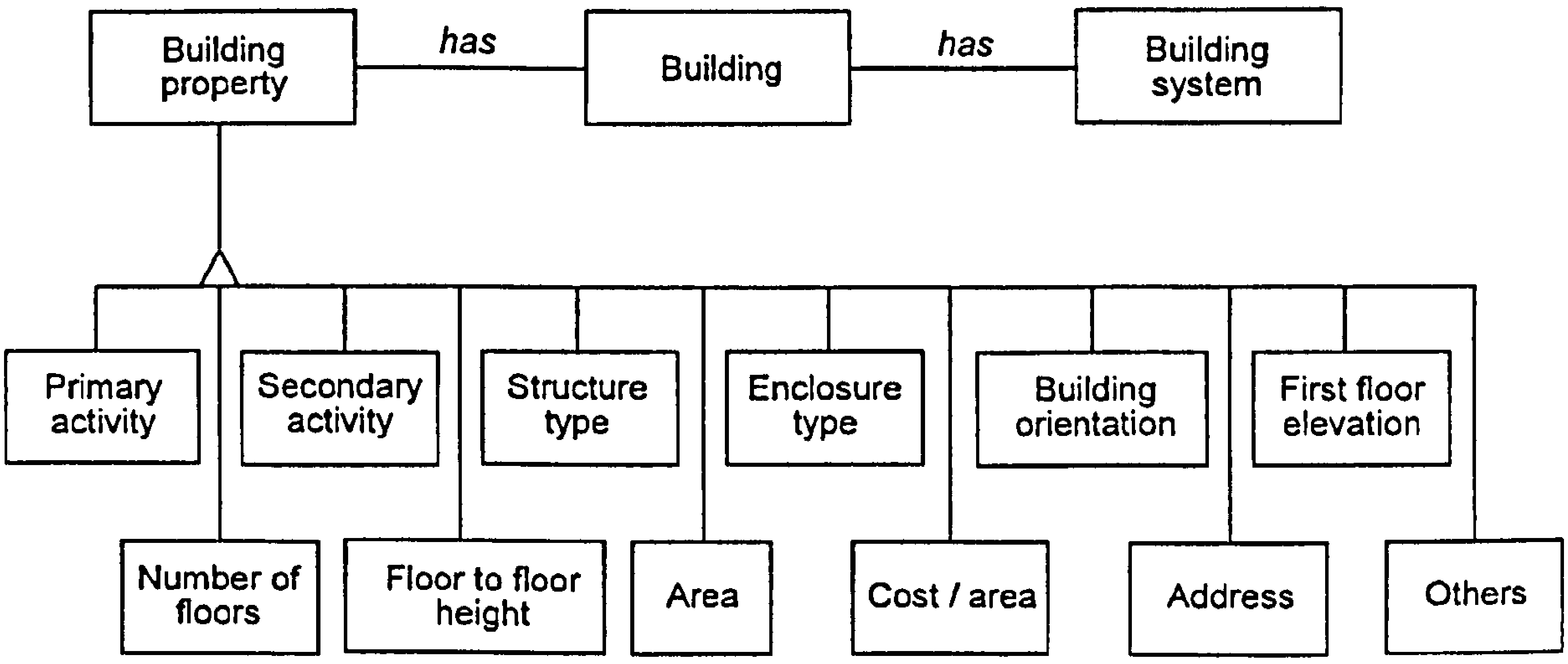


Figure 50 - Building and building properties.

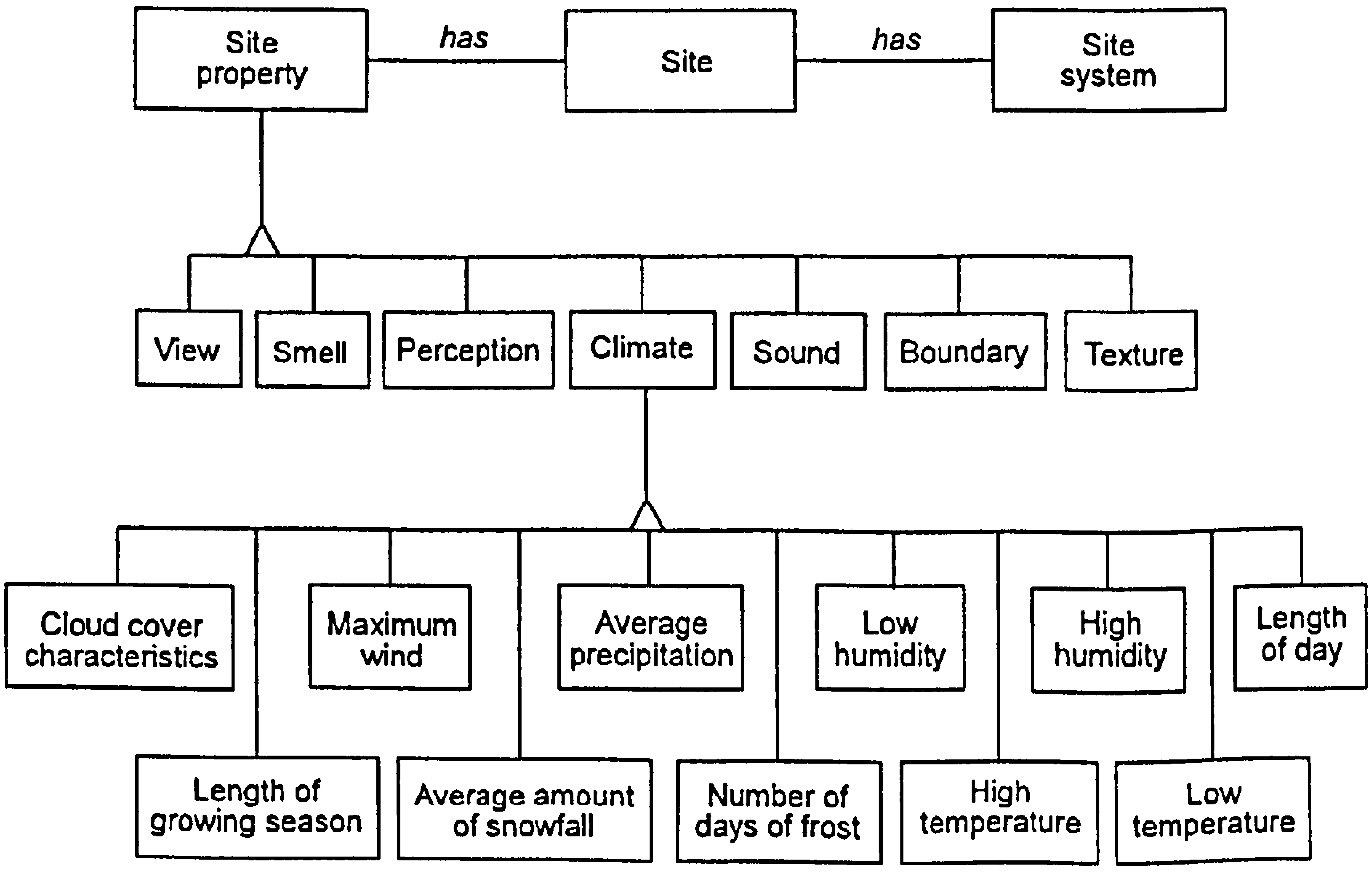


Figure 51 - Site and site properties.

In Figures 52 and 53 two possible building systems classifications are shown. These two classifications consider three main types of systems.

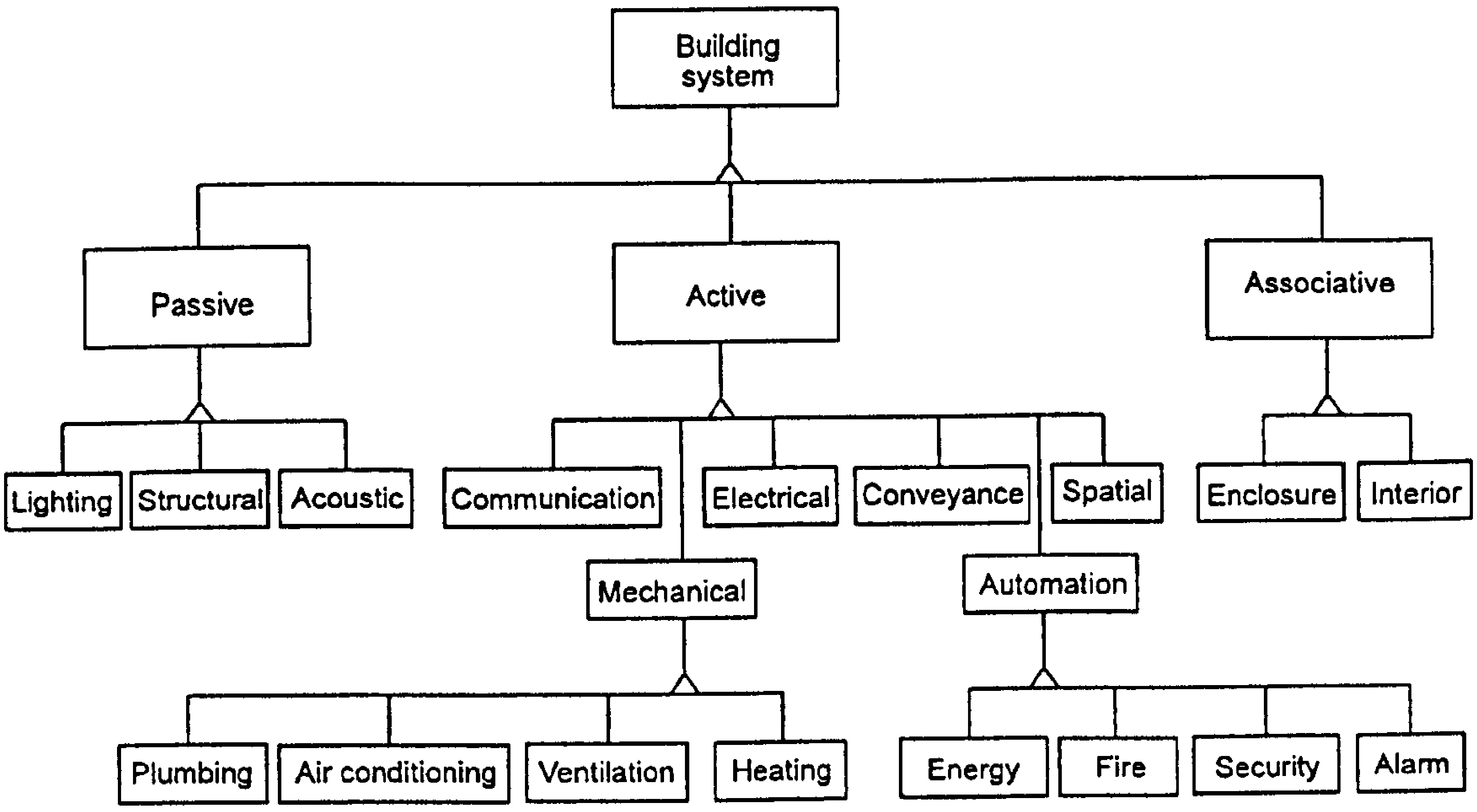


Figure 52 - Building systems.

The classification of Figure 52 considers three types of systems:

- **active**, which have an active distribution system (they carry throughput as air, water and electricity),
- **passive**, which have a passive distribution system (they carry throughput as sound and load),
- **associative**, which do not have a distribution system at all.

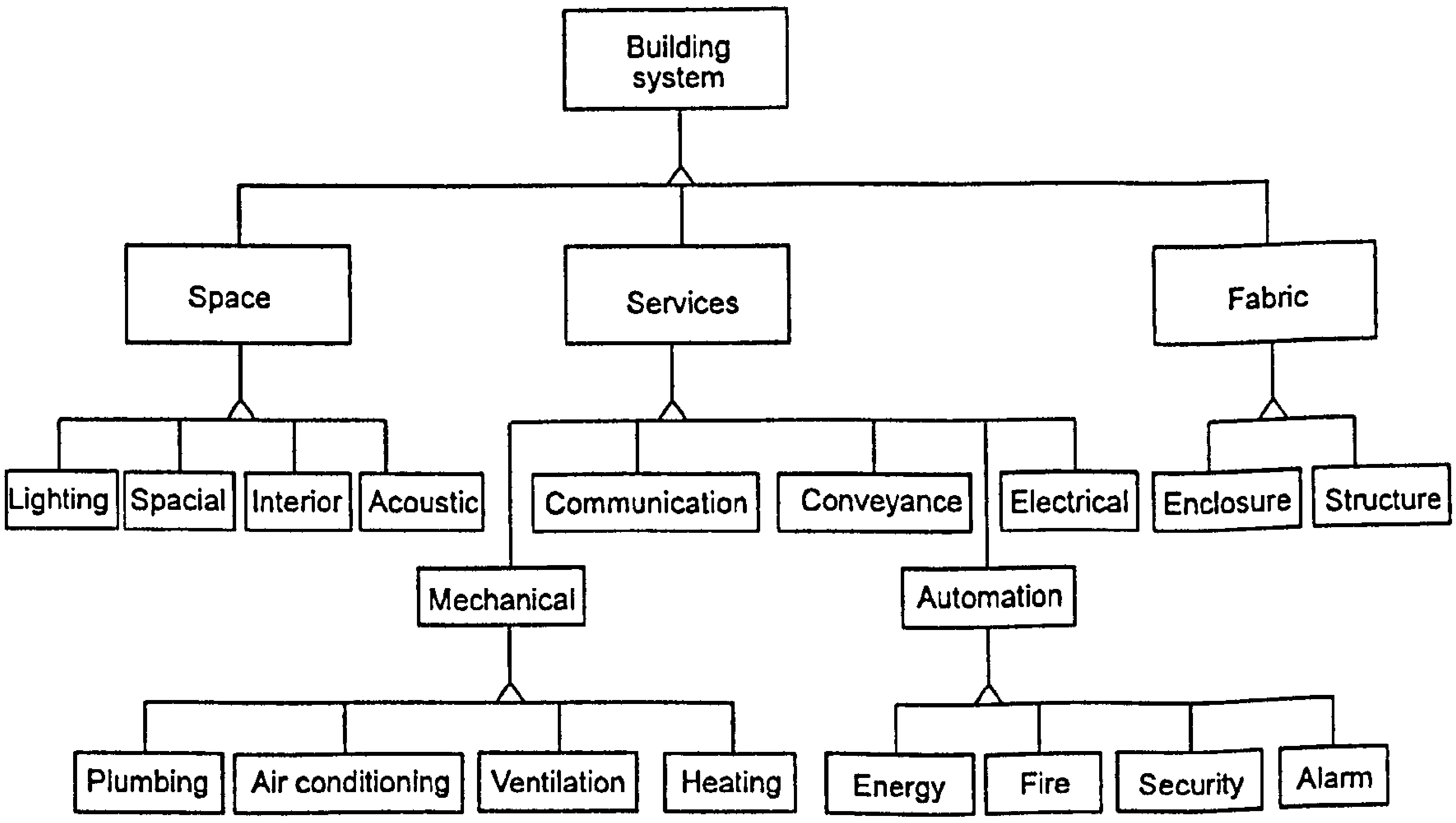


Figure 53 - Building systems (another approach).

The classification of Figure 53 considers: service, space and fabric related systems.

The sub-systems considered by these two classifications are the same but they are grouped in a different way.

The site systems can be artificial or natural and each one of these can be further divided into active or passive (see Figure 54).

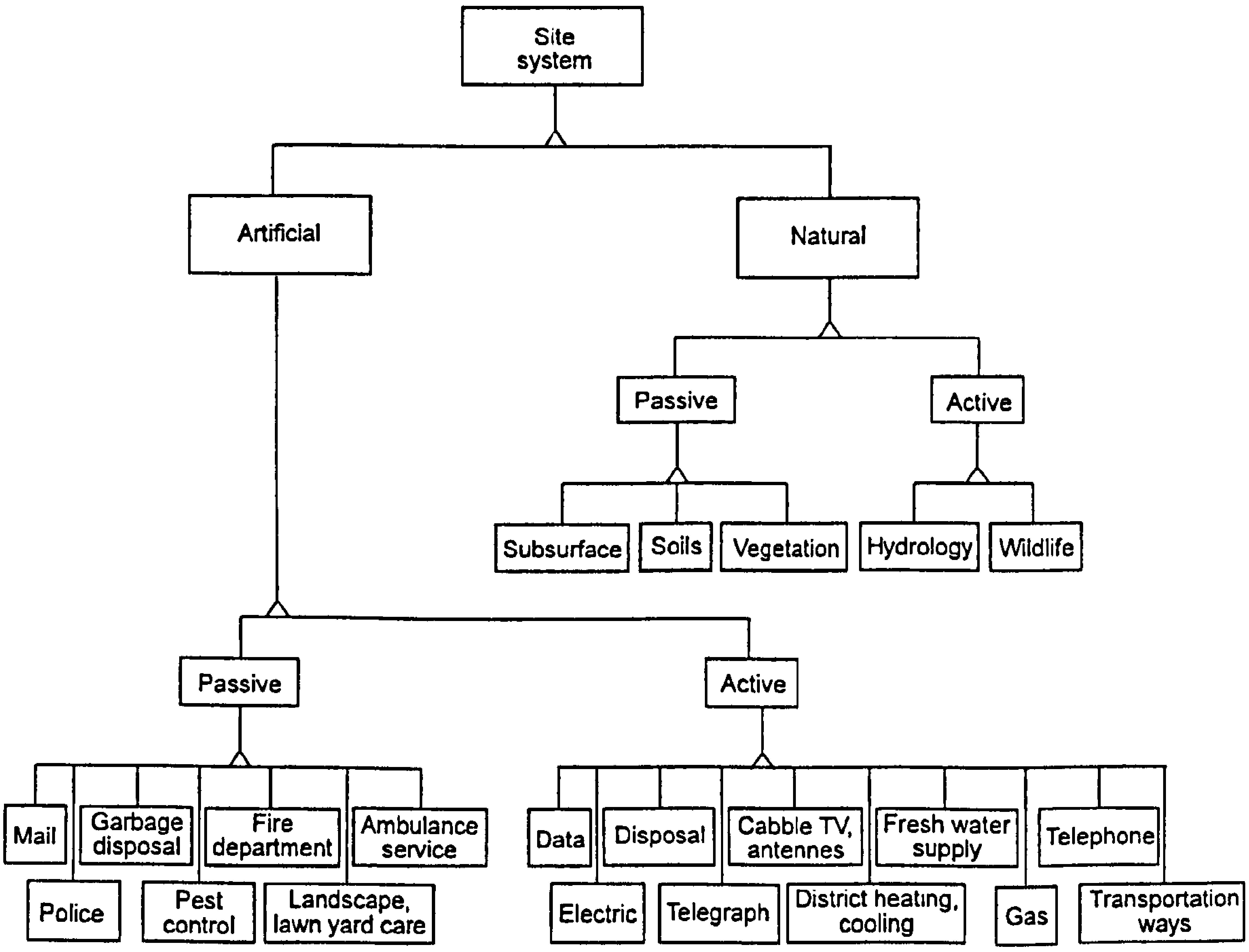


Figure 54 - Site systems.

Each system is defined according to the scheme of Figure 55. It is designed with the goal of generating a set of desired outputs for a particular range of inputs.

Systems exist to satisfy needs. The needs can be either human (social or individual) or natural. A system is designed to perform a specific function or set of functions. This set of functions is closely related with the needs.

Each system has one and only one name and identifier.

The spatial, enclosure and structural systems have been further analysed by Turner (1989, 1990a).

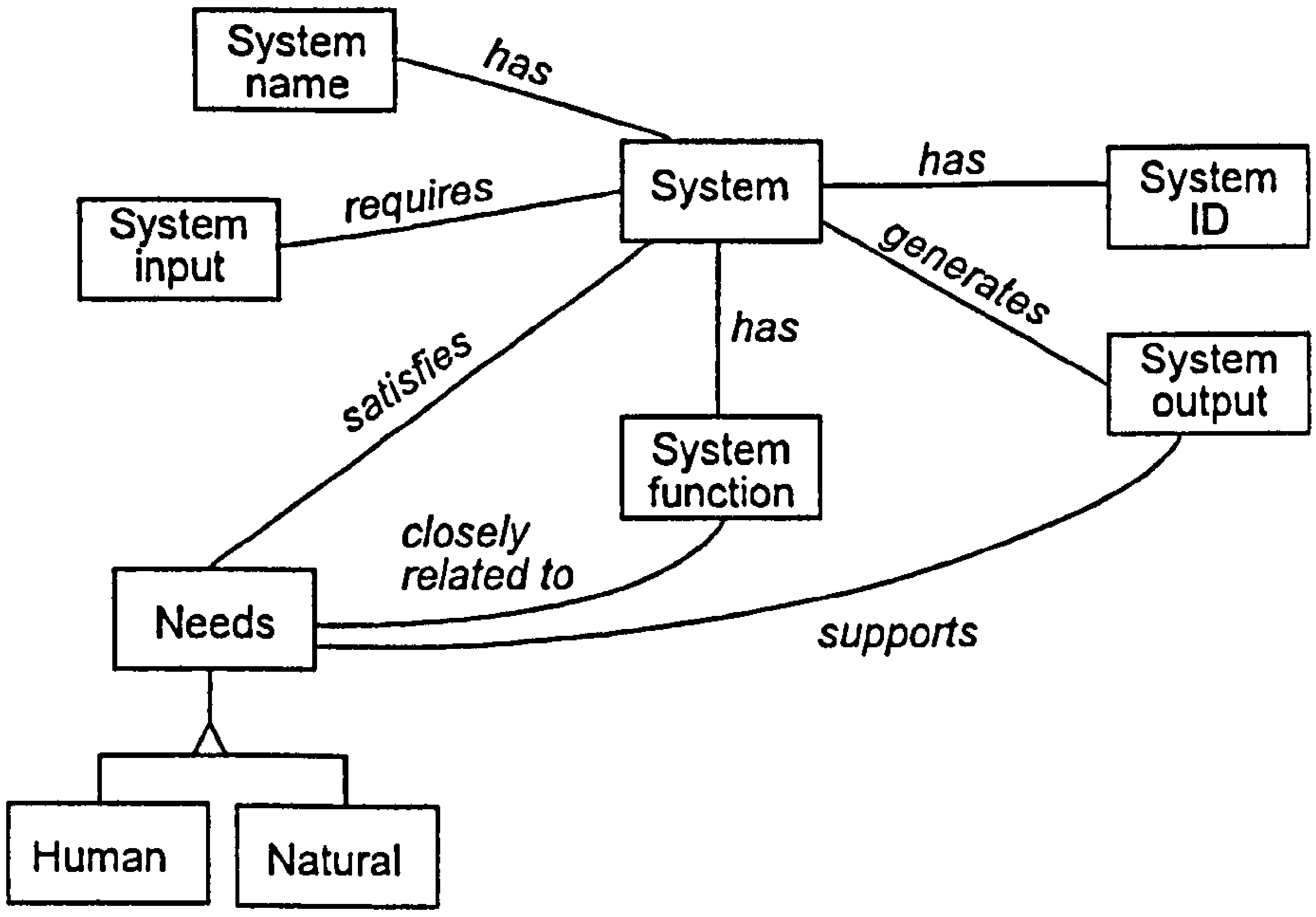


Figure 55 - System.

4.5 Product modelling and the object-oriented paradigm

Product modelling describes a product by describing its systems, sub-systems and parts, and the relations between them.

Traditional software development techniques are insufficient to express such a modular view of a product. They do not have appropriate modularity concepts. New software methods came from the field of simulation, where modularity is natural. The ideas of object-oriented programming are natural for product modelling. Product modelling is also contributing to the development of object-oriented programming (Wright et al. 1992).

Three models concerned with building have been reviewed: RATAS, GARM and AEC building systems model. All of them propose the division of a building into systems and sub-systems, which can be implemented as software objects.

They also propose the development of generalisation/specialisation hierarchies to organise the objects into classes and sub-classes (**a kind of** relationships). Aggregation is modelled using **a part of** relationships.

The RATAS model considers the relation **connected-to** to model spatial relations.

In the AEC building systems model properties of the objects are modelled using the relation **has** (an object **has** properties).

GARM gives a strong emphasis to the characteristics and life-cycle stage of a product or component. These are modelled using respectively the relations **is aspect of** and **is in stage.**

Object-oriented systems can represent **a kind of** relations in a very natural way using inheritance.

Other relations can be represented by associations and links. These are usually better modelled representing associations as classes and links as instances of these classes.

Complex systems like buildings produce very complex and wide models. The consistency of these models can be difficult to maintain if all the objects are allowed to communicate to each other. In GARM a solution to this problem is proposed, by only allowing the communication between objects that belong to the same Functional Unit. As Functional Units and Technical Solutions are organised in a hierarchical way, communication is possible in a disciplined way.

4.6 The relevance of product modelling to QDF

Product modelling attempts to represent all the information related to a product in an integrated way. To model a building in a comprehensive way is not yet a feasible task, and so it is more realistic to concentrate on the aspects which are relevant for an application or a group of applications. Product modelling is closely related to object-oriented analysis, design and programming techniques. Developments in this field will enable the implementation of complex product data models. For a model to be useful to the parties involved in the design and production of a product, the use of object-oriented databases would be desirable.

Another important aspect is standardisation. The STEP project is an important international effort in the direction of enabling the exchange of information between different programs.

Three important projects concerned with building have been reviewed: RATAS, GARM and AEC building systems model. They all represent an important contribution for the development of methods and techniques to model buildings. These models differ in their scope. RATAS and AEC building systems model are specific to buildings, while GARM is generic to all the AEC areas. RATAS gives more importance to the building in itself, while the AEC building systems model gives equal importance to the building and the site where it rests.

While more experience is gained both in product modelling and object-oriented programming, Local Product Models, proposed by Wright et al. (1992), intermediate between complete specialisation and complete generalisation, seem to be an adequate compromise.

While modelling a dwelling in a comprehensive way remains an unsolved problem, QDF is an attempt at modelling the quality evaluation of a dwelling. It benefits from the conceptual developments of product modelling and object-oriented programming. Some simplifying assumptions have been made in the present version of QDF in that inter-object relations which are not relevant for the quality aspects being analysed have not been included.

QDF will be developed in the next chapter. The aim of QDF is to evaluate quality. Product models developed in RATAS and AEC are descriptive and aim at being useful for other purposes. To the knowledge of the author, from a review of published literature, these product models are still at an early stage of development, where some solutions and general directions are suggested but no concrete solutions are given. In particular no implementation methods or languages are recommended, apart from a clear option for object-oriented techniques. QDF is an appropriate representation for specific quality evaluations in the scope of a Local Product Model as proposed by Wright et al. (1992). Clearly it is impossible to be complete, in the sense that all possible uses of the system can be included. QDF contains at the one extreme the conceptual description of a dwelling to the development and testing of a prototype for quality evaluation, implemented in an object-oriented system (KAPPA) at the other. However QDF must be used with an understanding of the information contained with it.

A comparative analysis of product modelling and QDF will be presented in Chapter 7.

4.7 Summary

In this chapter the definition and ideas behind product modelling have been presented, as well as a brief historical overview of the reasons for this approach. Product modelling is an attempt at defining a scheme for modelling products in a computer in a compressive way. The STandard for the Exchange of Product model data, STEP, has been briefly described. It is the first serious international effort for standardising product information, including not only graphical data but also information related to the manufacturing specifications of a product (CAD/CAM/CIM). Some examples of product modelling related to buildings were analysed, because of their relevance for the development of QDF. Finally, the importance of object-oriented programming for product modelling has been stressed, as well as the relevance of product modelling to QDF.

5. Quality dwelling framework

5.1 Objectives

The objectives of this chapter are:

- to present the methodology used to develop the framework,
- to develop the framework.

5.2 Introduction

The evaluation of the quality of dwellings is an important step in the direction of improving their quality. This chapter is an account of the development of a framework for a method to evaluate the quality of dwellings, named quality dwelling framework, QDF.

The dwelling is considered as a generalised artefact. It is classified as a part of a building, which is an immovable artefact.

In order to develop a method, a framework has to be established. Some notions about **classification** and the **methodology** behind the framework, the systems approach, will be presented. The dwelling will be classified into a hierarchy of systems, sub-systems and components and the relations between them will be presented. Each of the elements in a hierarchy is both a system and a part of a larger system, i.e. a **holon**, after Koestler (1976). This idea is further explored in section 5.5.1.

In order to develop a classification system for a dwelling it was decided to draw an analogy between a dwelling and a human body. The reason for doing this is that the human form is perhaps the most sophisticated and highly developed form on earth. The division of a human body and that of a dwelling into systems and components is analysed.

The framework to be developed should be suitable for computer implementation, using object oriented design. For that purpose, the regular structure of the holons (objects) across different levels of the hierarchies is a desirable property.

The relation of QDF and product modelling is now presented.

5.3 Classification

In order to develop QDF, a dwelling and its systems and sub-systems have to be classified.

Classification is the dividing of a given population into groups of individuals that exhibit common properties. These properties can be characteristics or relations.

Classification is related to the systems approach in that the organisation of systems in a hierarchy can be interpreted as classification.

Classification is most commonly associated with animals, plants and rocks, but as Gilmour (1940) states "the classification of animals and plants [...] is essentially similar in principle to the classification of inanimate things" (quoted by Dunn 1982). So on that basis the principles used for the classification of animals and plants can be applied to artefacts.

According to Murray (1981) a classification does three basic things:

- it sets out criteria for distinguishing between the items being classified,
- it allows grouping of similar items in an hierarchical scheme of classes,
- it establishes a scheme of nomenclature.

He thinks also that the ideal classification should be simple to use, should provide a workable system of nomenclature and should be acceptable to those using it.

Heywood (1976) comments that "which kind of features are employed depends on the kind of classification we have in mind, since classification is done for a purpose and different classifications are needed for different purposes".

According to Körner (1970) "classification involves judgement that one or more objects possess or lack one or more characteristics". Objects and characteristics are interrelated: objects possess characteristics and some characteristics possess characteristics. So some characteristics are also objects, but not all objects are characteristics. In this sense a wall is an object and is not a characteristic. The thermal transmittance coefficient of a wall can be modelled as an object, which is a characteristic of the wall, and that may have as characteristics (attributes) the value of the coefficient and a degree of insulation (the degree of insulation could be, for example, high, medium or low).

The classifications can be total if (Körner 1970):

- any two classes are exclusive,
- the objects belonging to each of the classes is again classified in the same manner,
- the process is repeated a finite number of times.

This type of classifications is illustrated by the a-kind-of hierarchies used in object-oriented systems with single inheritance. The hierarchy developed in section 6.4 (building elements) is an example (Figure 80-91).

Another important aspect is the way in which a classification is formed:

- partition into particulars (objects which are not themselves characteristics) and attributes (objects which are themselves characteristics),
- partition particulars (and attributes) into those which exist apart from and independently of others and those which do not.

The author owns a house in Portugal which has a wall facing south. This wall, called **south-wall**, can be modelled as an object which is a **particular**, south-wall is not a characteristic. An attribute of any wall is the material it is made from, say **wall-material**, which can be modelled as an object as well; wall-material is not a particular but rather an **attribute** (a characteristic of wall objects, namely of south-wall which has as wall-material **air-brick-of-south-wall**). So, in order to build a classification for the various elements of the author's house a first step would be to divide them into particulars and characteristics.

The second step consists of organising the objects, particulars and characteristics, into a hierarchies (a-kind-of hierarchies). Objects like **wall** and **wall-material** exist apart from the author's house. On the other hand **south-wall** and **air-brick-of-south-wall** are specific elements of the author's house. So south-wall will be classified as a-kind-of wall and air-brick-of-south-wall as a-kind-of wall-material.

These aspects are closely related with the problem of how to identify the objects in object-oriented analysis. Particulars are objects which can not be used as attributes of other objects. Objects which do not exist apart from and independently of others are usually object instances. Those which do are abstractions, usually classes. Extensive examples are presented later, while developing classifications for the systems of a building based on the human body analogy (section 5.6) and for their elements (section 6.4).

The attributes can be of two kinds:

- **constitutive** - those which characterise a particular as a member of a class,
- **individuating** - those which characterise a particular which is a member of a class as a distinct individual.

The author's house has two more walls, **east-wall** and **west-wall**. **South-wall**, **east-wall** and **west-wall** are elements of the author's house which have characteristics that are common to all of them and make it appropriate to model them as elements of the same class, **wall** (constitutive attributes). On the other hand all three walls have characteristics that are unique to each of them and make them distinct individuals, e.g. position in the building (individuating attributes).

In general all the authors agree that lower classes in a hierarchy inherit the characteristics of the classes above and the relationship between classes and subclasses is **a kind of**. According to Cain (1959) the relationships **a part of** and **a function of** can also be used to classify animals or plants.

In this thesis **classification** will be understood as the dividing of a given population into groups (classes), leading to a hierarchy of classes which are related by a **kind of** relationship. A residential building is **a kind of** building, which is **a kind of** immovable artefact.

Classification hierarchies are based on the notions of specialisation and generalisation. A subclass is more specialised than its superclass: a residential building is a special kind of building. It has some characteristics that are common to all buildings (constitutive) and some others that are specific to a residential building (individuating).

The relationship **a part of** will also be used to develop hierarchies. These will be referred as **aggregation** hierarchies (after Rumbaugh et al. 1991). Bricks, mortar and finishes are parts of a wall.

The relationship a **function of** will also be used in this thesis, and is related to the systems approach. The function of a system can be viewed as the co-operative work of various subsystems. The division of the human body into systems is based on the analysis of the different functions it performs.

5.4 The dwelling as an artefact

An artefact is a man made thing and so a dwelling is an artefact. A hierarchy for artefacts has been developed, as shown in Figure 56.

According to the EEC Directive on Liability for Defective Products (1985), artefacts can be classified as **movable** and **immovable** products. Dwellings are considered as immovable artefacts. Movable dwellings, as caravans and mobile homes, are not studied in this thesis.

Immovable artefacts are divided into buildings, roads, bridges, etc.. Movable artefacts are classified into powered (which have some form of engine, that converts energy or fuel into motion) and non-powered.

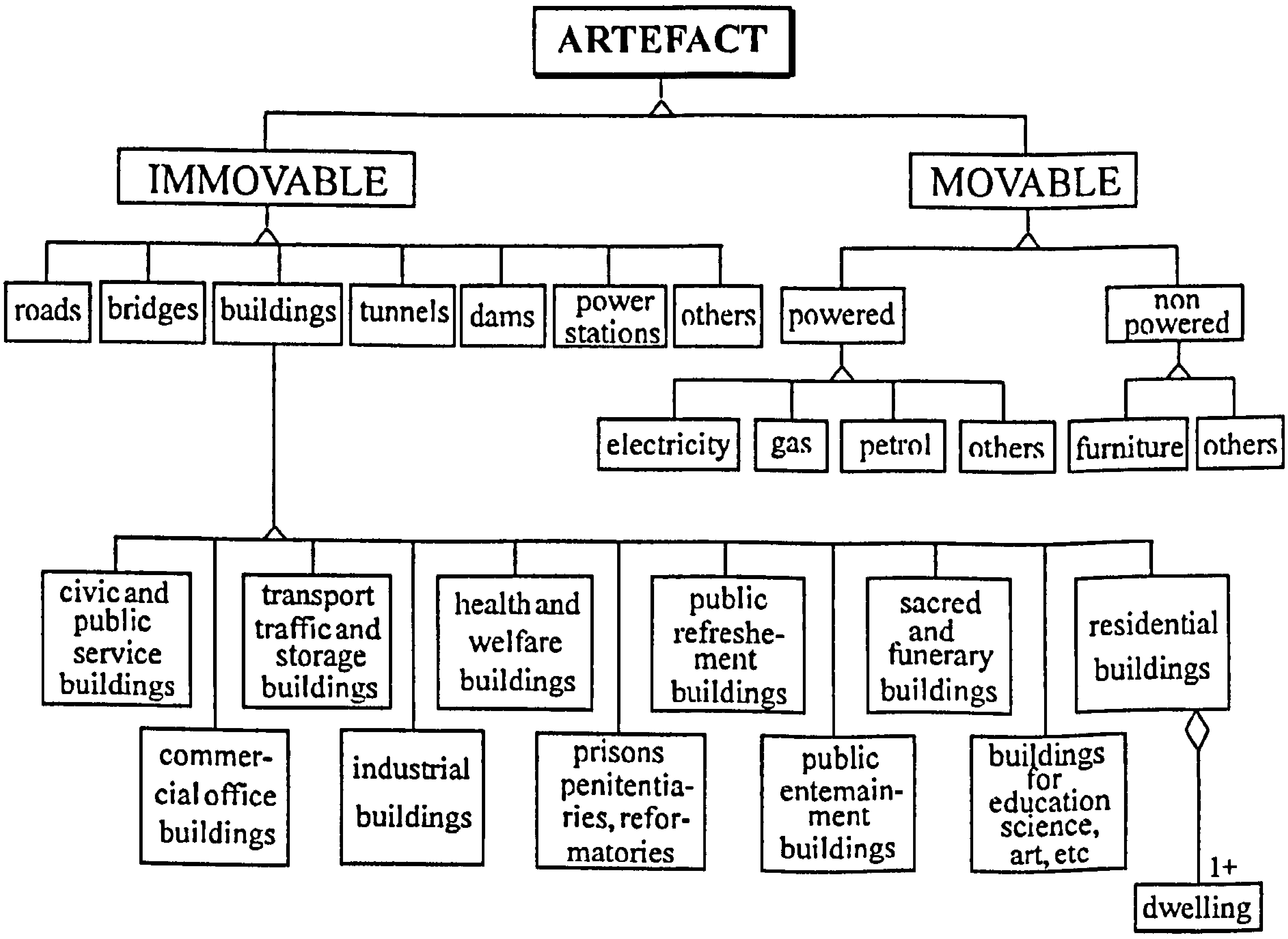


Figure 56 - The dwelling as an artefact.

Buildings are classified according to the CI/SfB (Construction Index/ Samarbetskommittén för Byggnadsfrägor) Construction Manual Index (CI/SfB 1976). In this Manual two classifications are presented, the UDC (Universal Decimal Classification) and the CI/SfB. They are very similar, but the UDC classification was chosen in this thesis because its nomenclature seems more appropriate to the purpose of this classification.

Form and **function** are the major characteristics of any artefact. All artefacts have at least one form and one function. Form and function are usually interrelated. The form of a dwelling will only be studied in this thesis to the extend where it relates to the functions performed by the dwelling. Aesthetical aspects in themselves will not be considered when evaluating the quality of dwellings.

The relationship between the elements at different levels in the hierarchy of Figure 56 is of the type "**a kind of**": a residential building is a kind of building, that is a kind of immovable artefact.

To study the functions of a dwelling a systems approach will be used.

5.5 Methodology

5.5.1 Systems Approach

To understand and study the world it is necessary to divide it into parts (sub-worlds).

This approach is similar to the idea of **classification**. The difference is that when classifying one looks for groups of things that exhibit **common properties**, and when organising the world into **systems** one looks for "groups of things or parts working together in a regular relation" (Hornby 1974).

The approach of dividing the world into parts is a reductionist philosophy. In this approach any whole can be broken into its components parts and once the parts are studied and separately understood then the whole is understood. The system is the sum of its component parts. The fact that many unknown interactions between the components may exist is ignored. This approach does not recognise that the system as a whole has properties that none of the parts have (Senge 1990).

This notion is emphasised by Checkland (1981). According to him "a system embodies the idea of a set of elements connected together which form a whole, this showing properties which are properties of the whole, rather than properties of its component parts". The emergent properties of the whole are a consequence of what could be characterised as a synergetic effect, produced by the combined actions of the elements.

This way of regarding and modelling the world is known as **systems approach.** It is a subject in which one can think and talk about other subjects, it is a meta-discipline. Checkland (1981) defines systems approach as being "an approach to a problem which takes a broad view, which tries to take all the aspects into account, which concentrates on interactions between the different parts of the problem. [...] The systems outlook assumes that the world contains structured wholes which can maintain their identity under a certain range of conditions and which exhibit certain general principles of **wholeness**".

Using the systems approach the world is divided into systems, subsystems and components. Usually any system can always be considered as a part of a larger system and as a whole system. To reflect this idea the word "**holon**" was created (Koestler 1976). The word is composed of the Greek word *holos* (whole), with the suffix *on*, which suggests a particle or a part (as in *proton* or *neutron*).

Systems can be organised in a hierarchical way. This helps showing the relations between the systems and to organise them in a structured way. According to Koestler (1976) "[...] there must be certain principles or laws which apply to all levels of a given hierarchy, and to all the varied types of hierarchy just mentioned - in other words, which define the meaning of **hierarchic order**". The main principle of hierarchic order is the relativity and ambiguity of the terms **part** and **whole** when applied to any of the **holons** (systems).

This approach has been used to study different subjects. Natural, physical, abstract or human activity systems have been used to model the world. Checkland (1981) is concerned with human activity systems and for these kinds of systems he considers that for an adequate definition six elements represented by the mnemonic **CATWOE** need to be identified. These letters stand for:

- **C - customers** of the system, beneficiaries or victims affected by the systems activities,

- **A - actors**, the agents who carry out or cause to be carried out the main activities of the system, especially its main transformation,
- **T - transformation process**, the means by which defined inputs are transformed into defined outputs,
- **W - weltanschauung** (world view), an outlook, framework or image which makes this definition meaningful,
- **O - ownership** of the system, some agency having a prime concern for the system and the ultimate power to the system to cease to exist,
- **E - environmental constraints** on the system, features of the system's environments and/or wider systems which it has been taken as "given".

Four basic ideas are:

- emergence, where the system has properties which are meaningful only when attributed to the whole,
- hierarchy, which is the principle according to which entities meaningfully treated as wholes are built up of smaller entities which are themselves wholes,
- communication, which is the transfer of information,
- control, which is the process by means of which a whole entity retains its identity and/or performance under changing circumstances.

In natural or man-made entities the crucial characteristics are the emergent properties of the whole.

This study is concerned with dwellings. An identification of the six elements represented by the mnemonic CATWOE in this case is presented:

- **C - customers**: the owners or the tenants of the dwelling.
- **A - actors**: all agents involved in the construction, maintenance and use of the dwelling, namely architects, engineers, builders, developers, authorities, quality inspectors and users.
- **T - transformation process**: sheltering (weather protection, physical protection, etc.).
- **W - weltanschauung** (world view): architects and engineers design dwellings, builders build dwellings, developers organise other parties involved in the construction and marketing of new dwellings, authorities

define town planning, quality inspectors verify the quality and users live in dwellings. According to his own role, each actor has a different world view.

- **O - ownership**: the owner and the authorities.
- **E - environmental constraints**: climate, town planning, landscape, orientation, etc..

It is important to emphasise that the systems approach is appropriate to the study of the quality of a dwelling. A dwelling can be considered as a holon in that is a whole (with a set of sub-systems, such as structural and ventilation systems) and a part (of a bigger system such as the regional development). The analysis of the performance of the transformation process **T** forwards defined objectives for the different systems that compose a dwelling will make it possible to define its level of quality.

One can see that the ideas of systems, classification and hierarchies are interrelated. These are the concepts behind the development of the model for the method to evaluate the quality of dwellings.

To define the systems to be considered in a dwelling an analogy with the human body will be used.

5.5.2 Human Body Analogy

An analogy between the **human body** and a dwelling was used to develop the classification and to express the various subsystems.

The human body is probably the most developed evolutionary system and hence the most complex system that science has to study.

The division of the human body into subsystems is typical of a systems approach. By studying an analogy between the human body and the dwelling it is possible to use the knowledge available about the human body in order to better organise the information about the dwelling. Although the dwelling is in itself a very complex system, it seems very simple when compared with the human body.

Both the human body and the dwelling can be divided into systems, which perform specific functions. Each system has one or more components. Each component, e.g. a wall, can be related to one or more systems.

The main systems of the human body are presented below:

- skeletal system,
- movement system,

- respiratory system,
- digestive system,
- urinary system,
- circulatory system,
- nervous system,
- skin system,
- reproduction system,
- spatial system.

An attempt was made to define the more important systems of a dwelling, based on the analogy with the human body. The systems of a dwelling should perform similar functions of the corresponding systems of the human body. The overall basis of the analogy is shown in Figure 57.

Human Body		Building
Skeletal System	→	Structural System
Movement System	→	Robotics System
Respiratory System	→	Ventilation System
Digestive System	→	Energy System
Urinary System	→	
Circulatory System	→	Circulation System
Nervous System	→	Information and Control System
Skin System	→	Containment System
Spatial System	→	Spatial System
Reproduction System	→	Evolution System
Environmental Interaction System	→	Environment System

Figure 57 - The systems of the human body and the systems of a dwelling.

This analogy is justified and further explored in the following section, while developing QDF.

5.6 The framework

QDF is presented in this section. The functions of each system are investigated. The systems, subsystems and components of a dwelling are studied, using the human body analogy. The structure of a component as an object-oriented software object is presented.

Figure 58 shows the systems found in a dwelling by using the analogy with the human body presented earlier. In order to explore this analogy, the systems of the human body are now analysed in terms of functions and components.

To begin with, the functions of the skeletal system are as follows:

1. to act as a framework and to support the soft tissues of the body,
2. to protect the delicate internal organs,
3. to produce blood cells,
4. to store calcium.

The functions of the structural system in a dwelling are similar to functions 1 and 2 of the skeletal system of a human body. To functions 3 and 4 no parallel was found.

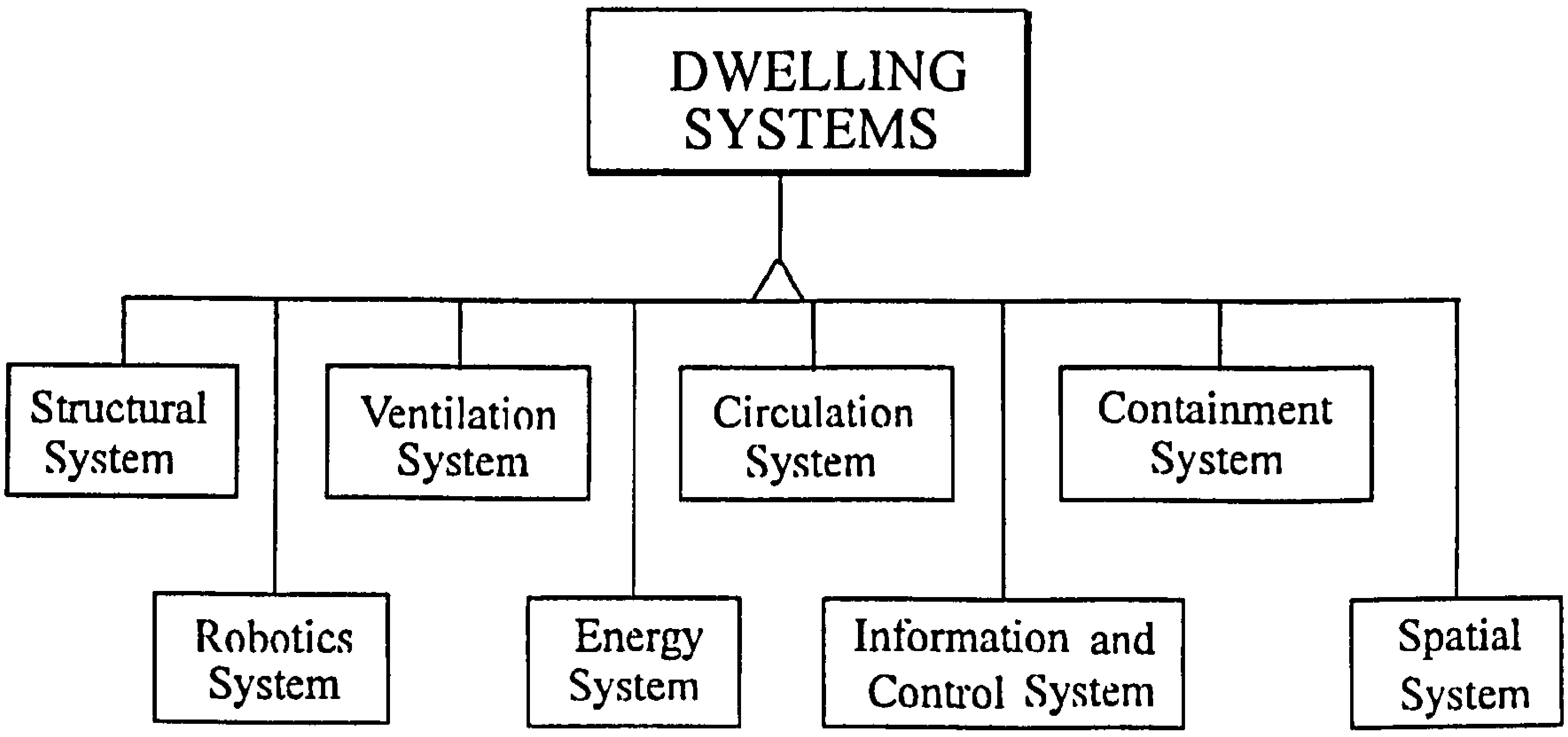


Figure 58 - The dwelling systems hierarchy.

Figure 59 shows the components of the skeletal system and the components of the structural system. They are listed bottom-up. It is possible to find a mapping between some of them, for example, feet can be considered as corresponding to the foundations. One can notice that in the skeleton of a human body the bones are joined by articulations, so that they can move. In the structural system of a dwelling some mobility must be allowed between different parts (expansion joints perform a similar function to articulations). The analogy could be extended to movable artefacts in future work.

Figure 60 presents a hierarchy for the structural system. Its main components are foundations, storeys and roofs.

HUMAN BODY	DWELLING
Components of the **skeletal system** (bones): feet, legs, knees, hips, back bones, ribs, shoulders, arms, neck, skull.	Components of the **structural system**: foundations, lintels, columns, beams, slabs, load bearing walls, retaining walls.

Figure 59 - The components of the skeletal and of the structural systems.

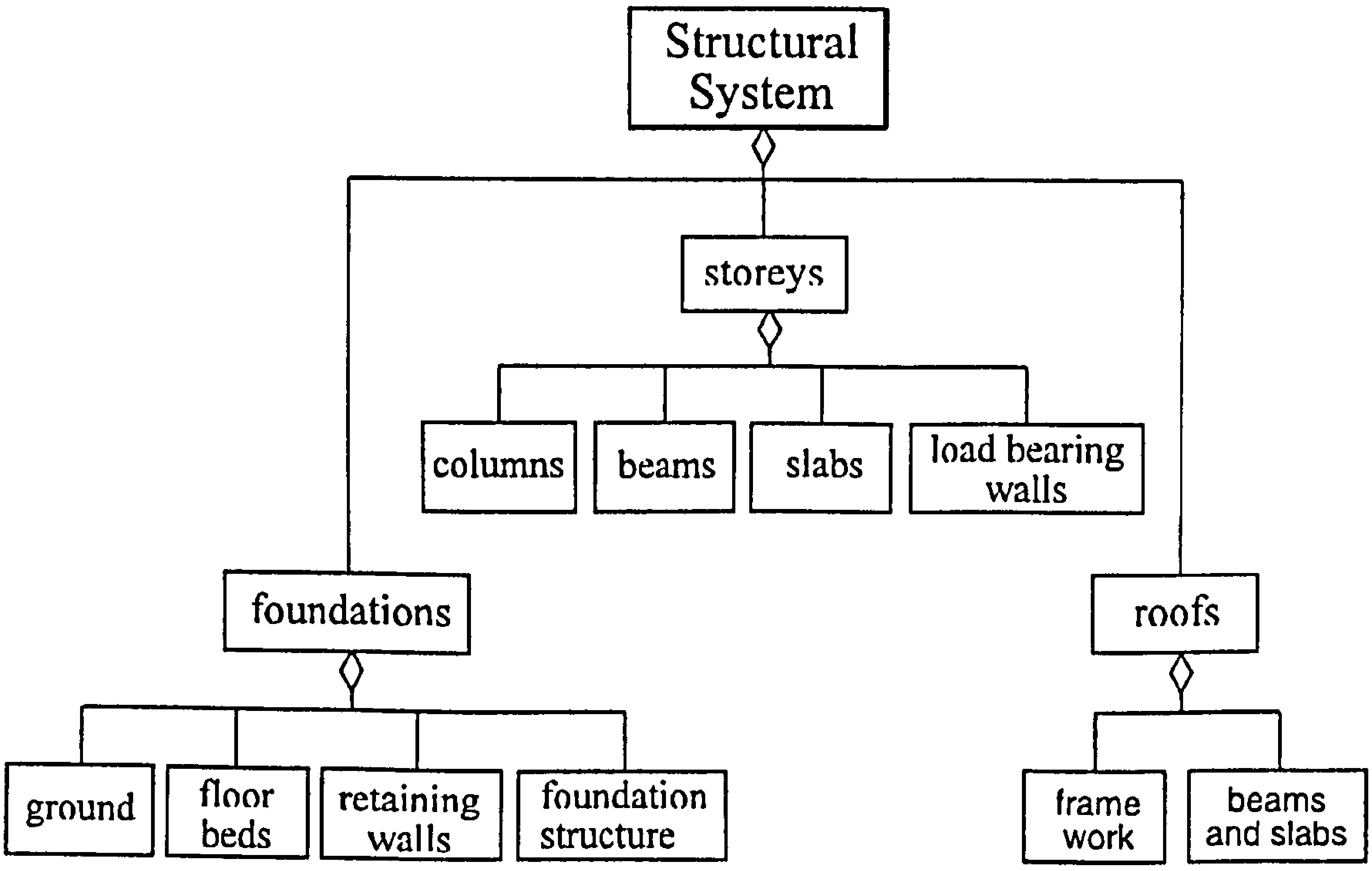


Figure 60 - The structural system hierarchy.

The movement system is considered as being the skeletal system together with the muscles because the bones that constitute the skeleton enable the free movement through the action of the muscles. A robotics system for a dwelling would perform a similar function. It does not usually allow the dwelling to move as a whole, but it enables some parts to move, as for example automatic doors, lifts and moving solar protections. The robotics system is not studied here into detail, because those found in dwellings are still very crude. Intelligent buildings, because at this time are still very expensive, are rarely used as residential buildings.

The respiratory system will be analysed and compared with the ventilation system. The functions of the respiratory system are :

1. production of voice,

2. exchange of gases between the blood and the atmosphere at the level of the lungs,
3. release of energy from glucose at the cells.

Only function 2 is common to both systems.

The components of these systems are listed in Figure 61. The correspondences found are indicated by arrows.

The hierarchy of the ventilation system is shown in Figure 62.

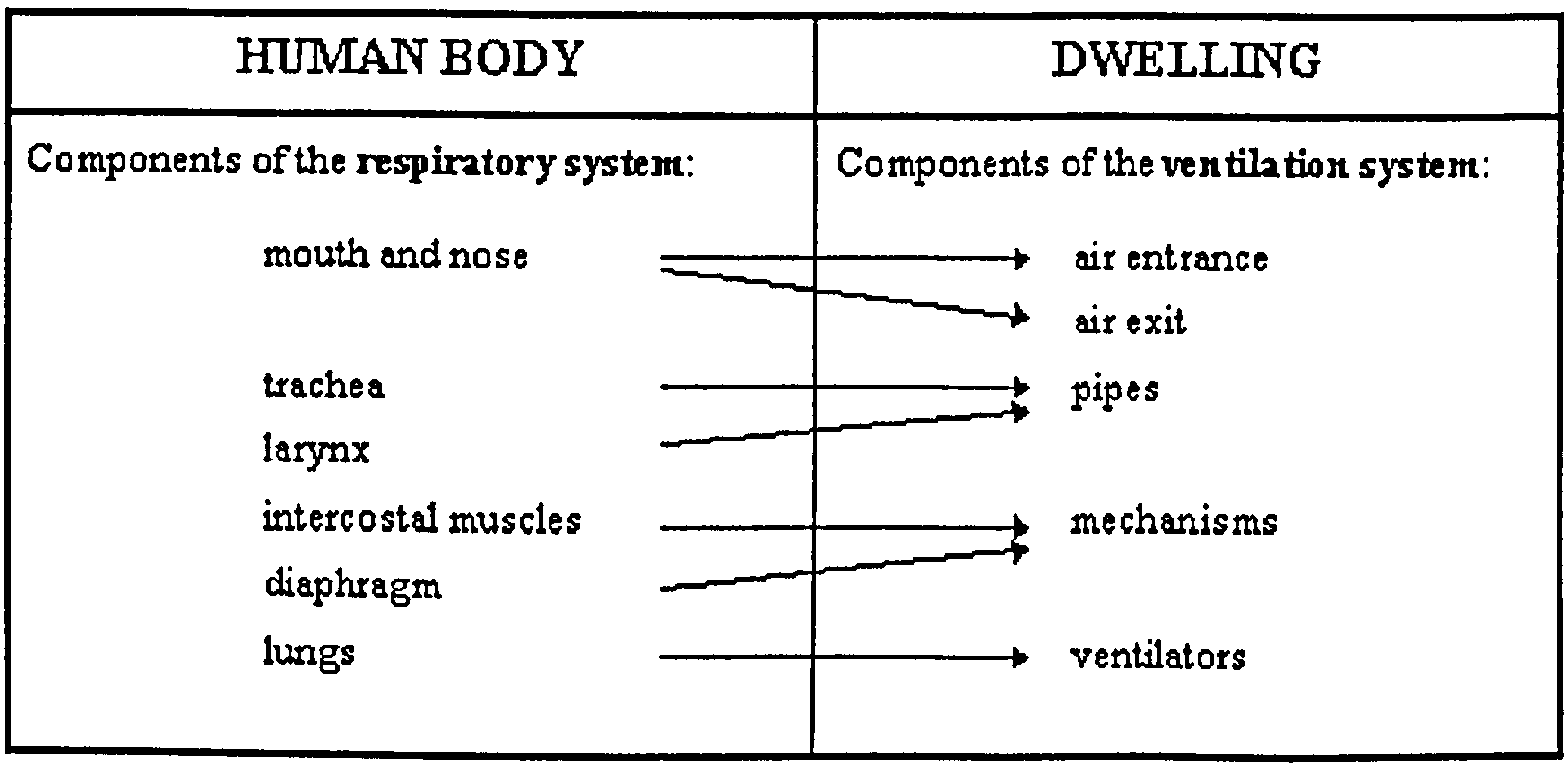


Figure 61 - Respiratory and ventilation systems.

The analysis of the digestive and urinary systems follows. The functions of the digestive system are:

1. ingestion of food,
2. transformation of the food into substances that can be carried by the blood and later on absorbed by the cells,
3. excretion of the waste of the digestion.

The functions of the urinary system are:

1. removal of harmful waste products,
2. regulation of body fluids by controlling the water and mineral salt content of the blood.

Figure 63 shows a possible mapping between the components of the digestive/urinary system and those of the energy system.

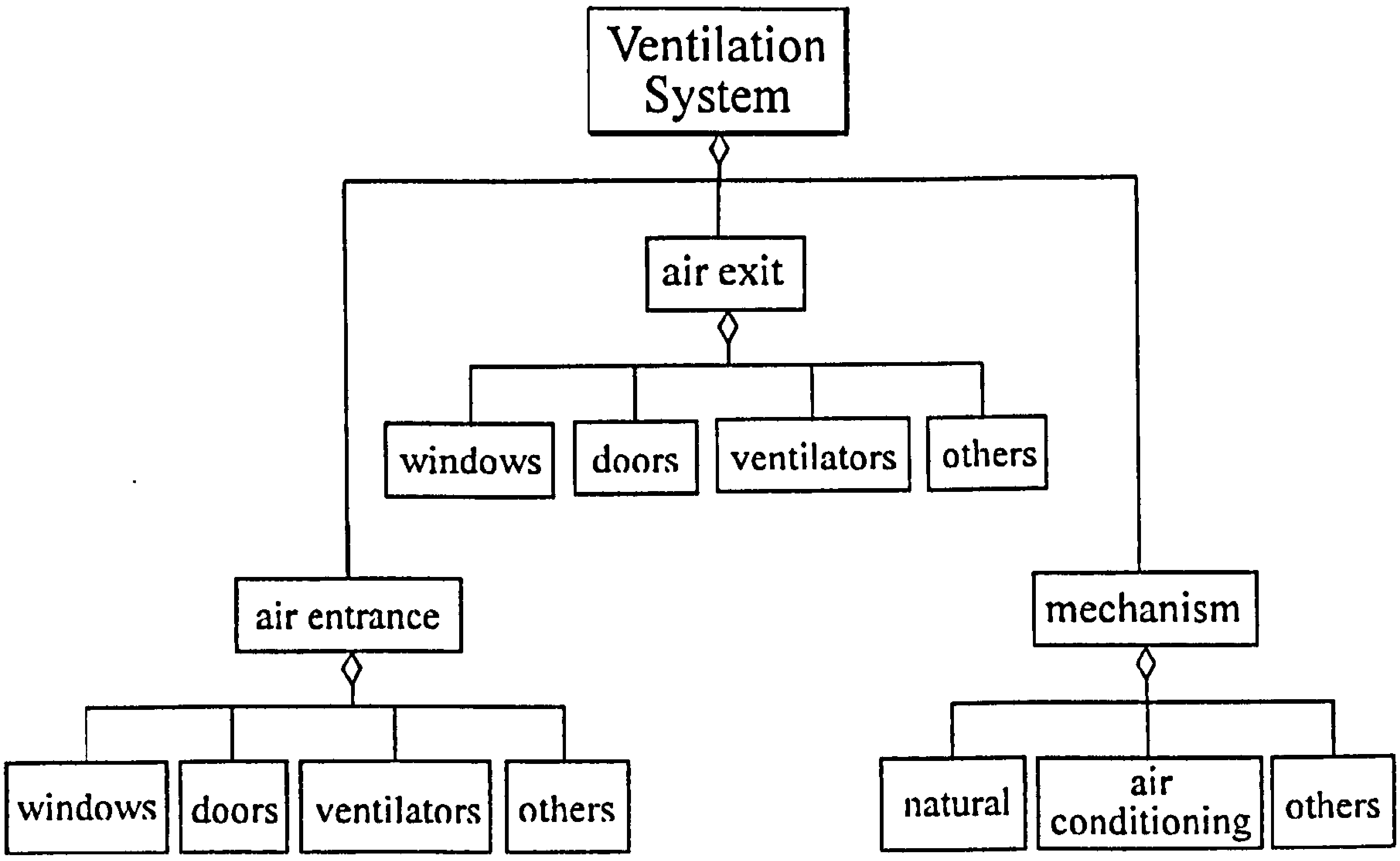


Figure 62 - The ventilation system hierarchy.

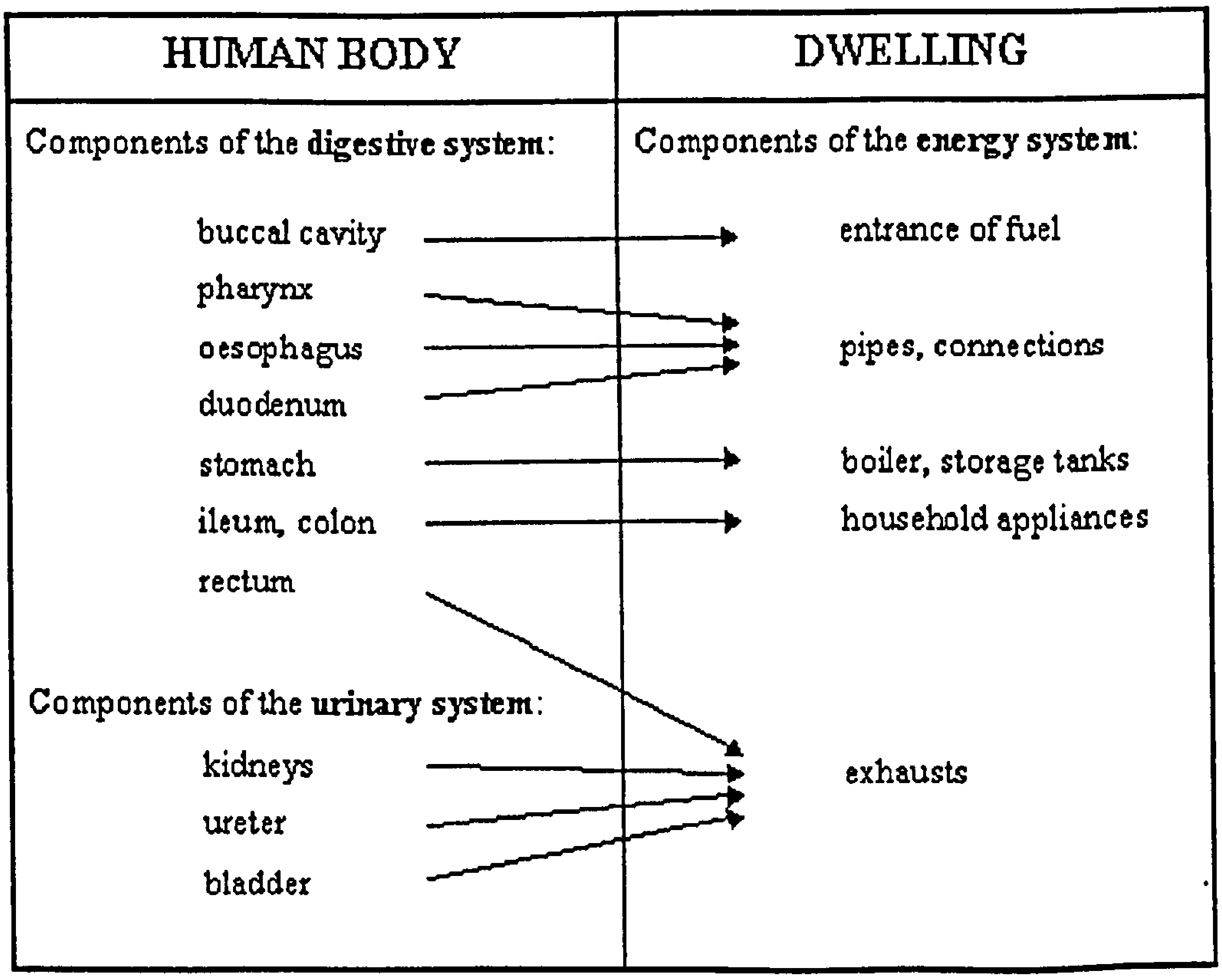


Figure 63 - Digestive/urinary and energy systems.

Figure 64 shows the hierarchy proposed for this system. The energy system of a dwelling can be viewed as organised into subsystems that carry out two main functions: entrance of fuel (**input**) and the result of the transformations of the fuel (**output**), that includes the waste.

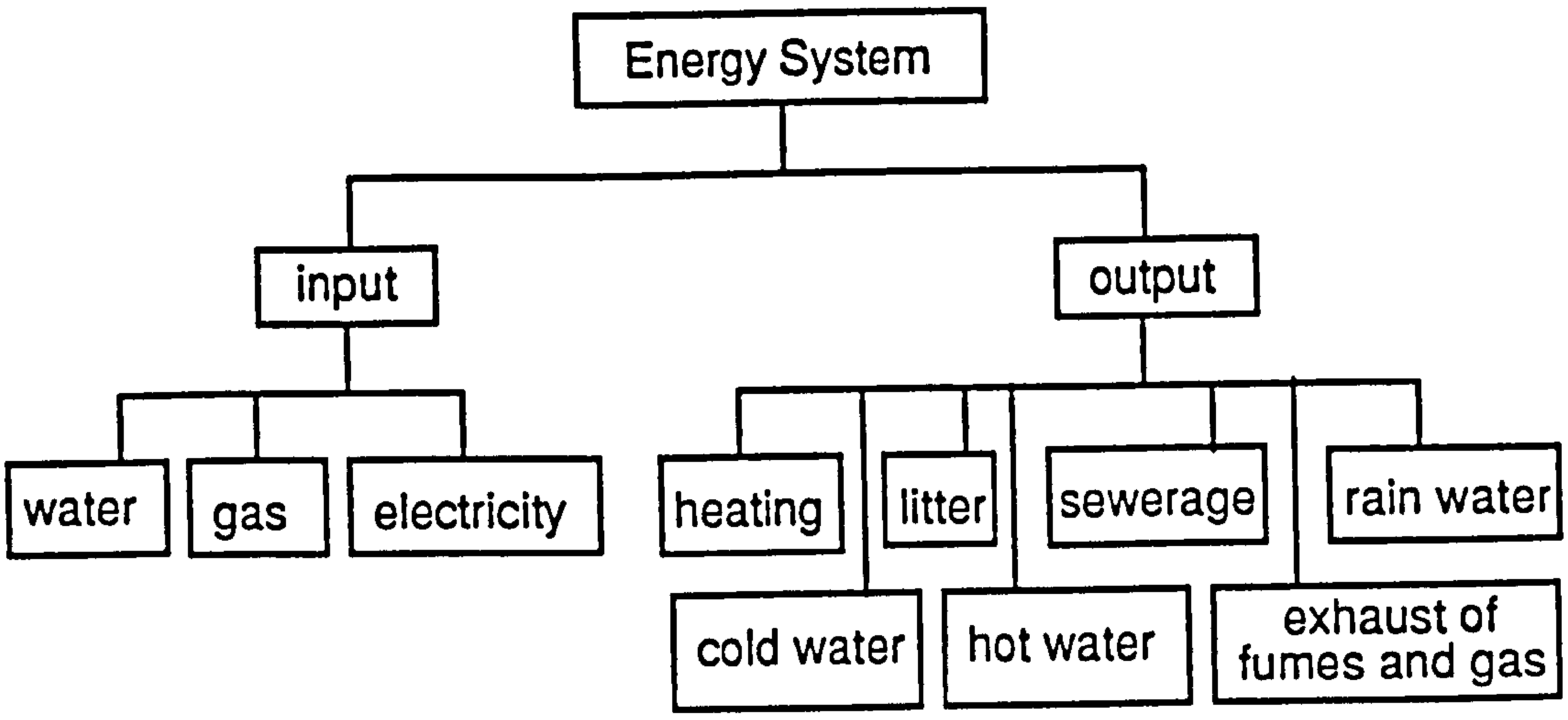


Figure 64 - The energy system hierarchy.

The next system to be analysed is the circulatory system. The function of this system is to distribute substances to the cells, like food and oxygen and to collect their waste products. As the blood circulates all over the body, through the veins and arteries, people circulate inside a building. It is this comparison that is used to study the circulation system of a dwelling. Figure 65 shows a mapping between the components of the circulatory system and those of the circulation system. Figure 66 shows the hierarchy of the circulation system. The components of this system have been divided horizontally and vertically, depending on whether they provide access to the same level or between different levels.

HUMAN BODY	DWELLING
Components of the **circulatory system**:	Components of the **circulation system**:
blood →	people
heart →	lifts, stairs, ramps, scalators
veins, arteries →	corridors

Figure 65 - Circulatory and circulation systems.

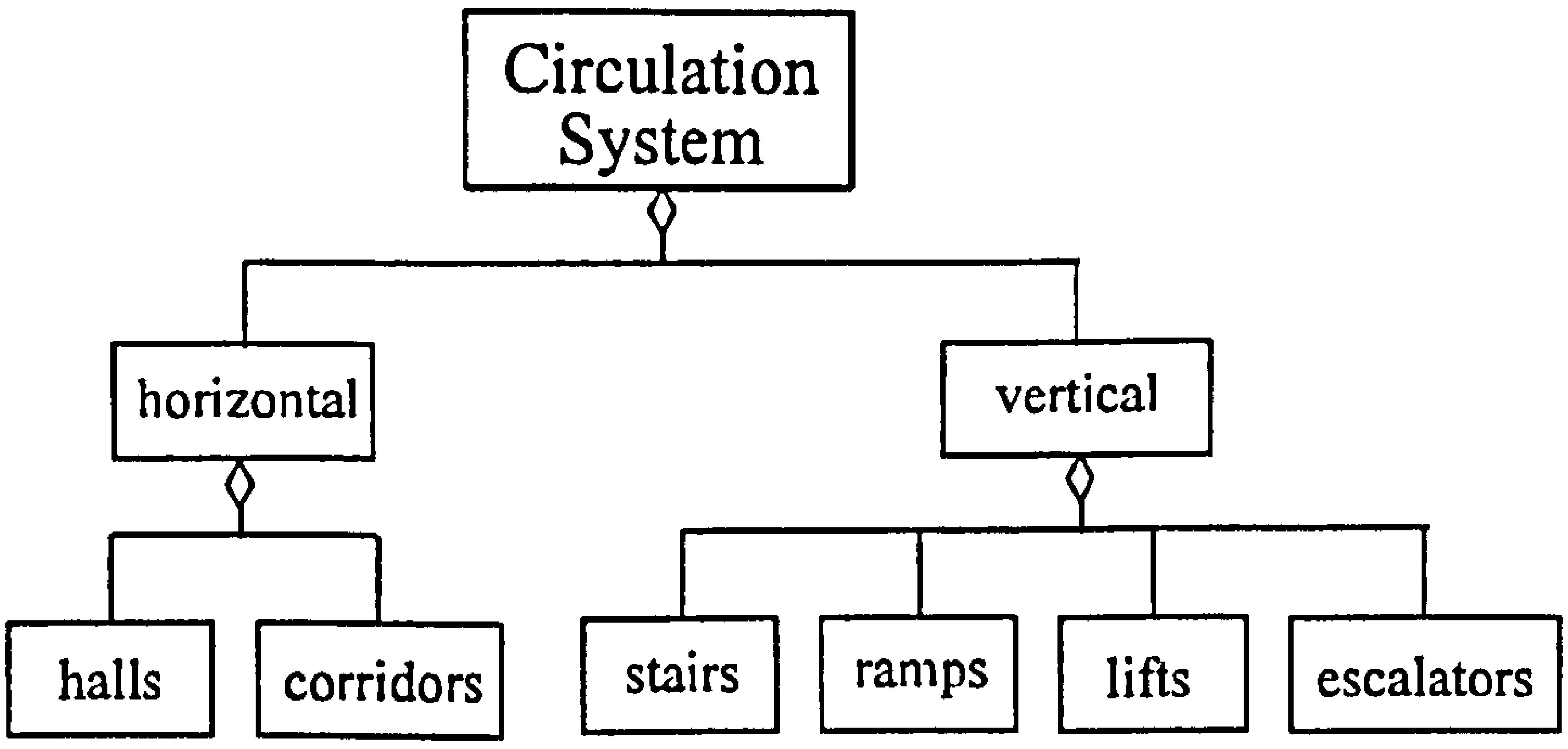


Figure 66 - Circulation system hierarchy.

The nervous system of a human body performs the following functions:

1. to perceive stimuli (changes in the surroundings),
2. to co-ordinate the reaction to the stimuli in such a way that it is to the advantage of the body.

In a dwelling the information and control system performs identical functions. The components of these systems are shown in Figure 67 and the hierarchy of the information and control system is presented in Figure 68.

HUMAN BODY	DWELLING
Components of the **nervous system**:	Components of the **information and control system**:
nerves endings and perception organs	sensors (fire detectors, thermostats, burglars detectors, etc.)
spinal cord, nerves	networks (computer, radio, tv, etc.)
brain	controllers

Figure 67 - Nervous and information/control systems.

The skin system of a human body is comparable to the containment system of a dwelling.

The functions of the skin are to:

1. protect tissues and organs from mechanical damage by providing a covering of cells replaceable from below,

2. maintain body shape. The elasticity of skin restores the shape when joints are used during movement,
3. protect against excessive loss of water from the body by evaporation,
4. protect against entry of bacteria, fungi and other harmful organisms,
5. act as an excretory organ by removing excess salts, water and urea from the body,
6. acts as a sense organ as it contains various tiny structures that react to stimuli such as temperature, pain and touch,
7. regulate temperature.

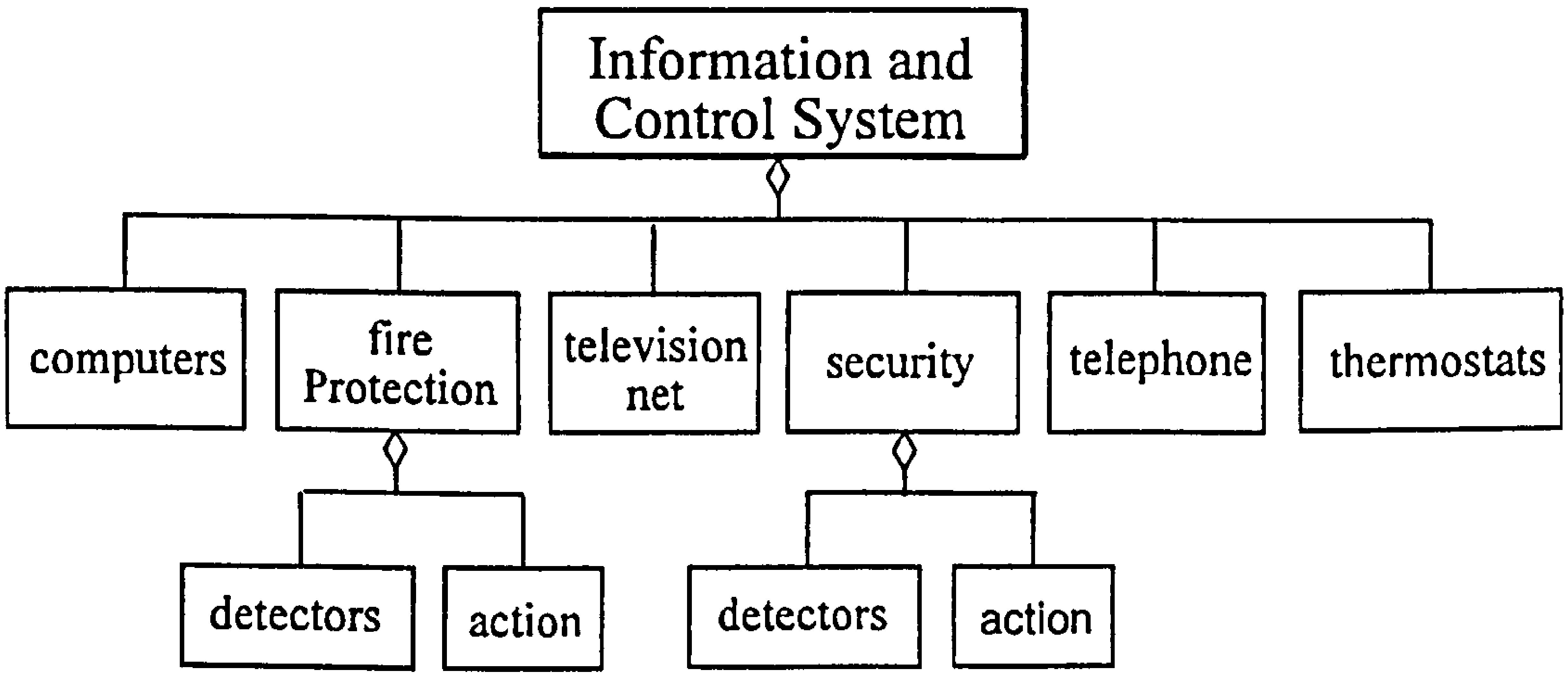


Figure 68 - Information and control system hierarchy.

The containment system performs some similar functions: protection (1,4); definition of the shape of the dwelling (2), which also has some aesthetical implications, and regulation of the temperature and humidity (3, 7).

Figure 69 shows the components of the skin and containment systems.

HUMAN BODY	DWELLING
Components of the **skin system**: skin →	Components of the **containment system**: walls, roofs, tiles, doors, windows

Figure 69 - Skin and containment systems.

Figure 70 shows a containment system components hierarchy. These components were defined in view of the protection functions they perform.

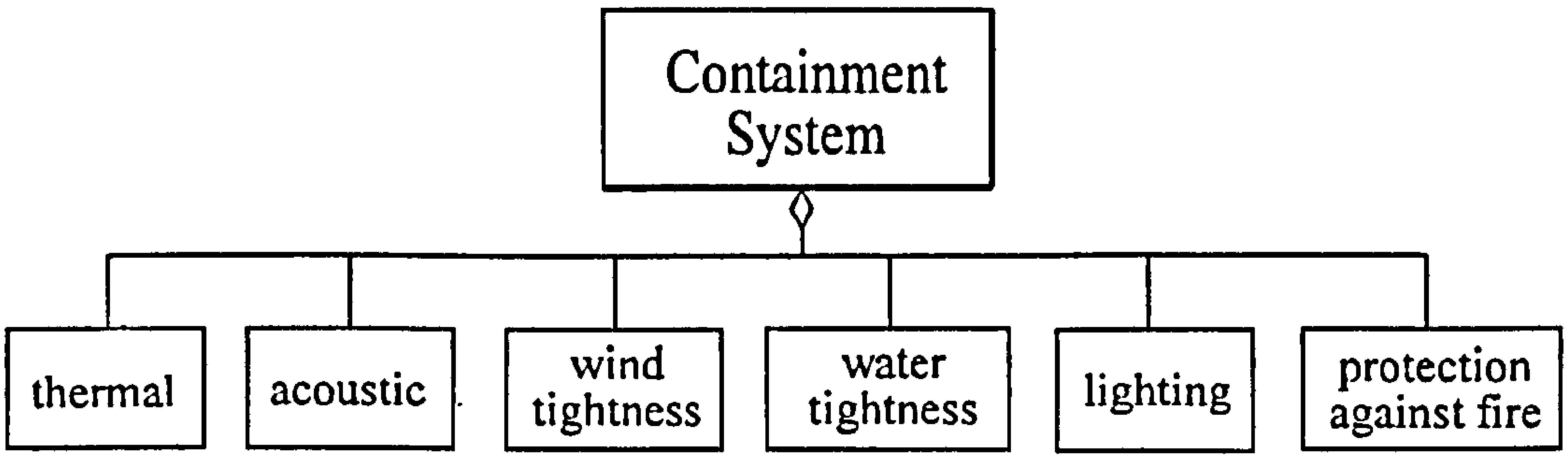


Figure 70 - Containment system hierarchy.

As stated earlier aesthetics of a dwelling are not considered in this work. So the shape of the dwelling in itself is not taken into account when analysing the containment system.

Another system that is related with aesthetics is the spatial system. In this work when analysing this system only functional aspects will be considered.

The function of the spatial system of the human body is to describe overall form which is the position of each part of the body with respect to the others. In a dwelling it performs a similar function, describing the position of each part of the building with respect to the others and the position of the building with respect to the surroundings (Figure 71).

HUMAN BODY	DWELLING
Components of the **spatial system**:	Components of the **spatial system**:
parts of the body →	→ parts of the dwelling (spaces)
relative position of the different parts →	→ relative position of the parts

Figure 71 - Spatial systems

The components of the spatial system can be physical components of the building, as well as associations between different parts of the building indicating their relative position (Figure 72).

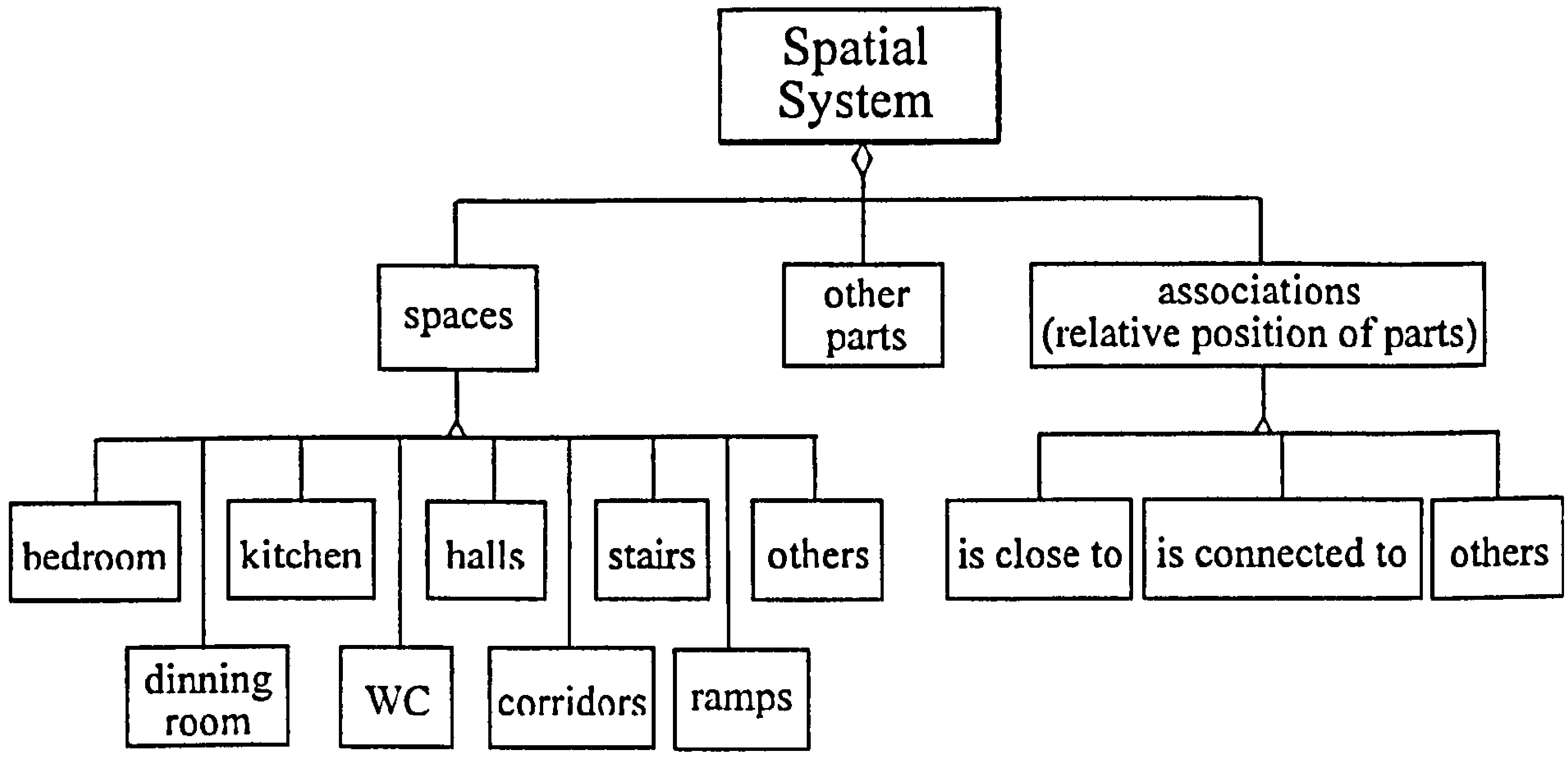


Figure 72 - Spatial system hierarchy.

In Figure 73 **room1** is **connected to** hall 1, **room1 is close to room2**. This association should have as attribute the slope between the centres of the rooms, for example. The association **is connected to** should have as attribute the position of the connection between **room1** and **hall1** and its size (how large is the door).

Other positioning associations could be defined. A general one (**has location**) would have as attributes the slope and distance between the spaces. This kind of general information does not seem necessary when analysing the functionality of the spaces, because the information used for this purpose is usually local.

The next system to be analysed is the reproduction system. Its function is to produce offspring.

From this point of view there is no direct parallel in a dwelling. Even so some similarities do exist when the evolution of the species is considered (see Figure 74). Just as human beings have adapted to the characteristics of the environment where they live also design and construction methods in buildings have been adapted to the environment. Well known examples are: the high slope of roofs in Switzerland because of the snow and the white painting of the houses in hot climates, like the south of Portugal, to reduce the effects of insolation. Quality standards evolve by refining good solutions and abandoning bad ones. New solutions could be compared to new arrangements of genes through reproduction and mutations. If they are well accepted they spread and evolve; if not they tend to disappear.

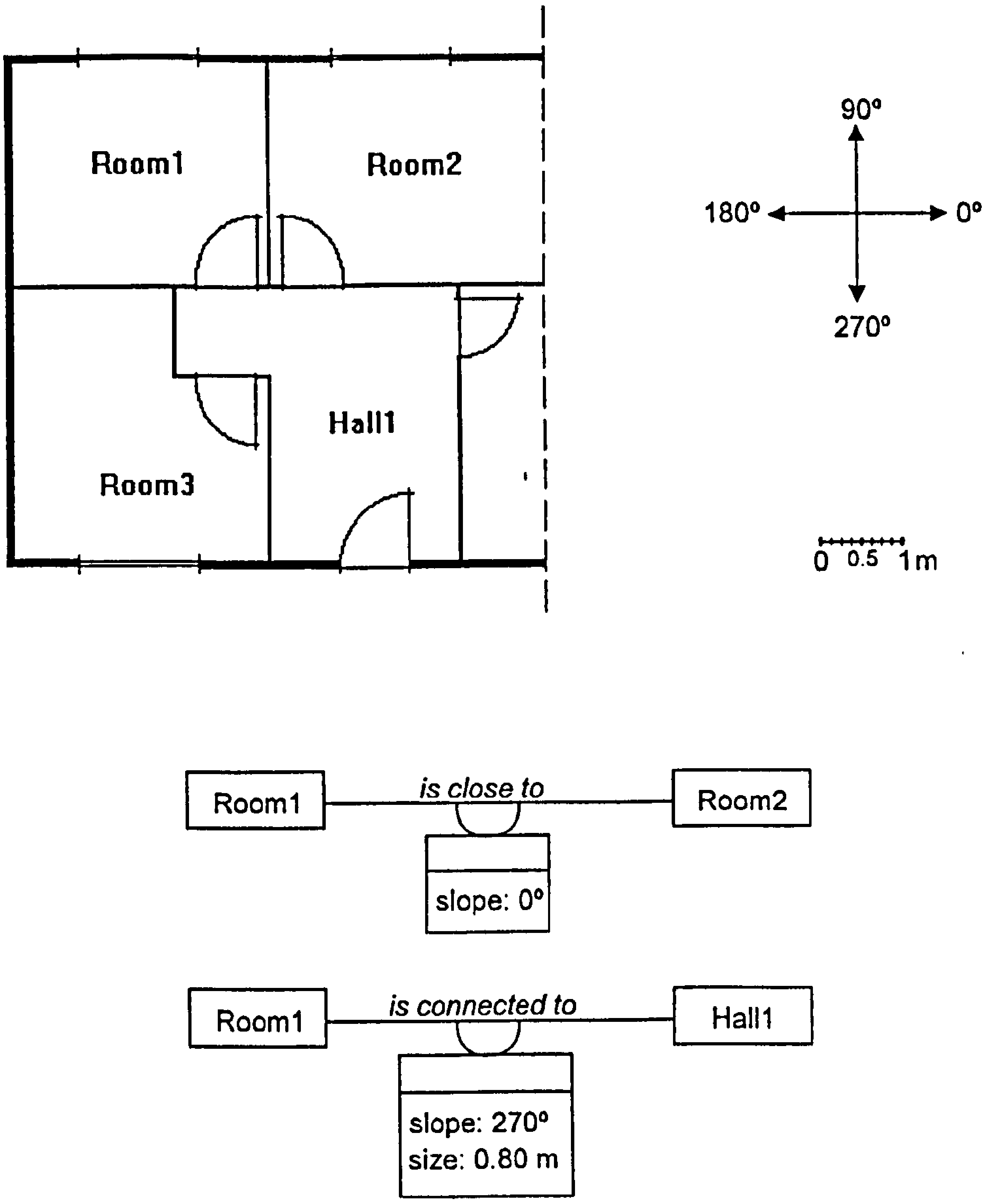


Figure 73 - Example of the relations is connected to and is close to.

HUMAN BODY	DWELLING
Components of the reproduction system (evolution of the human species): character selection mechanisms	Components of the quality evolution system: solutions selection mechanisms

Figure 74 - Reproduction and quality evolution systems.

The components of the quality evolution system are the mechanisms by which new solutions are selected and refined, namely the opinion of the users, the difficulty of implementation, availability, initial cost and costs of maintenance. This is illustrated in Figure 75.

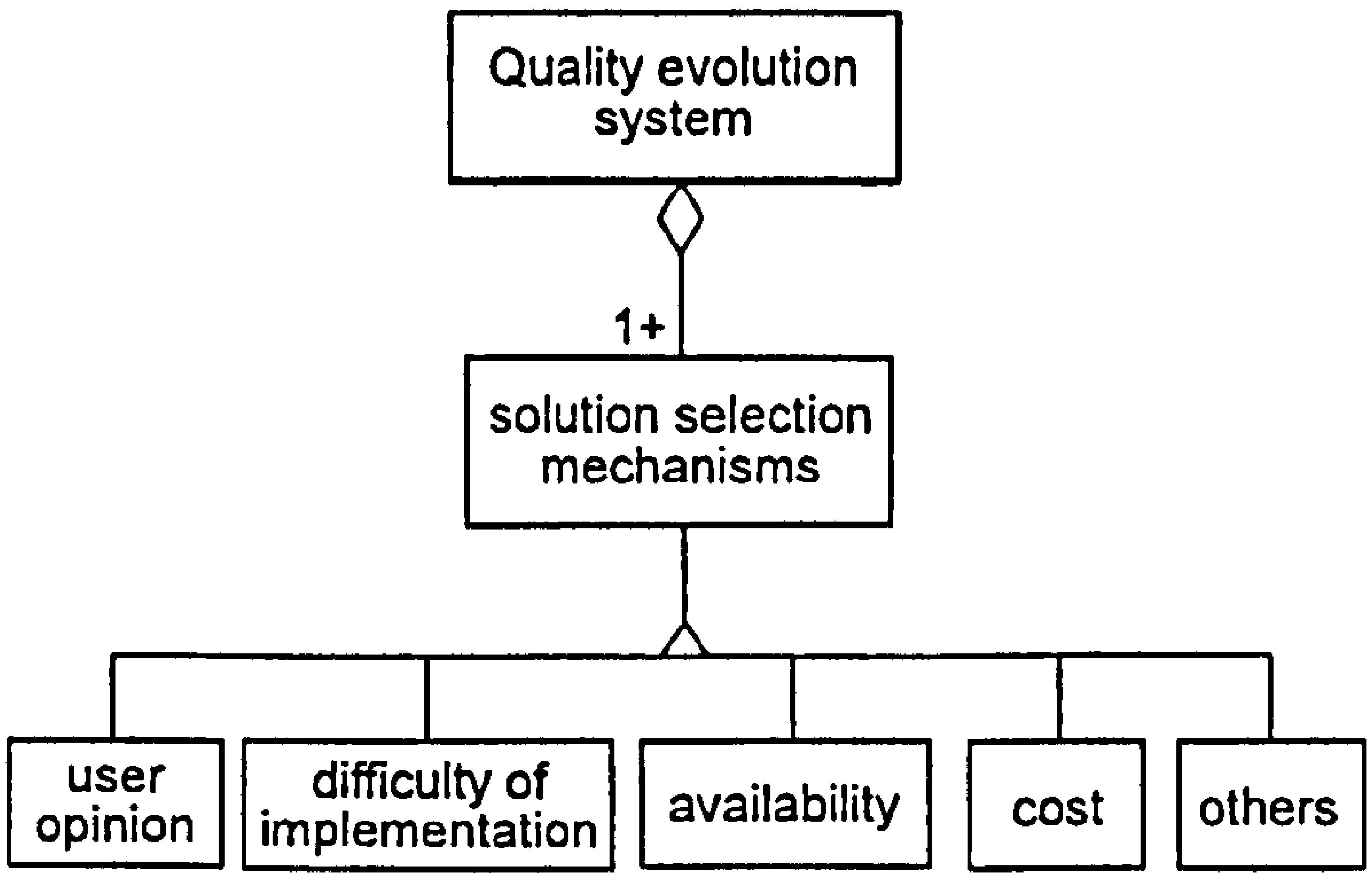


Figure 75 - Quality evolution system.

The environment influences a human body and vice-versa. Humans affect the natural environment and so does a dwelling. It is important for the quality of life of the people who will live in a dwelling the place where the dwelling is located. The environment systems of a human body and of a dwelling are very similar, but there are two important differences worth noting. A dwelling remains always in the same environment (mobile dwellings excluded), while a human body can change of environment. A dwelling belongs and is an important component of a human body environment (home). Figure 76 shows a parallel between the components of a dwelling environment system and of a human body environment system.

HUMAN BODY	DWELLING
Components of the **environment system**:	Components of the **environment system**:
home →	the site where it rests
family →	surrounding dwellings
physical/chemical environment →	physical/chemical environment
services →	services
communications →	communications

Figure 76 - Environment systems.

As a dwelling is a sub-system of a building, the interaction of the dwelling and the environment are analysed taking into account the whole building. Figure 77 shows a hierarchy for the environment system of a building. A distinction has to be made here between houses and flats. In the case of flats it is also important to consider the floor, block and building (and in some cases the development) where the dwelling is located, because it is important to consider aspects like the common facilities inside of the building and the common accesses.

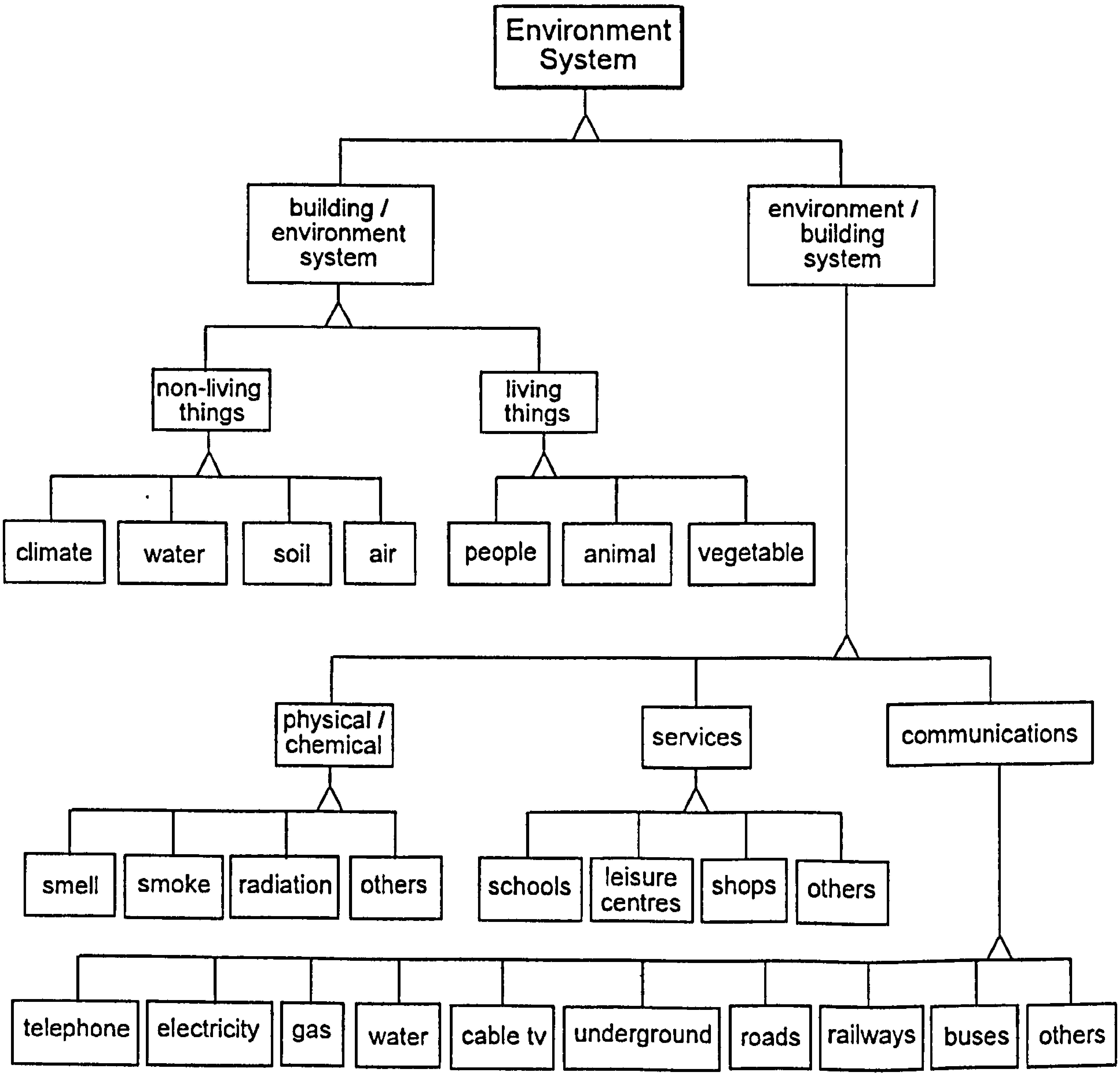


Figure 77 - Environment system.

While comparing a human body and a dwelling another important aspect is the parallel between birth and ageing process of a human body and of a dwelling. The temporal dimension involves two main aspects:

- Quality evaluation should consider the life-cycle of the dwelling, i.e. design, construction, maintenance, exploitation and demolition. The present version of QDF only applies to the design phase.

- Quality evaluation of the design should take into account the implications of ageing in design decisions. The present version of QDF evaluates the quality as it is previewed soon after construction.

The first aspect involves an extension of the quality assessment to the various phases of the life of the dwelling. The second aspect is closely related with the estimation of maintenance, exploitation and demolition costs, although it involves another aspect which is the prevision of the evolution of quality standards (e.g. 5 years after construction, 10 years after, etc.).

In the present version of QDF the temporal dimension is not explicitly modeled, i.e. the objects represent the state of a dwelling at a given moment in time. QDF can be extended to take the temporal dimension into account by modeling a dwelling at sufficiently close time intervals. In the present version quality is evaluated in the design phase and it is assumed that the dwelling will be well built and maintained. Furthermore no distinction is made between two design solutions which are expected to last for different periods of time.

5.7 Summary

The methodology used to develop QDF has been presented. It is based in the systems approach and uses a human body analogy. This is justified by the fact that a human body is perhaps the most sophisticated and highly developed form on earth. A comprehensive set of systems for modelling the quality of dwellings has been proposed, by drawing a parallel with the human body systems. The quality of a dwelling is evaluated by analysing the quality of its systems. In the present version QDF is suitable to evaluate the quality of dwelling designs and does not contemplate other phases of the building life cycle (e.g. construction). The regular structure of the holons (objects) across different levels of the hierarchies makes the framework suitable to be implemented using object-oriented techniques and tools, as will be shown in the following chapter while developing a prototype.

6. Implementation of the framework

6.1 Objectives

The objectives of this chapter are:

- to present a design for computer implementation of QDF,
- to present a prototype implementation, using the object-oriented tool KAPPA.

6.2 Introduction

The design and implementation of a prototype system for the evaluation of quality of dwellings will be presented in this chapter. This implementation will help in the evaluation of QDF.

As discussed in Chapter 3, the tool chosen for the implementation is the object-oriented programming environment KAPPA.

A prototype program has been developed to test QDF. It includes evaluation methods for:

- a **thermal system**. The metrics used for evaluating the thermal winter quality have been defined by Paiva (1991a, 1991b) and are based in the Portuguese Thermal Regulations (RCCTE 1990). Those used for evaluating the thermal summer quality follow the Portuguese Thermal Regulations;
- an **electrical system**. The metrics used are those defined in the Qualitel method for the electrical fittings;
- an **environment system**. The metrics used are those defined in the SEL method, in the relevant criteria.

The program design and implementation are explained and discussed. Finally some conclusions are presented.

6.3 Program Design

In this section the design of a program to implement QDF will be presented. In the previous chapter a division of a dwelling into systems, subsystems and elements has been proposed, using the human body analogy. The human body analogy is taken a step further, by exploring a way of organising the information about each system.

The human body system's hierarchy has at the bottom level elements which are organs, bones veins, etc.. These elements can belong to more than one system (e.g. the lungs are important organs of the respiratory and circulatory systems). The division of a complex system into subsystems is a way of better understanding a complex net of relations, which implies some simplifications (modelling is after all capturing the most relevant aspects of a system for a given purpose).

The quality of a dwelling is measured by analysing the quality of its systems. The quality of a system is determined on the basis of the quality of its components and their interactions. Complex systems can be modelled as collections of interacting objects, as suggested by Chandra (1992) in the context of process modelling: "a body can be considered as a set of objects {...} all behaving in parallel and interacting with each other through an exchange of messages".

A complex system like the human body has been classified into systems, subsystems and components. The relevant information of each component is usually attached to the component: information about the lungs is normally associated with the lungs, rather than with the respiratory system or the circulatory system. By analogy, in the computer model of the dwelling proposed in this thesis, information about an element of the dwelling will be local to the element, rather than associated directly to the system or systems to which the element belongs. This has also the added advantage of avoiding duplication of information.

The design of the computer implementation of QDF is based on the idea that a system is analysed by analysing its elements, which "know" the information regarding themselves (responsibility driven approach referred in Chapter 3). Being so, a composition hierarchy is used: a dwelling is composed of systems (software objects), which are composed of elements (software objects). In the parallel that has been drawn in Chapter 5, the dwelling elements (e.g. columns, beams, walls, pipes) correspond to the elements of the human body (e.g. organs, bones, veins).

How should a model of a system of the human body be "built", for example the skeleton system? If a comprehensive set of templates for the bones is available, each bone will be generated using a template. Different bones may be generated from the same template if they are of the same kind. In object-oriented software design the templates are classes, while the bones are instances. The templates can be organised into a classification hierarchy (class hierarchy). A class hierarchy for the dwelling elements has been designed and will be presented later.

Another design issue is how to store the information related to each dwelling element. The information concerning a dwelling element can be stored directly in the corresponding software object. Alternatively, objects which represent the relevant characteristics for each system can be defined and associated with the elements of the dwelling. These objects could be organised in a hierarchy of CharacteristicContainer, as shown in Figure 78. For example, an object CCThermalSystem would be the container of the information required by the thermal system to analyse its components. This approach would be ideal if the characteristics of the components of a system were homogeneous; in many cases they are not. For example, the attributes for evaluation of the winter thermal behaviour of a wall are quite different from the ones of a glazed area. A solution could be to develop the hierarchy of CharacteristicContainer further down, specialising the containers according to the characteristics of the different building systems elements. This solution represents a good design alternative, but has the drawback of "spreading" the information and making the implementation more demanding in terms of resources. It has not been adopted in this thesis because implementation difficulties were experienced when increasing the number of software objects in KAPPA. Although a partial solution to this problem has been implemented by saving to disk objects that are not needed for the evaluation of the "active system" (e.g. thermal, electrical), it is not easy to increase the number of software objects in present implementation. This will not be a problem in future implementations, because the increasing power of computer systems, means these memory limitations will be less relevant in future.

QDF has been designed so that it could benefit from the speed improvements available when using parallel hardware architectures. Although to the knowledge of the author no user friendly tools are yet available in this kind of platforms. Future implementations of QDF could benefit from new developments in this area.

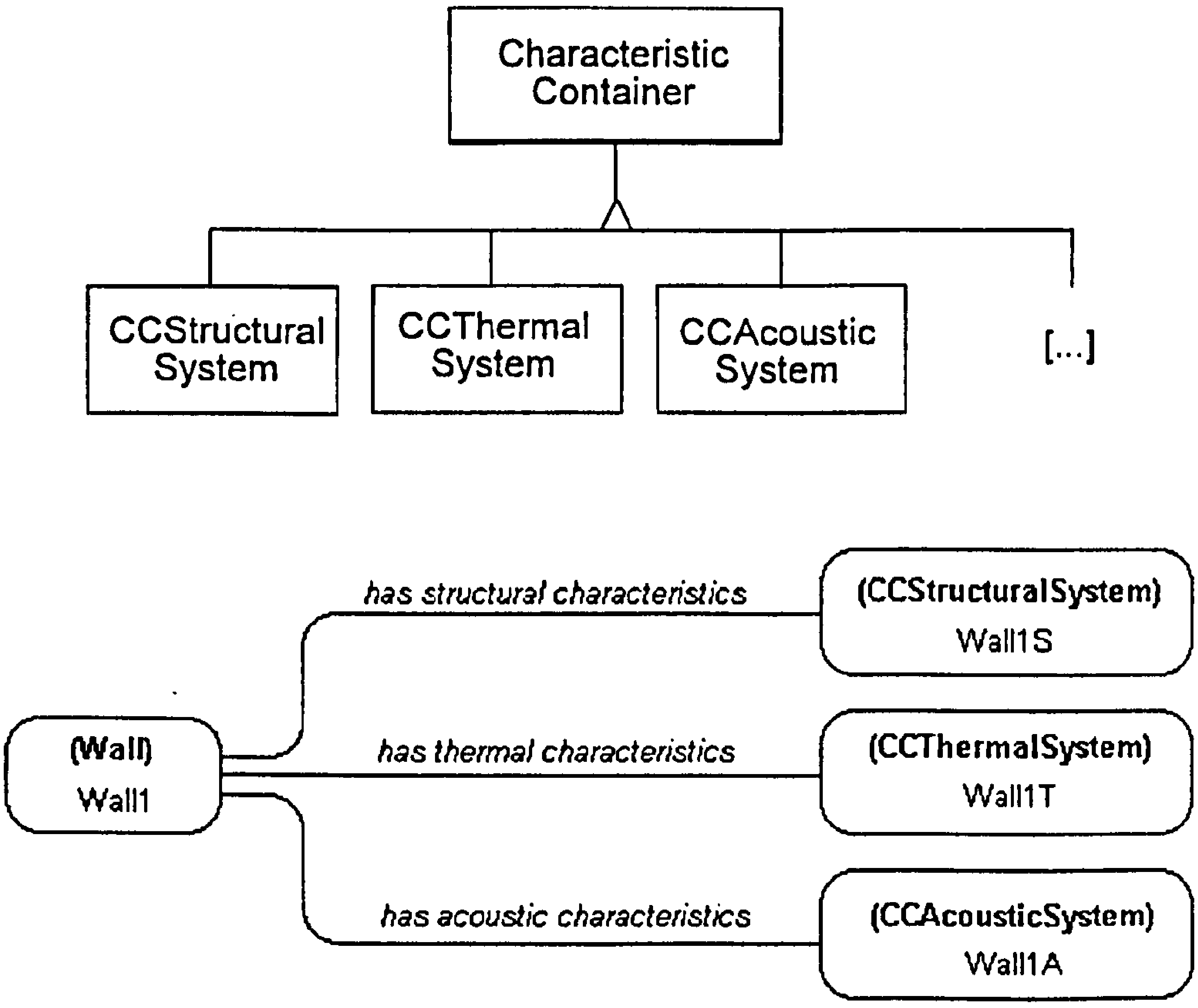


Figure 78 - An hypothesis for the organisation of information.

The adopted solution was to store directly the information about a dwelling element in the corresponding software object. It provides a good design alternative and leads to a robust implementation. All the information about an element is stored locally, although different pieces of information will be relevant to different systems, e.g. the information related to the structural system, the thermal system and the acoustic system of a wall will be inside the software object representing that wall, as shown in Figure 79.

In order to organise the dwelling elements into a hierarchy, a literature survey about decomposition of a building into its physical components was done (CI/SfB 1976, Bezelga 1981). The most important classifications are:

- Decomposition according to the SfB System.
- Decomposition of the INH (Instituto Nacional da Habitação - Portugal).
- Decomposition of the Ministry of Education (U. K.).
- Decomposition of the Direction of the School Buildings (Direcção Geral das Construções Escolares - Portugal).

- Decomposition of the Standard Form of Cost Analysis (UK).
- Decomposition according to the method U. N. T. E. C. (Union National des Techniciens de l'Economie de la Construction).
- Decomposition of the " Liste Systematique des Ouvrages du Batiment".
- Decomposition of the method of IEOB (Institut pour l'Economie et l'Organisation du Batiment).
- Decomposition of the method "ESTIM".
- Decomposition of a method of the "Architect's Journal".
- Decomposition according the system BSAB.

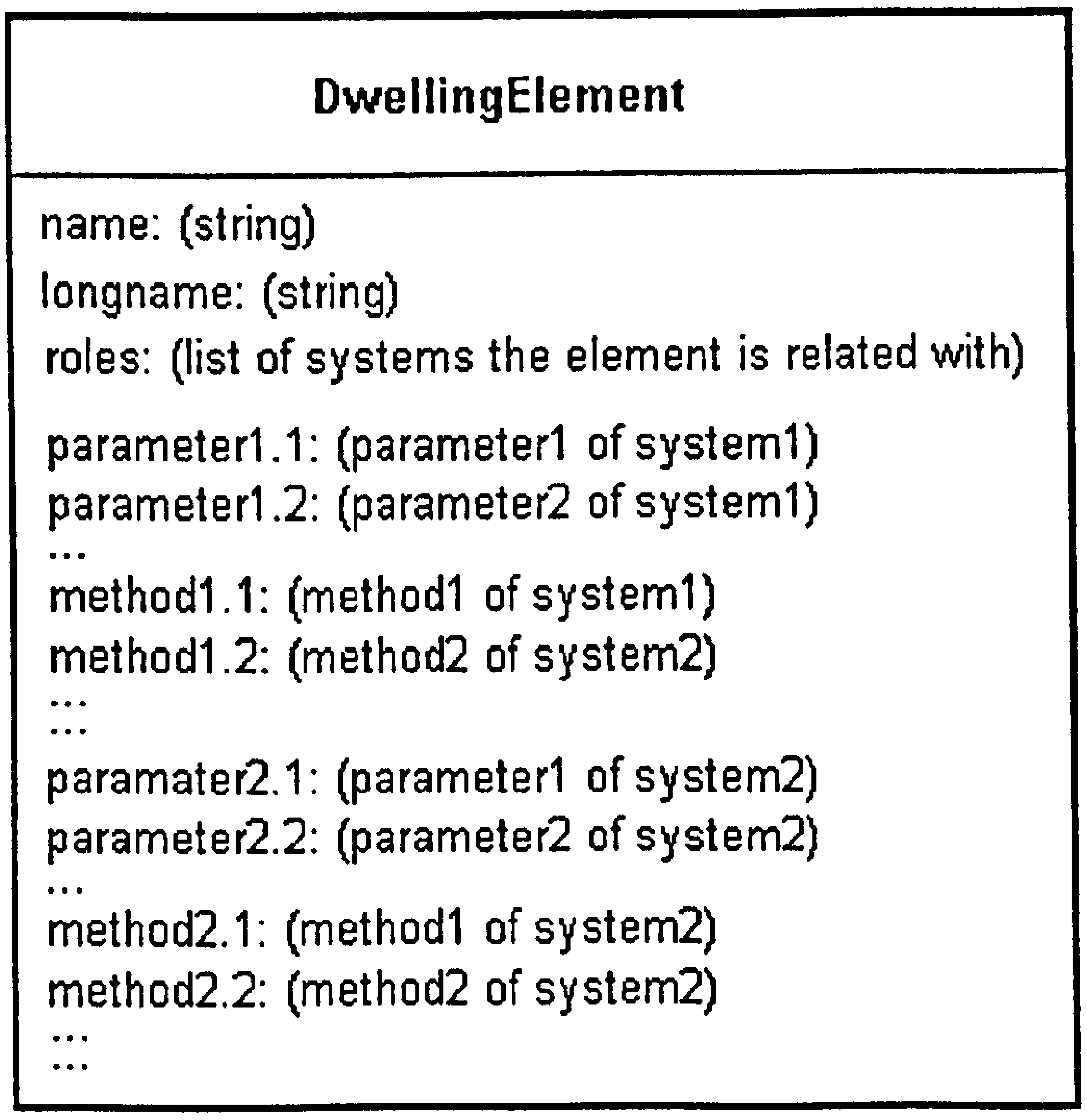


Figure 79 - Structure of a dwelling element.

A short summary of each one of these classifications is presented in the following pages (Page 116 to Page 120).

In order to compare these classifications, a set of criteria was defined. It assumes that a classification suitable for developing a decomposition hierarchy of a residential building into elements should be:

- adequate for residential buildings,
- detailed, i.e. to take into account all the components of any residential building and classify them from broad classes down to narrow ones,

- total, in the sense defined by Körner (1970), as referred to in chapter 5,
- simple, in the sense that it is easy to situate a given building element in the hierarchy.

Decomposition of a building into elements according to SfB system:

1 - Ground, substructure
1.1 - Ground
1.2 - Empty (not used)
1.3 - Floor beds
1.4 - Empty (not used)
1.5 - Empty (not used)
1.6 - Retaining walls, foundations
1.7 - Pile foundations
1.8 - Other substructure elements
1.9 - Parts, accessories, etc. special to substructure elements

2 - Structure primary elements, carcass
2.1 - Walls, external walls
2.2 - Internal walls, partitions
2.3 - Floors, galleries
2.4 - Stairs, ramps
2.5 - Empty (not used)
2.6 - Empty (not used)
2.7 - Roofs
2.8 - Building frames, other primary elements
2.9 - Parts, accessories, etc. special to primary elements, carcass

3 - Secondary elements, completion of structure
3.1 - Secondary elements to walls, external walls
3.2 - Secondary elements to internal walls, partitions
3.3 - Secondary elements to floors
3.4 - Secondary elements to stairs
3.5 - Suspended ceilings
3.6 - Empty (not used)
3.7 - Secondary elements to roofs
3.8 - Empty (not used)
3.9 - Minor parts of secondary elements

4 - Finishes to structure
4.1 - Wall finishes, external
4.2 - Wall finishes, internal
4.3 - Floor finishes
4.4 - Stair finishes
4.5 - Ceiling finishes
4.6 - Empty (not used)
4.7 - Roof finishes
4.8 - Other finishes to structure
4.9 - Parts, accessories, etc. special to finishes to structure elements

5 - Services
5.1 - Empty (not used)
5.2 - Waste disposal, drainage
5.3 - Hot and cold water supply
5.4 - Gases supply
5.5 - Refrigeration
5.6 - Space heating
5.7 - Air conditioning, ventilation
5.8 - Other piped, ducted services
5.9 - Parts, accessories, etc. special to piped, ducted services elements

6 - Services, mainly electrical
6.1 - Electrical supply
6.2 - Power
6.3 - Lighting
6.4 - Communications
6.5 - Empty (not used)
6.6 - Transport
6.7 - Empty (not used)
6.8 - Security, control, other services
6.9 - Parts, accessories, etc. special to electrical services elements

7 - Fittings
7.1 - Circulation fittings
7.2 - Rest, work fittings
7.3 - Culinary fittings
7.4 - Sanitary, hygiene fittings
7.5 - Cleaning, maintenance fittings
7.6 - Storage, screening fittings
7.7 - Special activity fittings
7.8 - Other fittings
7.9 - Parts, accessories, etc. special to fittings elements

8 - Loose furniture, equipment
8.1 - Circulation loose furniture equipment
8.2 - Rest, work loose furniture equipment
8.3 - Culinary loose furniture equipment
8.4 - Sanitary, hygiene loose furniture equipment
8.5 - Cleaning, maintenance loose furniture equipment
8.6 - Storage, screening loose furniture equipment
8.7 - Special activity loose furniture equipment
8.8 - Other loose furniture equipment
8.9 - Parts, accessories, etc. special to loose furniture equipment

Decomposition of a building into elements according to INH

1 - General characteristics of the construction
2 - Primary elements
2.1 - Infrastructures
2.2 - Superstructures
2.3 - Walls
2.4 - Floors
2.5 - Stairs
2.6 - Roofs
3 - Secondary Elements
3.1 - External framing
3.2 - Solar protections
3.3 - External doors
3.4 - Internal framing
3.5 - Internal doors
3.6 - Locksmith's work and guards
3.7 - Suspended ceilings
3.8 - Skylights and other secondary elements of the roofs
4 - Finishes
4.1 - Wall finishes, external
4.2 - Wall finishes, internal
4.3 - Floor finishes
4.4 - Stairs and ramps finishes
4.5 - Ceiling finishes
4.6 - Roof finishes
5 - Waste, sewerage, water and gas services
5.1 - Waste disposal
5.2 - Sewerage
5.3 - Hot and cold water supply
5.4 - Gas supply
5.5 - Heating, chimneys and ventilation
6 - Electrical and electromechanical services
6.1 - Electrical fittings
6.2 - Telecommunications
6.3 - Electromechanical services
7 - Equipment
7.1 - Kitchen equipment
7.2 - Sanitary equipment
7.3 - Washing up and dry equipment
7.4 - Storage equipment

Decomposition of a building into elements according to the Ministry of Education (UK)

1 - Preliminaries, assurances
2 - Foundations
3 - External walls, doors and windows
4 - Framed structure
5 - Roof, including finishes
6 - Ceiling lighting
7 - Partitions and internal doors
8 - Sanitary equipment
9 - Floor finishes
10 - Ceilings (including decorations)
11 - Furniture
12 - Water supply and sewerage
13 - Electrical fittings
14 - Heating and hot water supply
15 - Drainage
16 - External work
17 - Special decoration

Decomposition of a building into elements according to the Direction of School Buildings (Portugal)

1 - Work above the ground floor
2 - External walls
3 - Internal partitions
4 - External doors and windows
5 - Internal doors and windows
6 - Floors
7 - Vertical circulations
8 - Roof
9 - Ceiling finishes
10 - Wall finishes
11 - Floor finishes
12 - Prefabricated panels elements
13 - Sanitary equipment and installation
14 - Sewerage
15 - Electrical fittings
16 - Heating and ventilation
Furniture and equipment
17 - Fixed equipment
18 - Sports equipment
19 - Furniture, movable equipment and curtains
20 - School equipment
External work
21 - General leveling of the ground
22 - Paved areas
23 - Plantation
24 - Fences
25 - Services
26 - Diverse

Decomposition of a building into elements according to the "Standard Form of Cost Analysis" (UK)

1 - Substructure

2 - Superstructure
2.1 - Framed Structure
2.2 - Floors
2.3 - Roof
2.4 - Stairs
2.5 - External walls
2.6 - External windows and doors
2.7 - Internal walls and partitions
2.8 - Internal doors

3 - Internal finishes
3.1 - Walls finishes
3.2 - Floor finishes
3.3 - Ceiling finishes

4 - Furniture and equipment

5 - Services and equipment
5.1 - Sanitary equipment
5.2 - Domestic and functional equipment
5.3 - Sewerage
5.4 - Water supply
5.5 - Heating source
5.6 - Heating and air conditioning
5.7 - Ventilation system
5.8 - Electrical fittings
5.9 - Gas supply
5.10 - Lifts
5.11 - Protection services
5.12 - Communication services
5.13 - Special services
5.14 - Construction work related with the services
5.15 - Indirect costs related with the services

6 - External work
6.1 - Site work
6.2 - Drainage
6.3 - External work of the services (water , fire, heating, gas electricity, etc.)
6.4 - Diverse

Decomposition of a building into elements according to the method UNTEC

A - Construction itself
A.1 - Substructure
A.1.1 - Escavation and transport
A.1.2 - Normal foundations
A.1.3 - Transition volumes
A.2 - Superstructure
A.2.1 - Load bearing system
A.2.2 - Roof
A.2.3 - External walls
A.2.4 - Stairs
A.3 - Equipment
A.3.1 - Structural equipment
A.3.2 - Organic equipment
A.3.3 - Finishes equipment

B - Connection work
B.1 - Preparation of the ground
B.2 - Special foundations
B.3 - Organic nets
B.3.1 - Input nets
B.3.2 - Output nets
B.4 - External work

C - Special equipment

Decomposition of a building into elements according to the "Liste Systématique des Ouvrages du Bâtiment"

1 - Ground
2 - Foundations
3 - Walls
4 - Horizontal work
5 - Communications
6 - Roof
7 - Organic equipment
8 - Specialized equipment
9 - Finishes

Decomposition of a building into elements according to the method of IEOB

1 - Foundations
2 - Structure of the ground floor slab
3 - Framed structure
4 - Roof slab
5 - Other slabs
6 - Suspended ceilings
7 - External walls
8 - Non load bearing partition walls
9 - Stairs
10 - Water blocks
11 - Water pipes and ducts
12 - Heating
13 - Ventilation
14 - Gas supply
15 - Electrical fitting - high voltage
16 - Electrical fitting - low voltage
17 - Sports equipment
18 - Doors and storage panels
19 - Equipment of the building
20 - Cost of the construction equipment

Decomposition of a building into elements according to the method “ESTIM”

1 - Infrastructure
1.1 - Preparatory work
1.2 - Foundations
1.3 - Ground floor slab
1.4 - Horizontal structure
1.5 - Retaining walls
1.6 - Inferior vertical structure
1.7 - Watertightness
1.8 - Pipes

2 - Superstructure
2.1 - Horizontal structure of the ground floor
2.2 - Horizontal structure
2.3 - Vertical structure of the ground floor
2.4 - Vertical structure
2.5 - Carpentry
2.6 - Roof
2.7 - Watertightness
2.8 - Flat roofs

3 - Facades
4 - Finishes
5 - Water supply and sewerage
6 - Thermal supply
7 - Electromechanical supply
8 - Diverse work - special equipment
9 - External work
9.1 - Filling in and leveling the ground
9.2 - Streets and parks
9.3 - Diverse nets
9.4 - Sewerage
9.5 - Fences
9.6 - Green areas
9.7 - Diverse

Decomposition of a building into elements according to the “Architect’s Journal””

1 - Substructure
2 - Structures
3 - Floors
4 - Roofs
5 - Skylights
6 - Stairs
7 - External envelope
8 - Windows
9 - External doors
10 - Walls and partitions
11 - Internal doors
12 - Metal work
13 - Wall finishes
14 - Floor finishes
15 - Ceiling finishes
16 - Movable equipment
17 - Fixed equipment
18 - Hot water supply
19 - Heating
20 - Gas supply
21 - Electrical fittings
22 - Drainage
23 - External work

Decomposition of a building into elements according to the BSAB system

1 - Ground
2 - Empty (not used)
3 - Building
3.1 - Load bearing structure
3.2 - Non load bearing structure
3.3 - Openings
3.4 - External walls finishes
3.5 - Floor finishes
3.6 - Internal walls finishes
3.7 - Ceiling finishes
3.8 - Secondary elements
3.9 - Other elements
4 - Empty (not used)
5 - Services (water, sewerage, gas, refrigeration, air conditioning, control systems, etc.)
6 - Electrical fittings
7- Transport equipment(lifts, transport of goods, people, waste, etc.)
8- Empty (not used)
9- Other elements

A comparative table of the classification schemes is shown in Figure 80, using three ratings 1 (poor), 2 (medium) and 3 (good). The classifications that achieved the best ratings (SfB and INH) were used as a basis to develop the **BuildingElement** hierarchy. Two classes that are not part of any of the referred classifications have been included, **SpatialElement** and **EnvironmentElement**. This is because the model adopted for a dwelling includes as components spatial elements and environment elements.

	adequation res. buil.	level of detail	totality	simplicity	rating
SfB (UK)	3	3	3	3	12
INH (Portugal)	3	3	3	3	12
Ministry of Education (UK)	1	1	3	3	8
School buildings (Portugal)	1	1	3	3	8
SFCA (UK)	3	2	3	3	11
UNTEC (France)	3	1	3	3	10
LSOB (France)	3	1	3	3	10
IEOB (France)	3	1	3	3	10
ESTIM (France)	3	2	3	3	11
Architects Journal (UK)	3	1	3	3	10
BSAB (UK)	3	1	3	3	10

Figure 80 - Comparative table of building elements classifications (as judged by the author).

The following subclasses of **BuildingElement** have been defined (see Figure 81), and are later further developed:

- FoundationElement - Figure 82.

- PrimaryElement - Figures 83 to 86.
- SecondaryElement - Figure 87.
- FinishElement - Figure 88.
- ServiceElement - Figures 89 to 91.
- FittingElement - Figure 92.
- SpatialElement - Figure 93.
- EnvironmentElement - Figure 94.

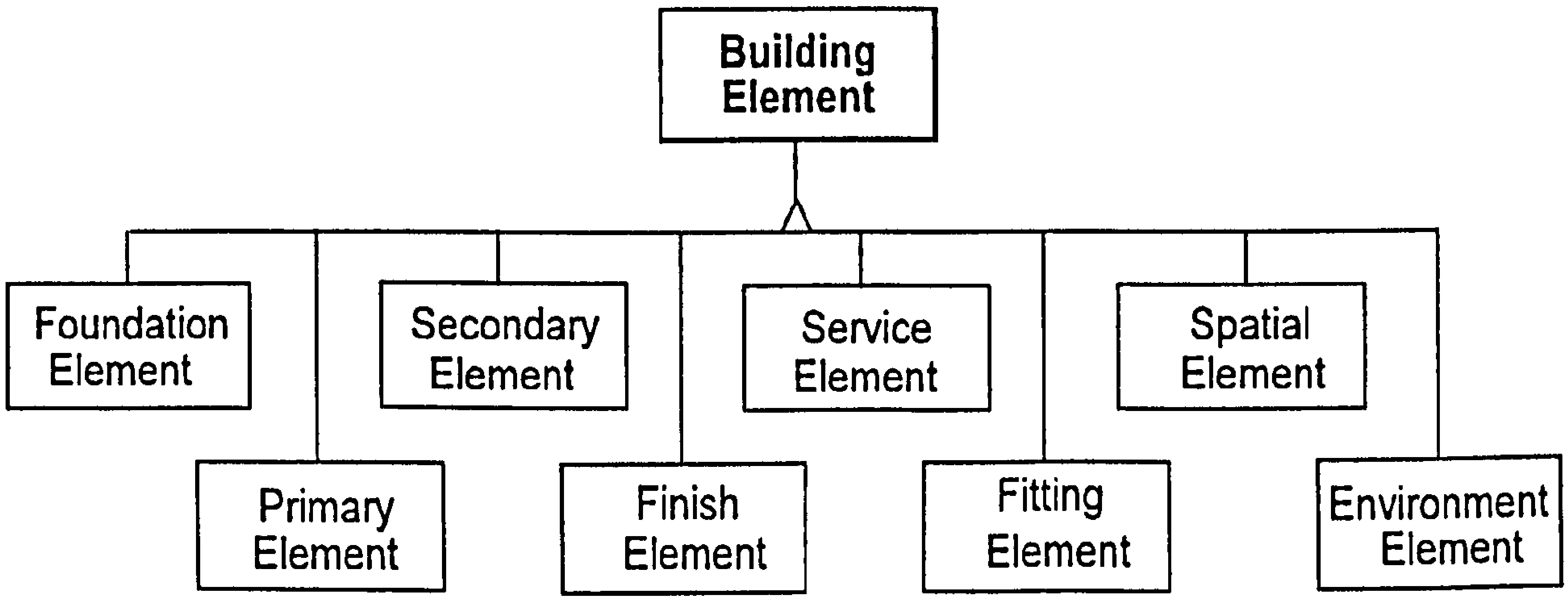


Figure 81 - Building component hierarchy.

In Figure 82 the building components belonging to the foundation are divided in five subclasses:

- **Ground** - ground for construction. This is considered as a component of the building, because it is relevant to the analysis of the foundation.
- **Floor bed** - floor in direct contact with the ground.
- **Retaining wall** - wall below the lowest floor level, in direct contact with the ground.
- **Normal foundation** - foundation elements commonly used in hard ground.
- **Specialist foundation** - foundation elements used when the ground has special characteristics, as being too soft, humid, etc..

Figures 83 to 86 show the hierarchies for the building elements which belong to the carcass, primary elements (e.g. floors, roofs, walls, columns, beams).

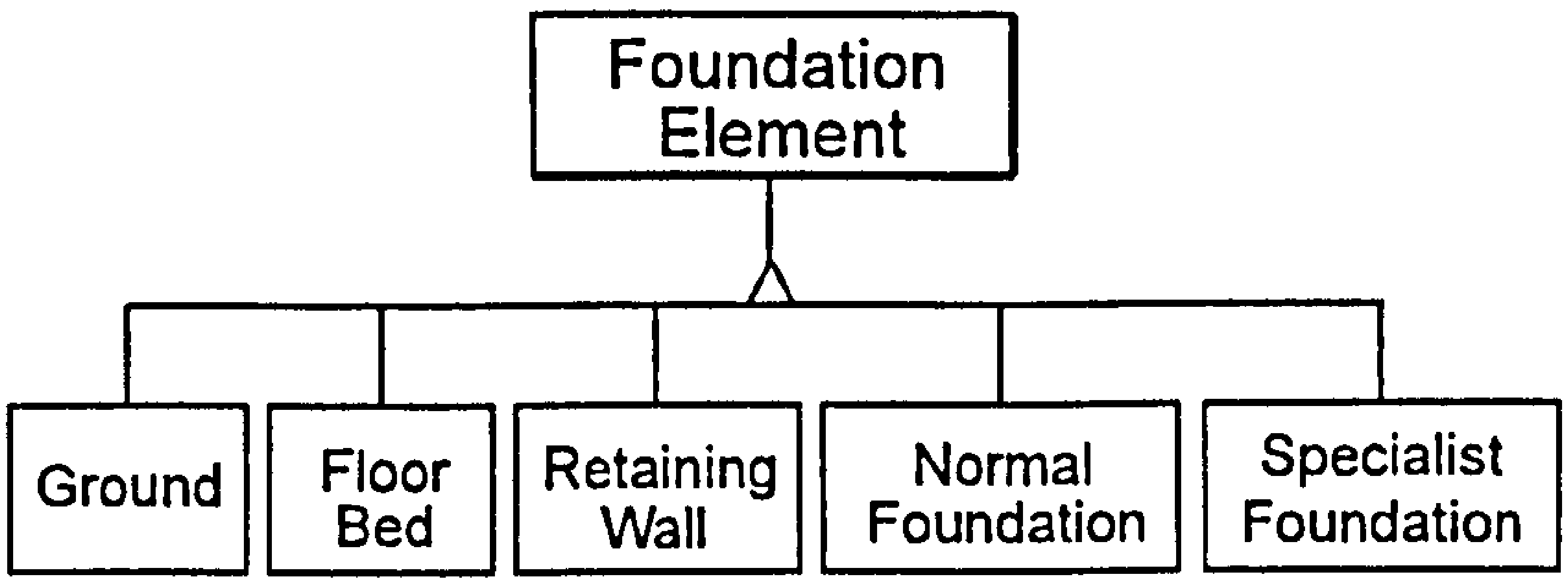


Figure 82 - Foundation element hierarchy.

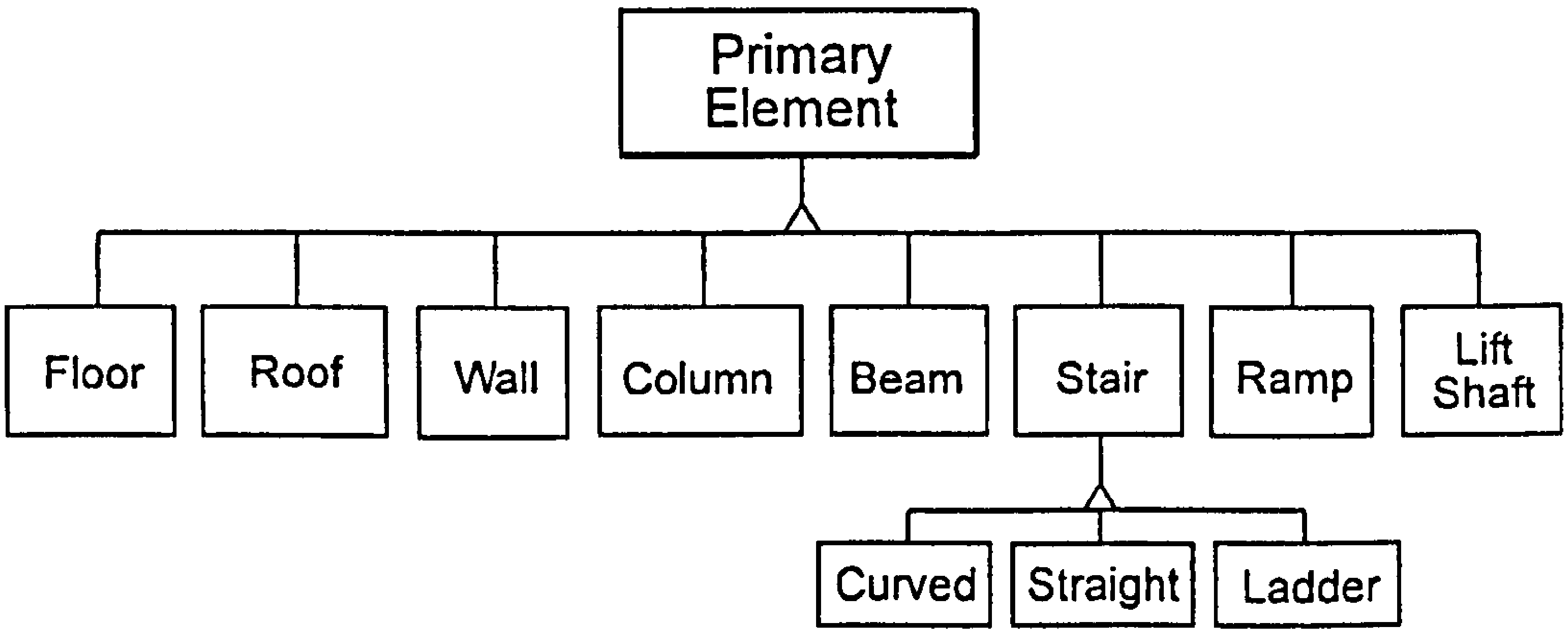


Figure 83 - Primary element hierarchy.

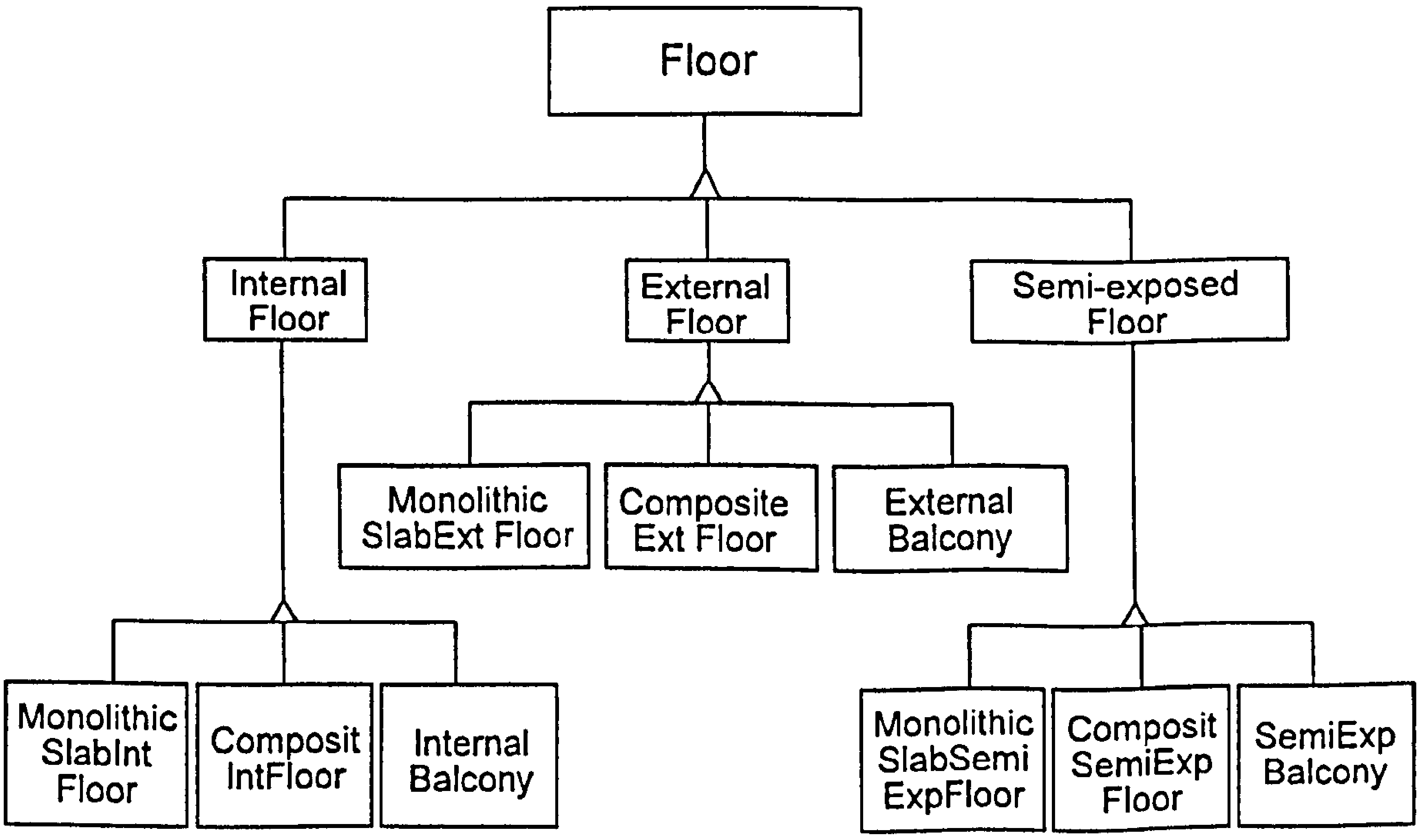


Figure 84 - Floor hierarchy.

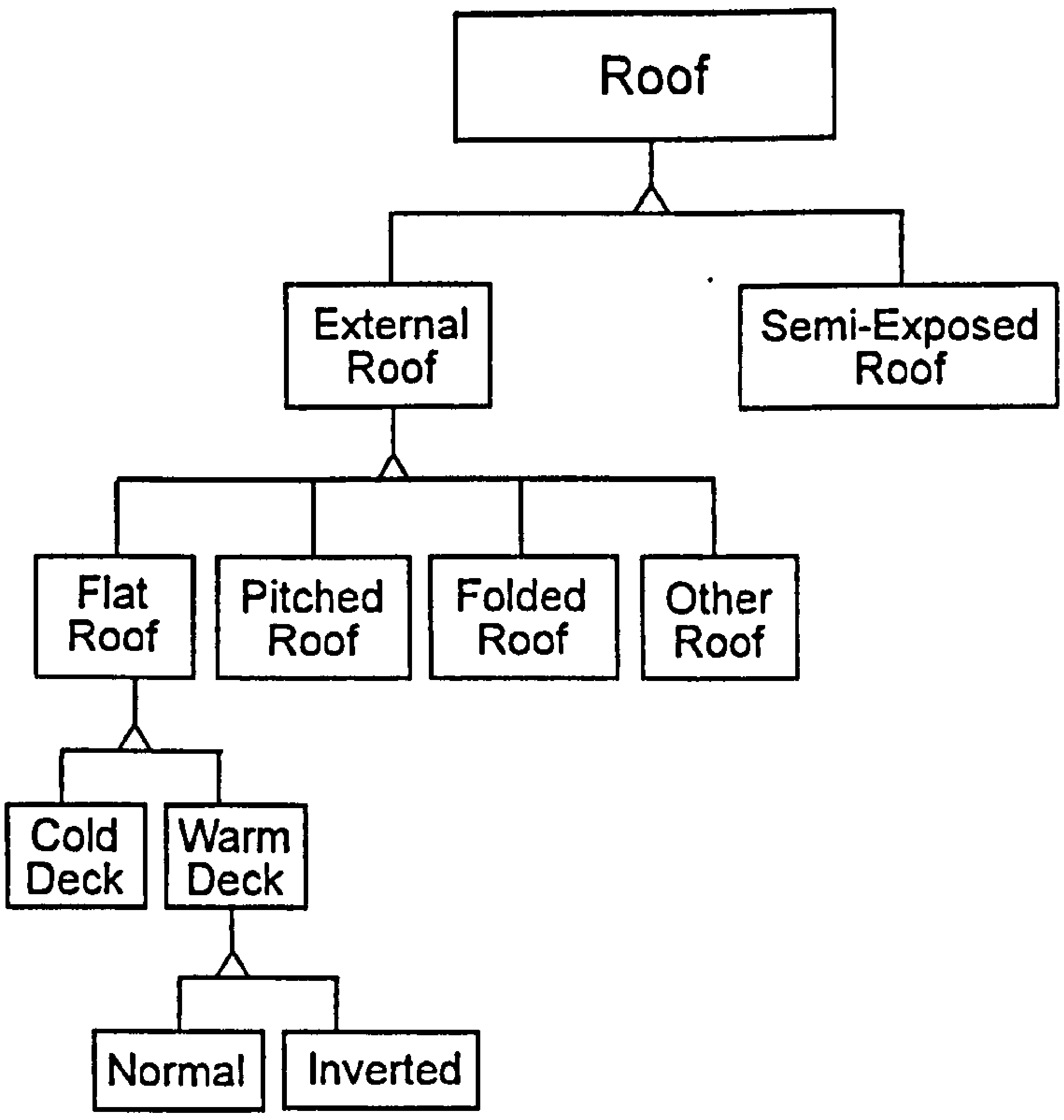


Figure 85 - Roof hierarchy.

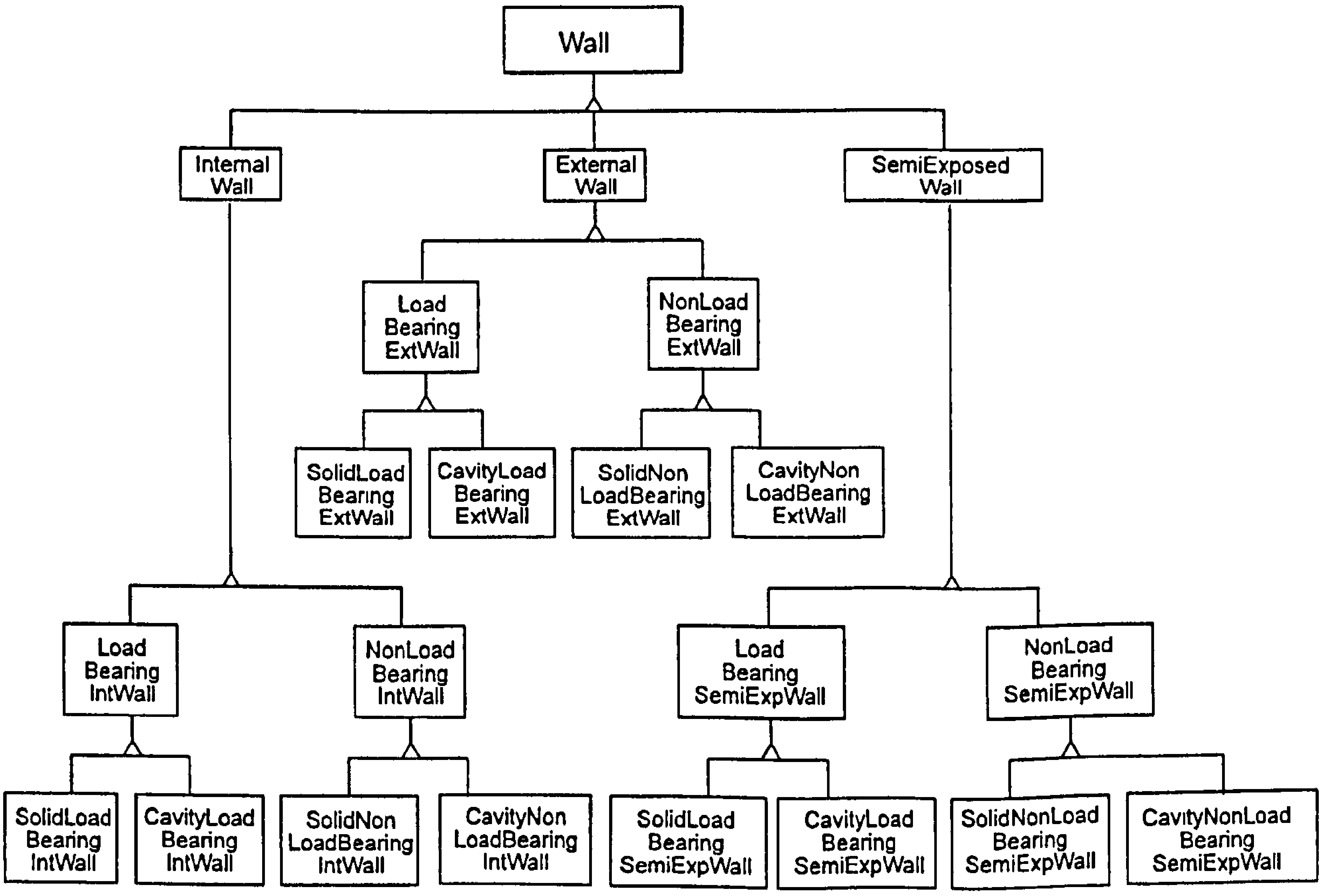


Figure 86 - Wall hierarchy.

Figure 87 shows the secondary elements hierarchy, which are usually building components that fill the openings of the carcass (e.g. doors, glazed).

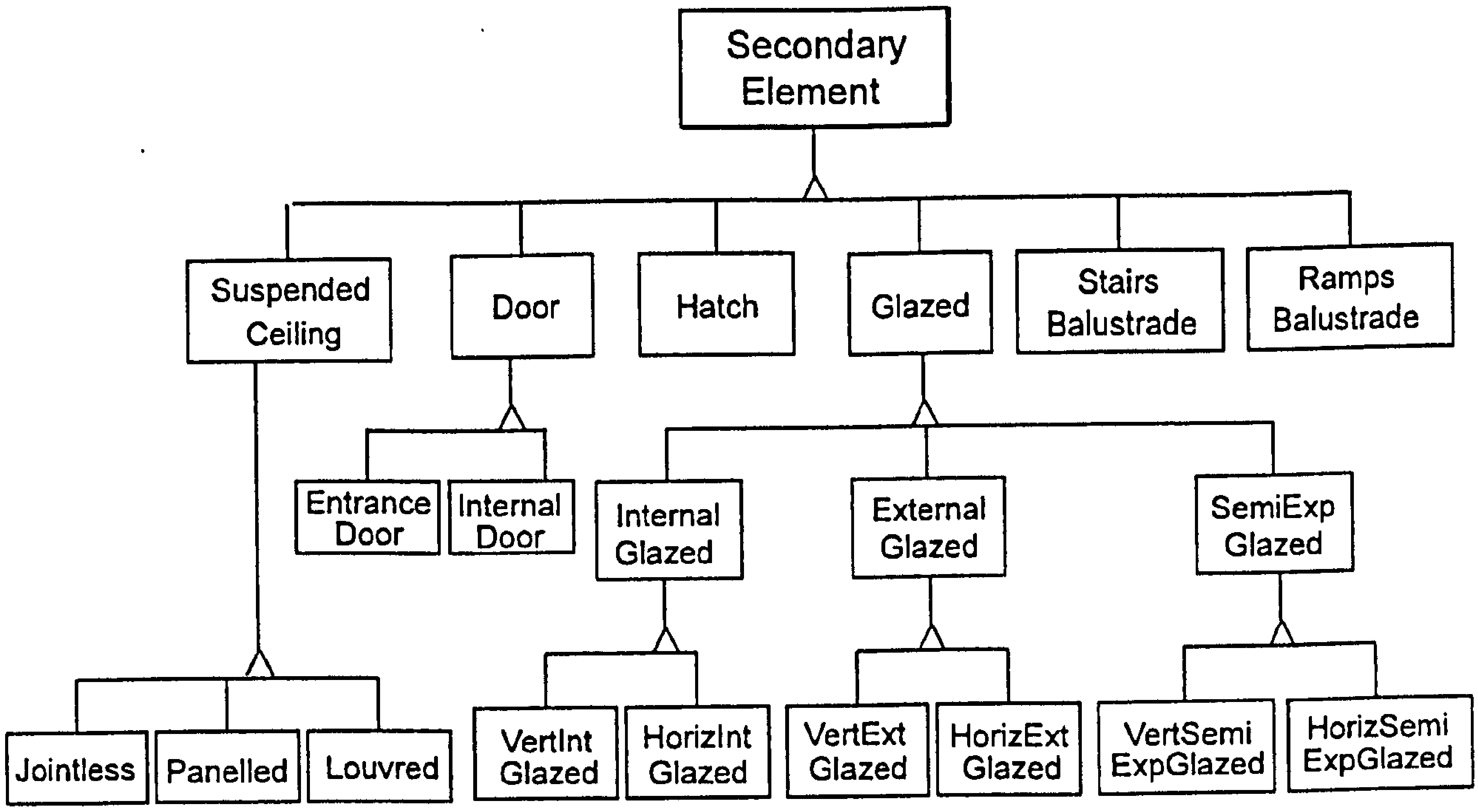


Figure 87 - Secondary element hierarchy.

Figure 88 shows the finish hierarchy. Finishes represent the elements which are applied to the surface of the structure, including preparatory work, sublayers and support.

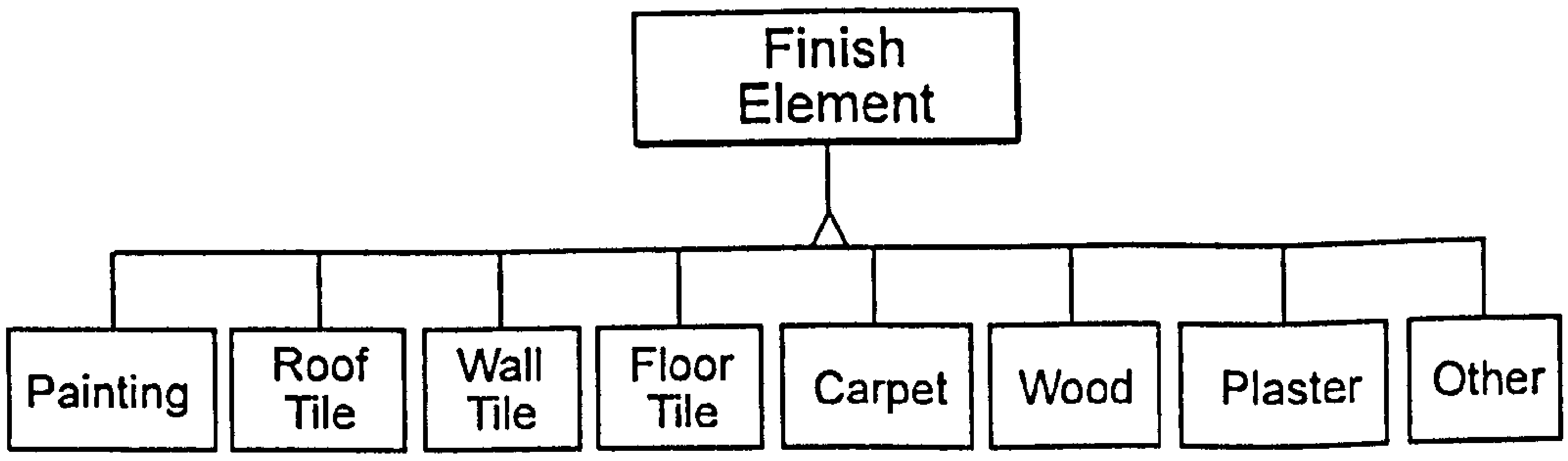


Figure 88 - Finish element hierarchy.

In Figures 89 to 91 the service hierarchies are shown. Services represent the building elements related with the energy system (inputs and outputs of the dwelling). Examples of inputs are: water supply, gas and electrical; examples of outputs are: ventilation, air conditioning, central heating, waste disposal, sewerage and rainwater.

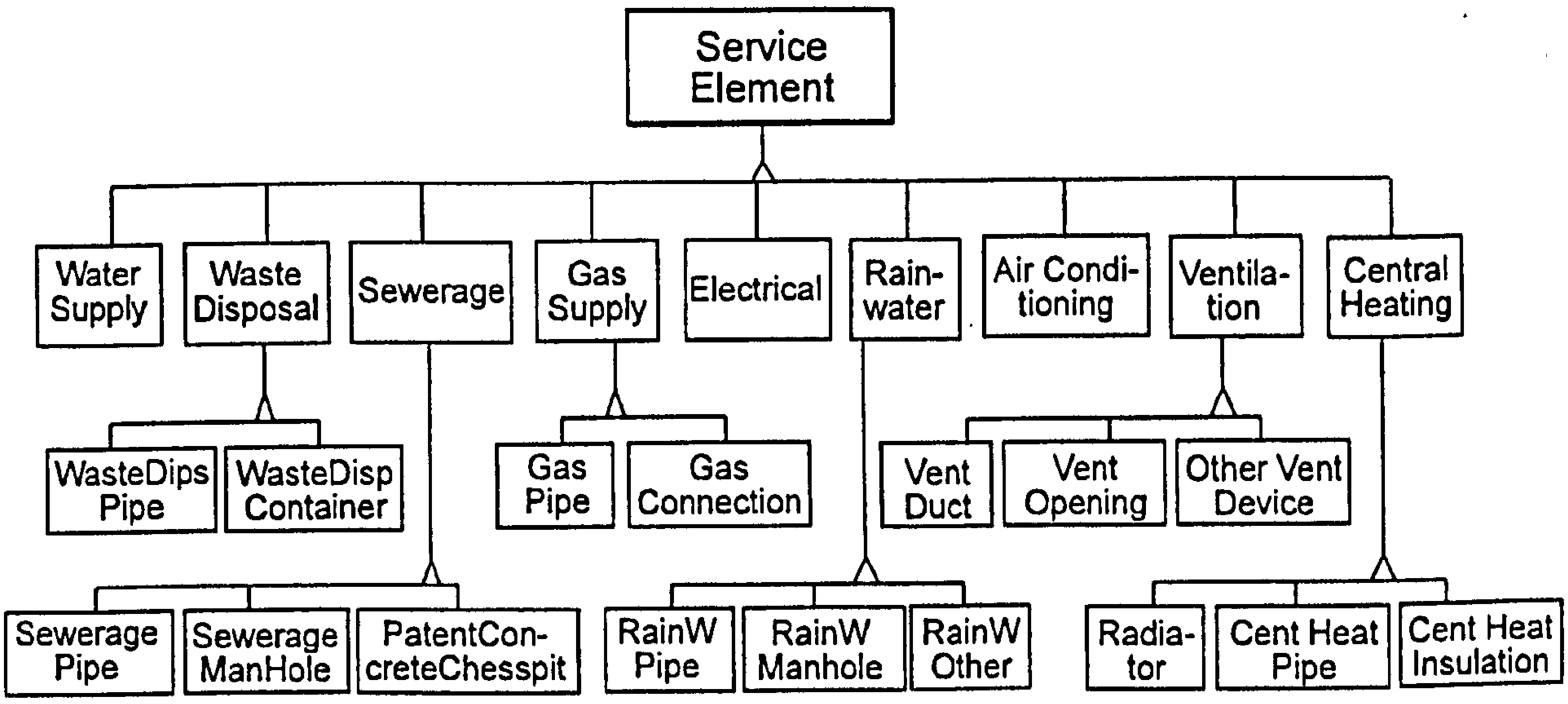


Figure 89 - Service element hierarchy.

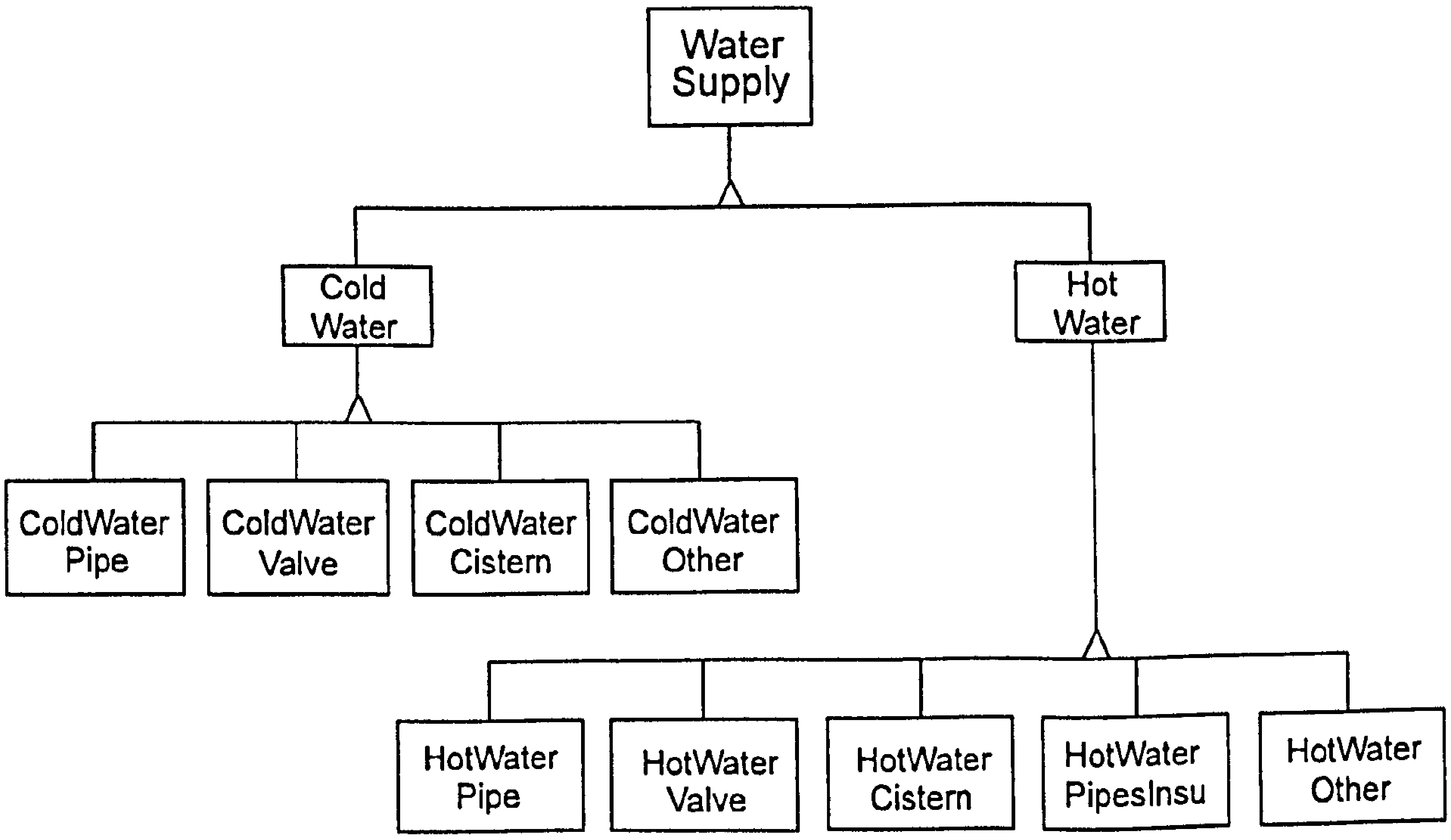


Figure 90 - Water supply hierarchy.

The fitting elements are classified in Figure 92. They include sanitary, storage, kitchen and circulation fittings.

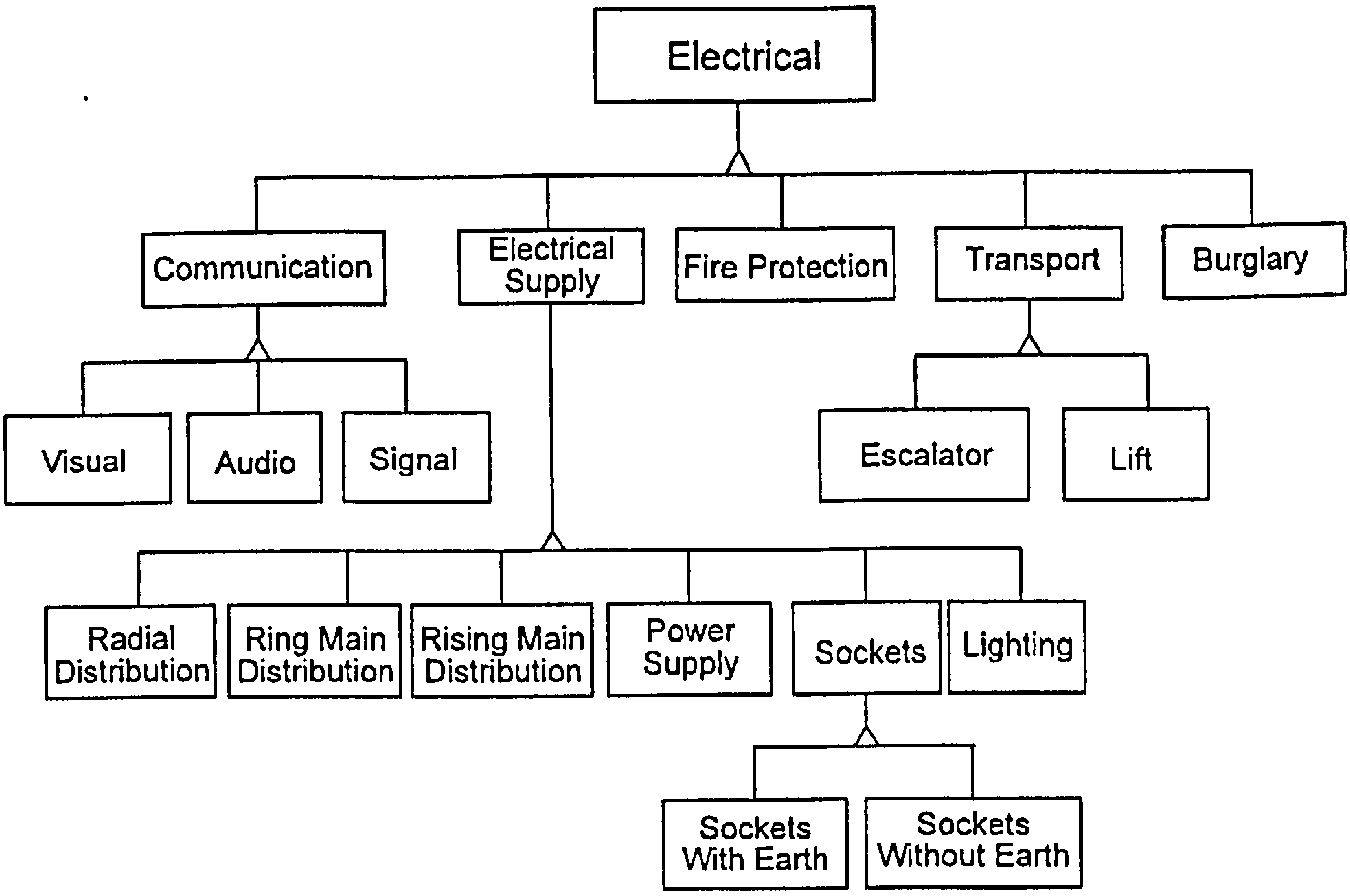


Figure 91 - Electrical hierarchy.

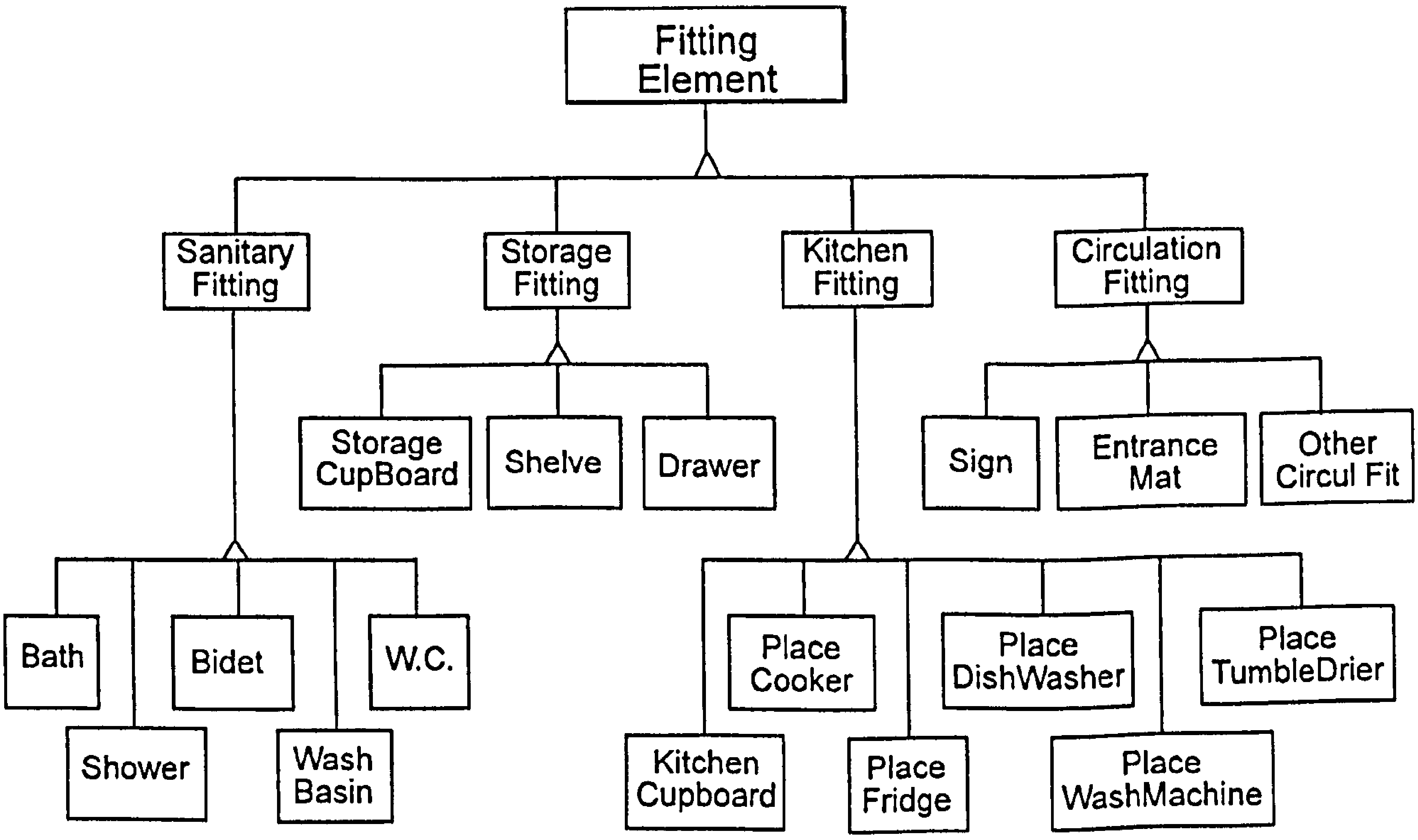


Figure 92 - Fitting element hierarchy.

The spatial element hierarchy is presented in Figure 93. In this hierarchy the internal spaces of a dwelling as well as some external spaces which are private to the dwelling are classified.

Figure 94 shows the environment element hierarchy, which has as main branches close and wide environment elements. The close environment elements include spaces and services that are common to more than one dwelling and are situated in the close surroundings of the dwelling. The hierarchy could be further developed, but there are to many elements to list them comprehensively. Examples are the "village centre", which should include food shops, newsagent, post office, pharmacy, etc., and the "regional centre", which comprehends a hospital, a wide variety of stores, cinemas, theatres, etc..

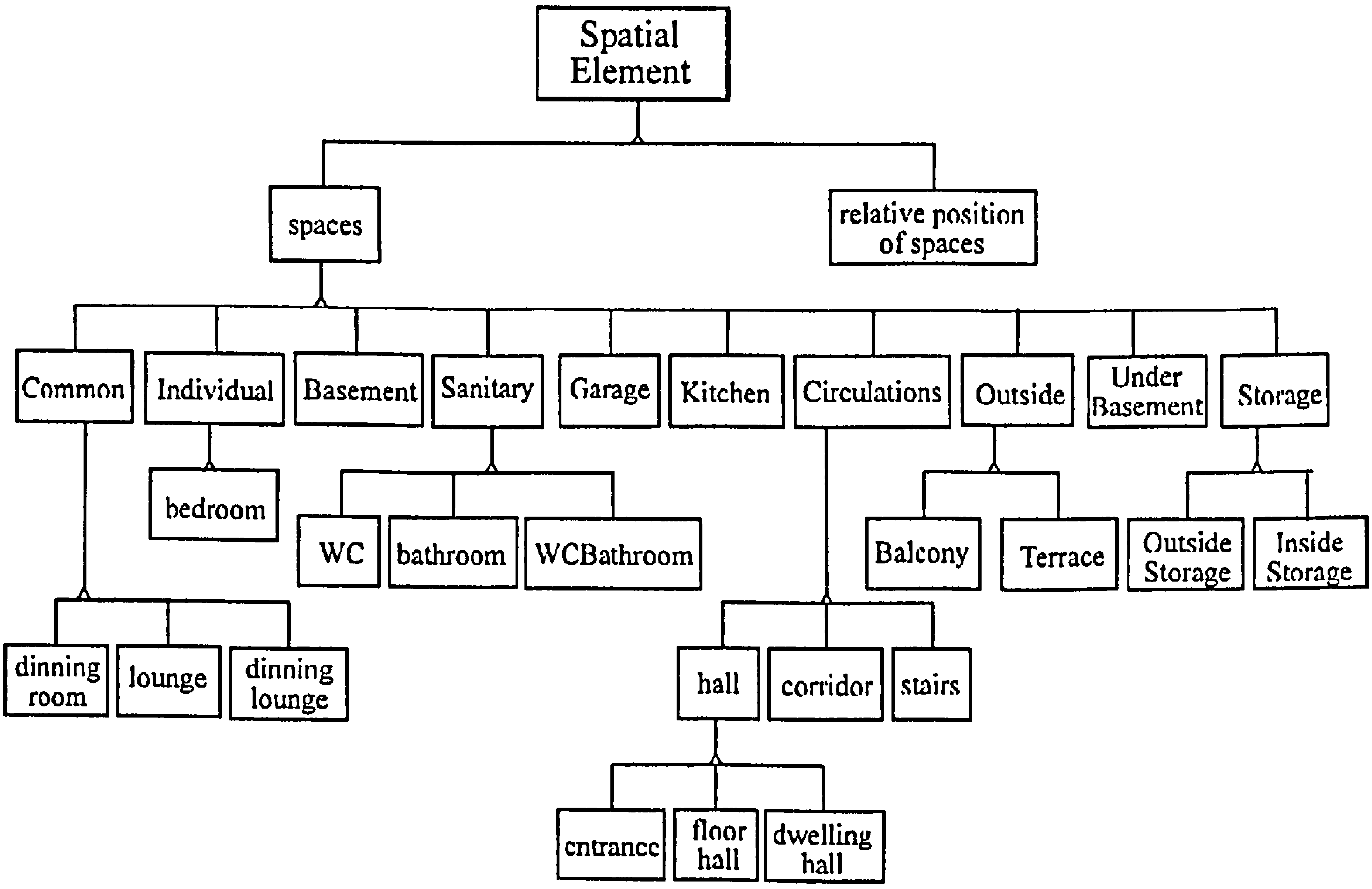


Figure 93 - Spatial element hierarchy.

In order to relate a dwelling and its components an association has been defined between the classes **Dwelling** and **DwellingElement**, as shown in Figure 95.

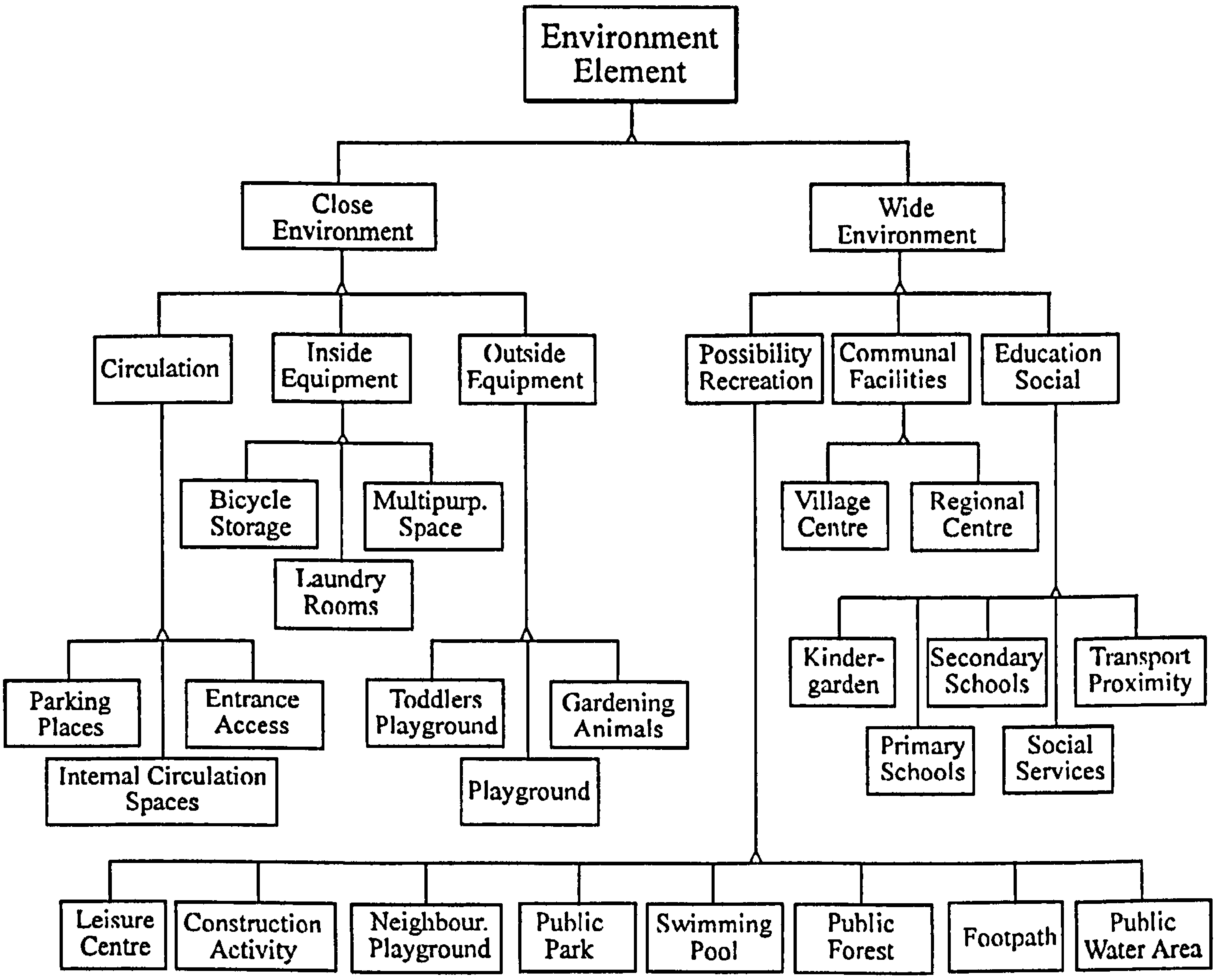


Figure 94 - Environment element hierarchy.

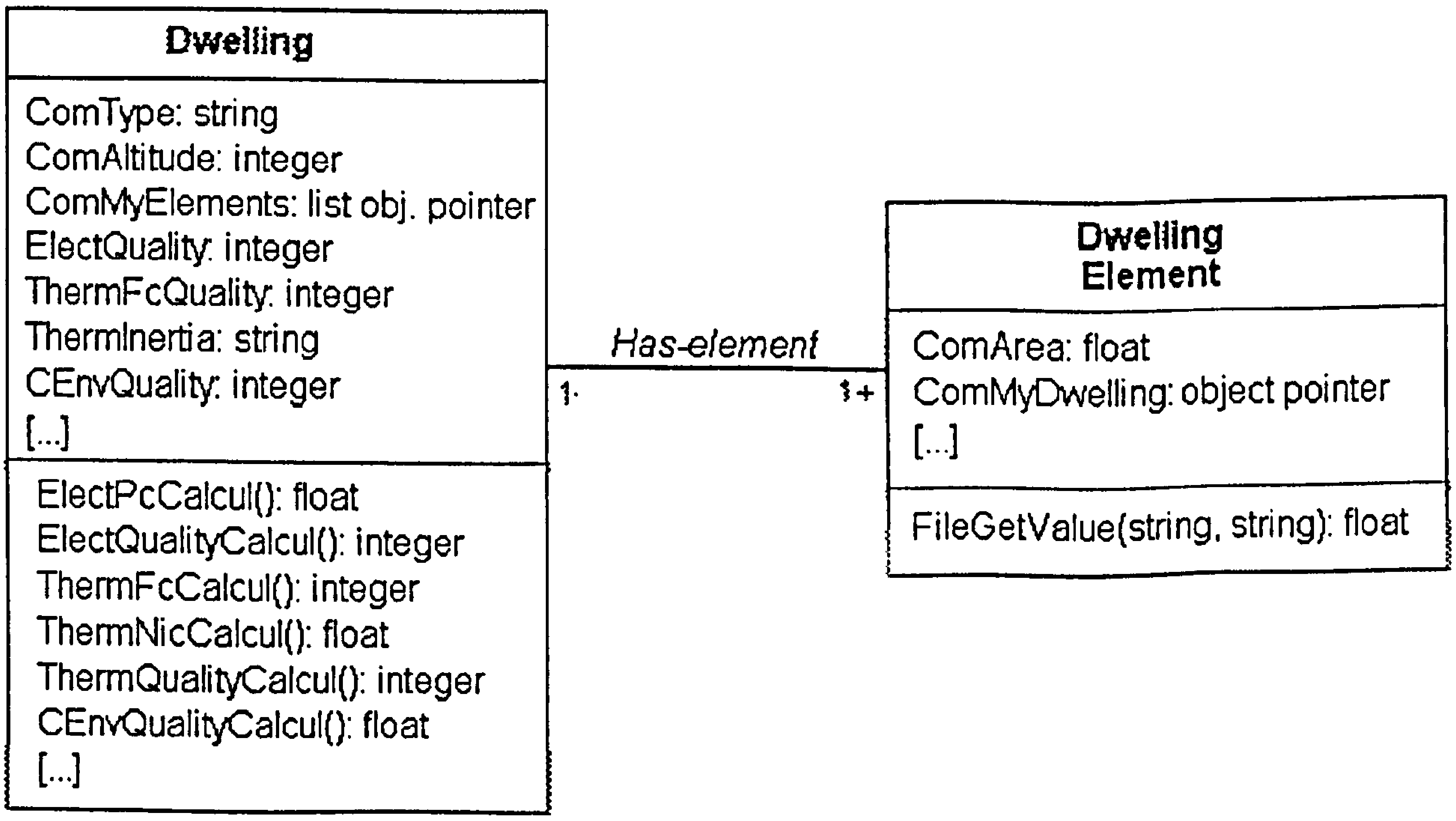


Figure 95 - Association between classes **Dwelling** and **DwellingElement**.

In the following section the implementation of the QDF prototype will be described.

6.4 Program Implementation

The components of the dwelling are modelled using objects. All the information about the systems of a dwelling is modelled using a set of attributes and a set of procedures (methods), stored inside the objects involved in the functions performed by those systems. Each attribute describes a state of nature of the component at a given time *t* (attributes may change through time). As mentioned in Chapter 5, in the present formulation of QDF *t* is constant. Each procedure models the behaviour of the component.

In order to build the QDF prototype a set of classes (with their attributes and methods) has been created in KAPPA. All KAPPA objects are subclasses or instances of a **Root** system defined class, what implies that all the hierarchies derive from **Root**. The relevant branches of the **Root** hierarchy are shown in Figure 96.

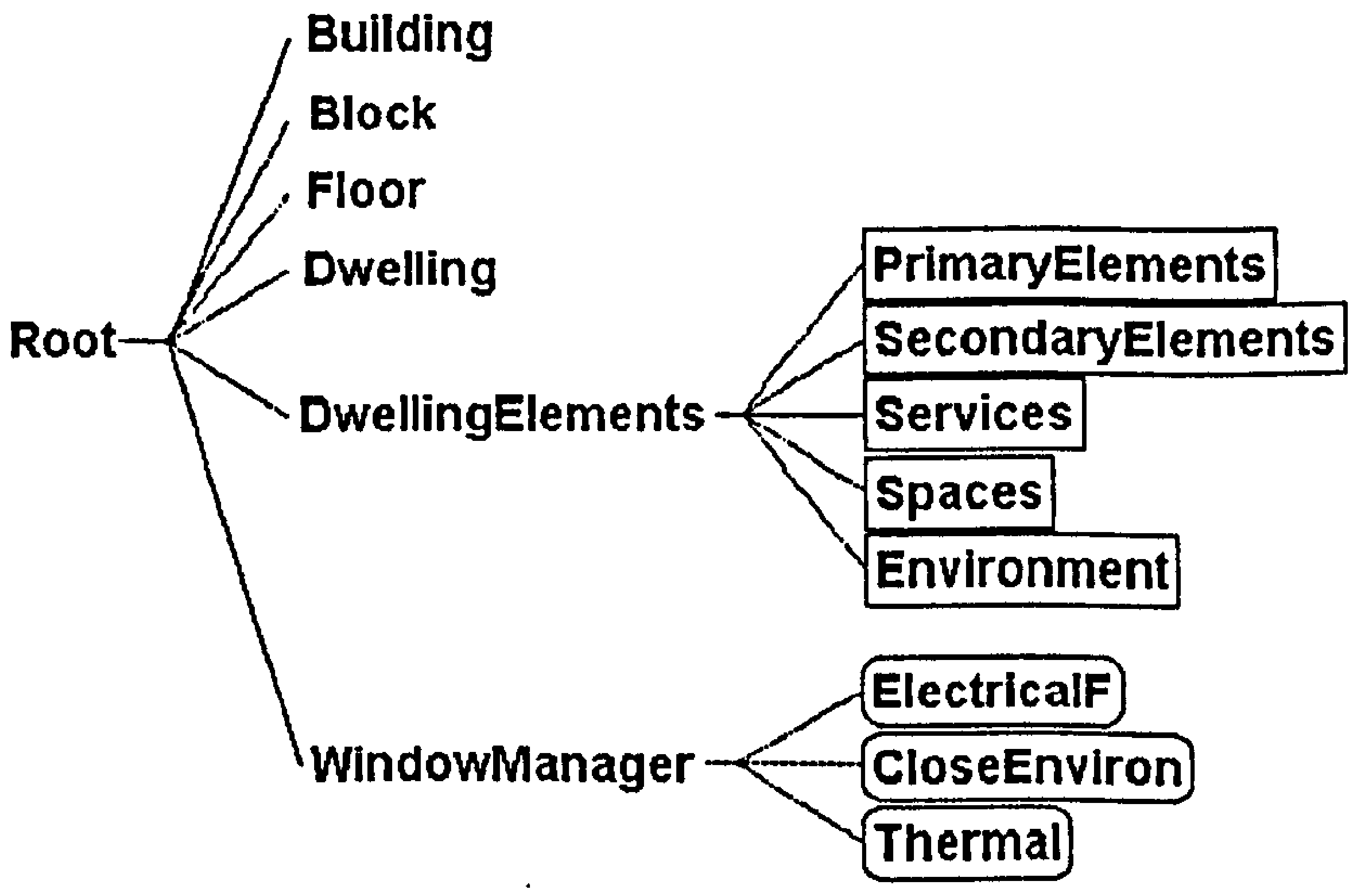


Figure 96 - Root hierarchy.

The first three subclasses of Figure 96 (**Building, Block** and **Floor**) are only used in the case of a flat to represent the building, block and floor to which it belongs. **Dwelling** is used to generate dwelling instances, while **DwellingElement** contains the various components of a dwelling. **WindowManager** is an implementation auxiliary class, used for the management of the program user interface.

The parts of the dwelling element hierarchy developed in section 6.3 which are relevant for the QDF prototype (thermal, electrical fittings and close environment) are presented in Figures 97 to 101. These figures are a reproduction of parts of KAPPA's object browser hierarchy, after some manual arrangements (e.g. completion of truncated names).

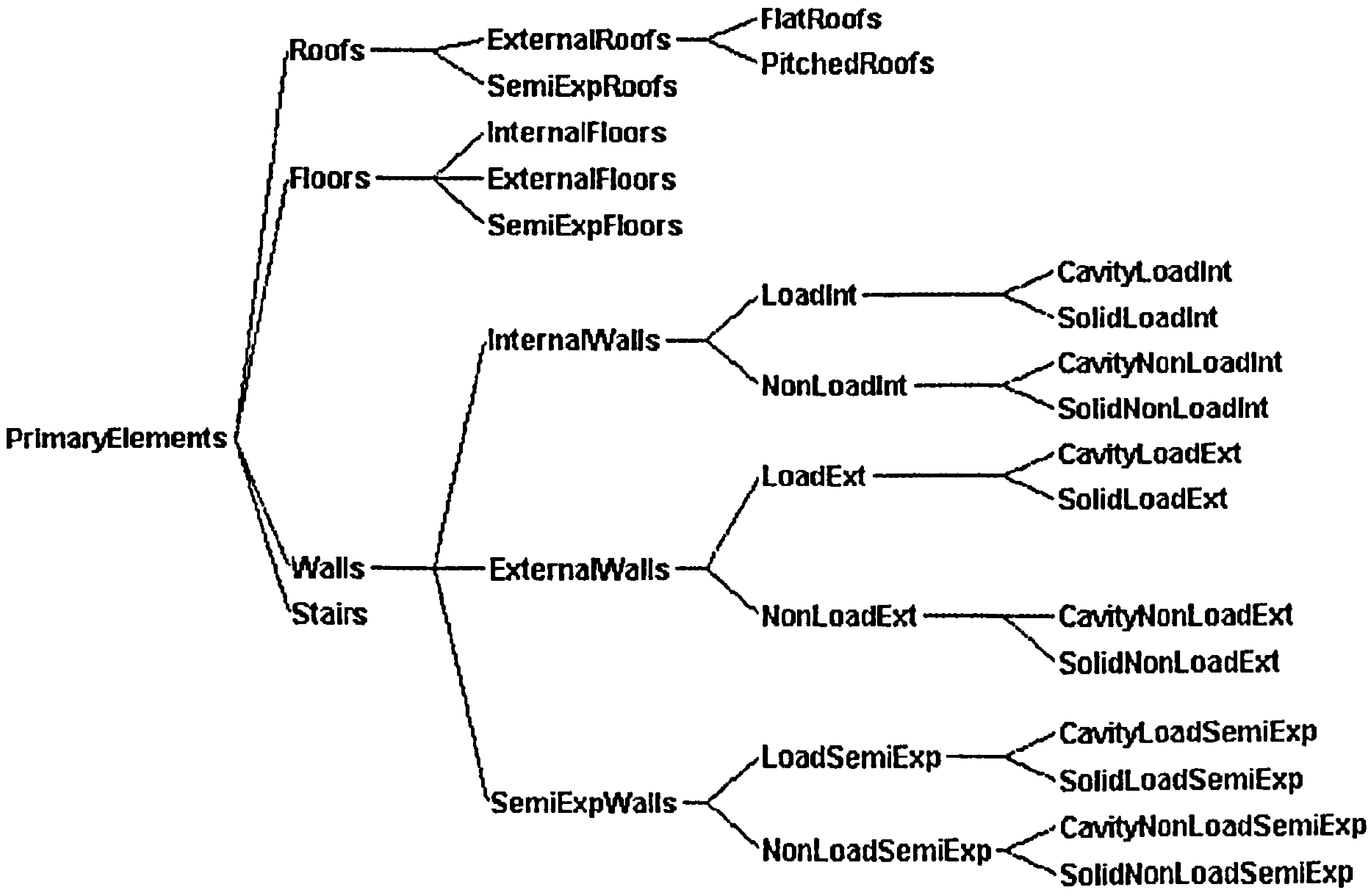


Figure 97 - DwellingElement hierarchy (Primary Elements).

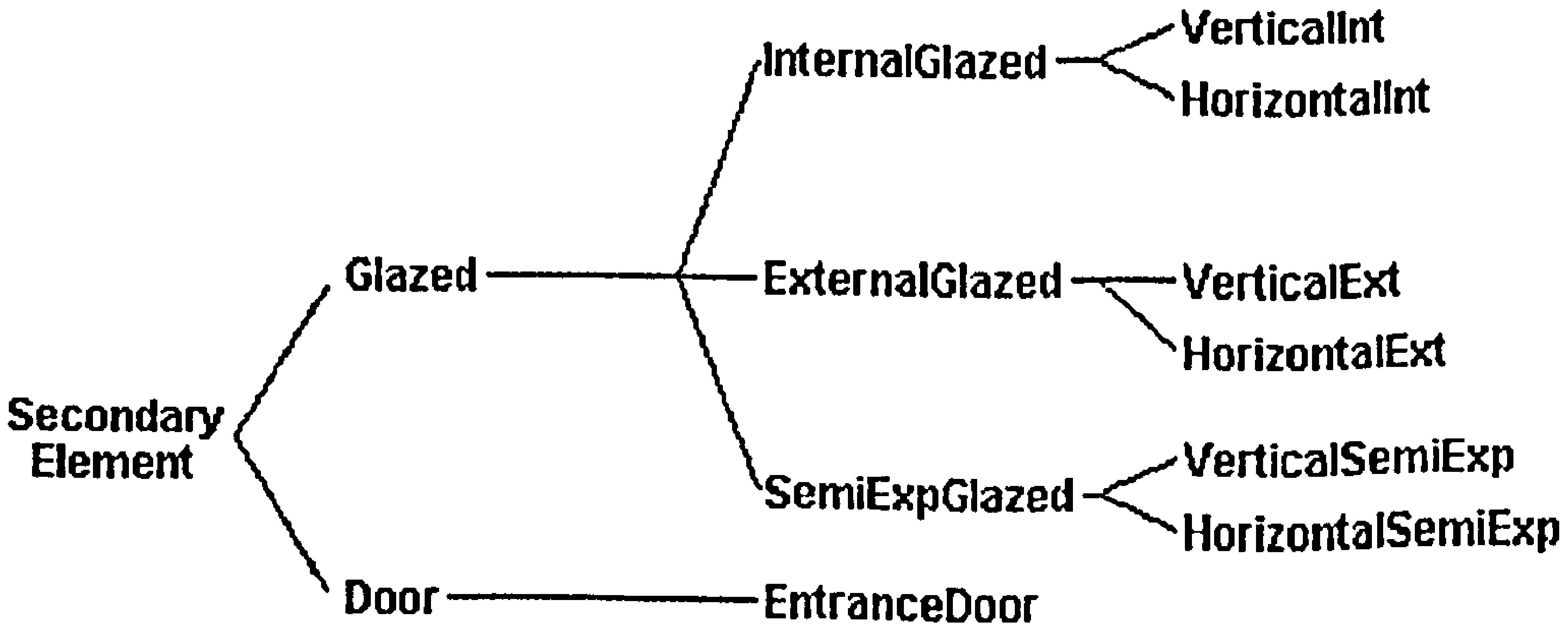


Figure 98 - DwellingElement hierarchy (Secondary Elements).

The hierarchies of Figure 97 (**PrimaryElements**) and Figure 98 (**SecondaryElements**) are essentially used for the evaluation of the thermal system. The hierarchies in Figures 99 and 100 (**Services and Spaces**) are used for the evaluation of the electrical fittings. The hierarchies of Figures 100 and 101 (**Spaces and Environment**) are used for the evaluation of the close environment.

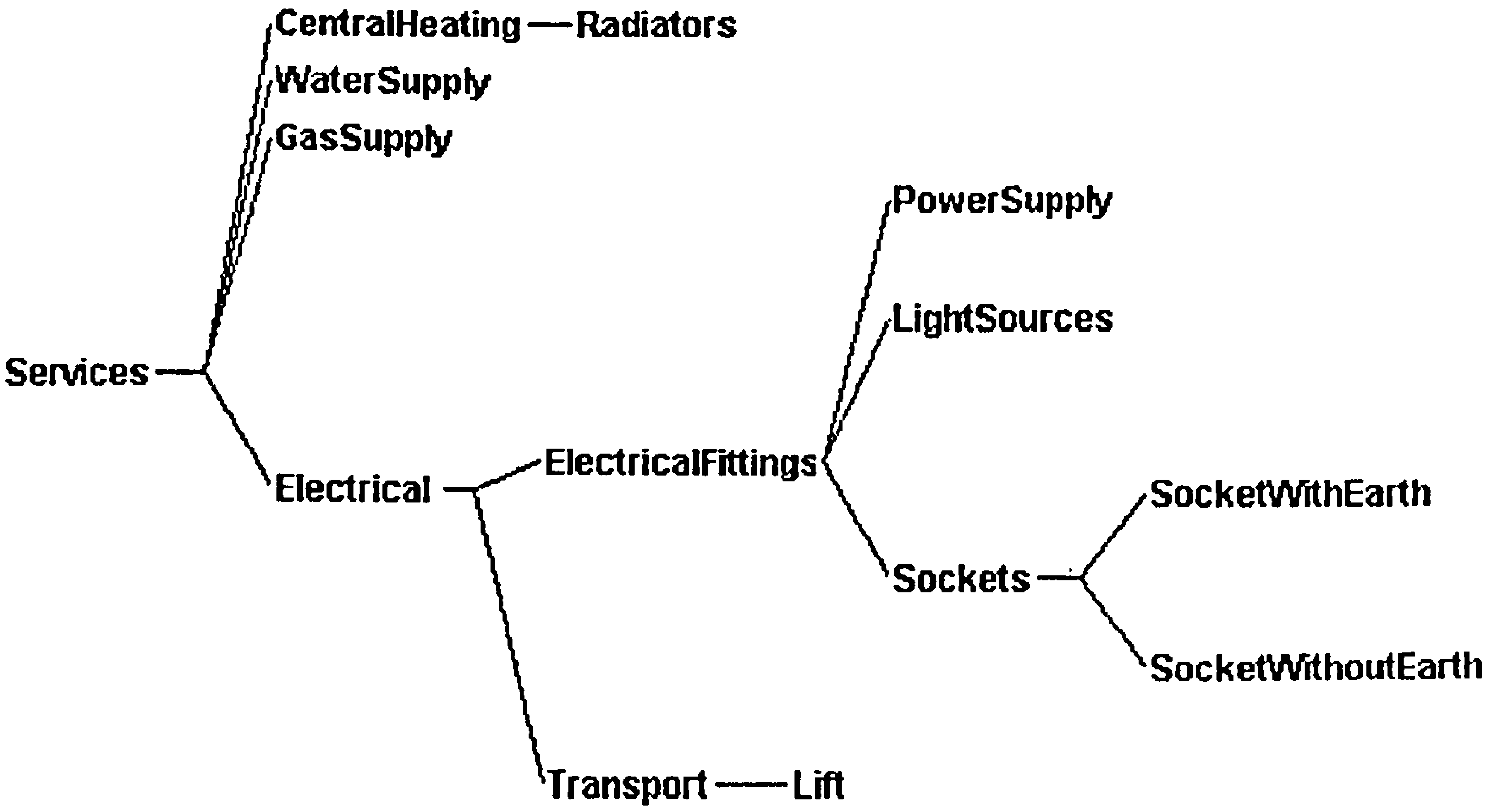


Figure 99 - DwellingElement hierarchy (Services).

An important aspect is how to group the information related to each system. The adopted solution was to put the same prefix in all the attributes and methods of a building element related with a system. The prefix **Therm** has been used for the thermal system, **Elect** for the electrical fittings and **CEnv** for the close environment. The attributes and methods which are involved in more than one function have been considered common and have been given the prefix **Com**.

The classes **Dwelling** and **DwellingElement** capture most of the information required for quality evaluation. In the human body analogy drawn in Chapter 5, Dwelling is equivalent to human body, while DwellingElement is equivalent to the human body components (organs, bones, veins, etc.).

The **Dwelling** hierarchy has as instances the different dwellings to be evaluated. Class **Dwelling** has attributes and methods that are related to the systems of the dwelling. It also contains data which is related to the dwelling as a whole (e.g. orientation and location).

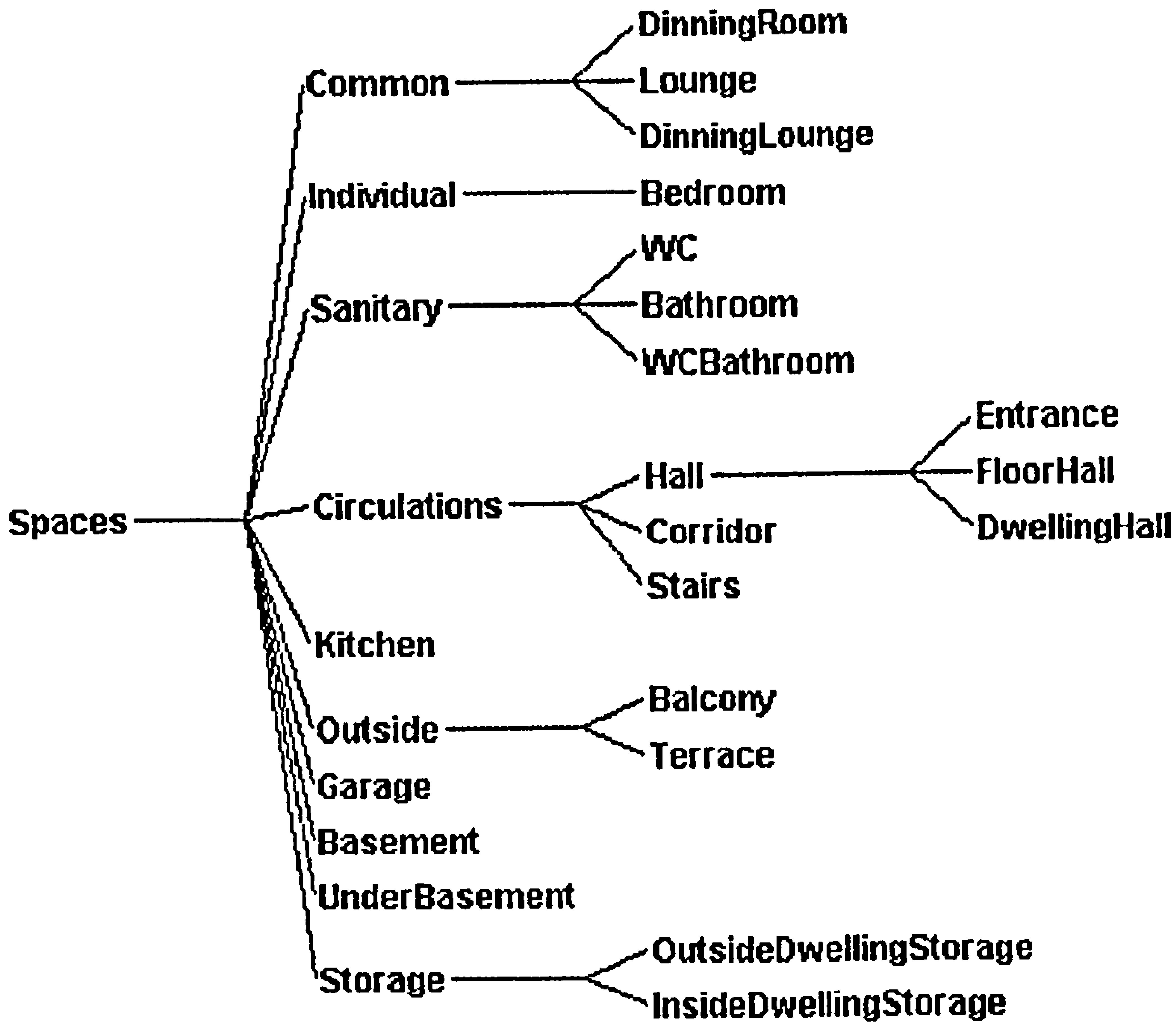


Figure 100 - DwellingElement hierarchy (Spaces).

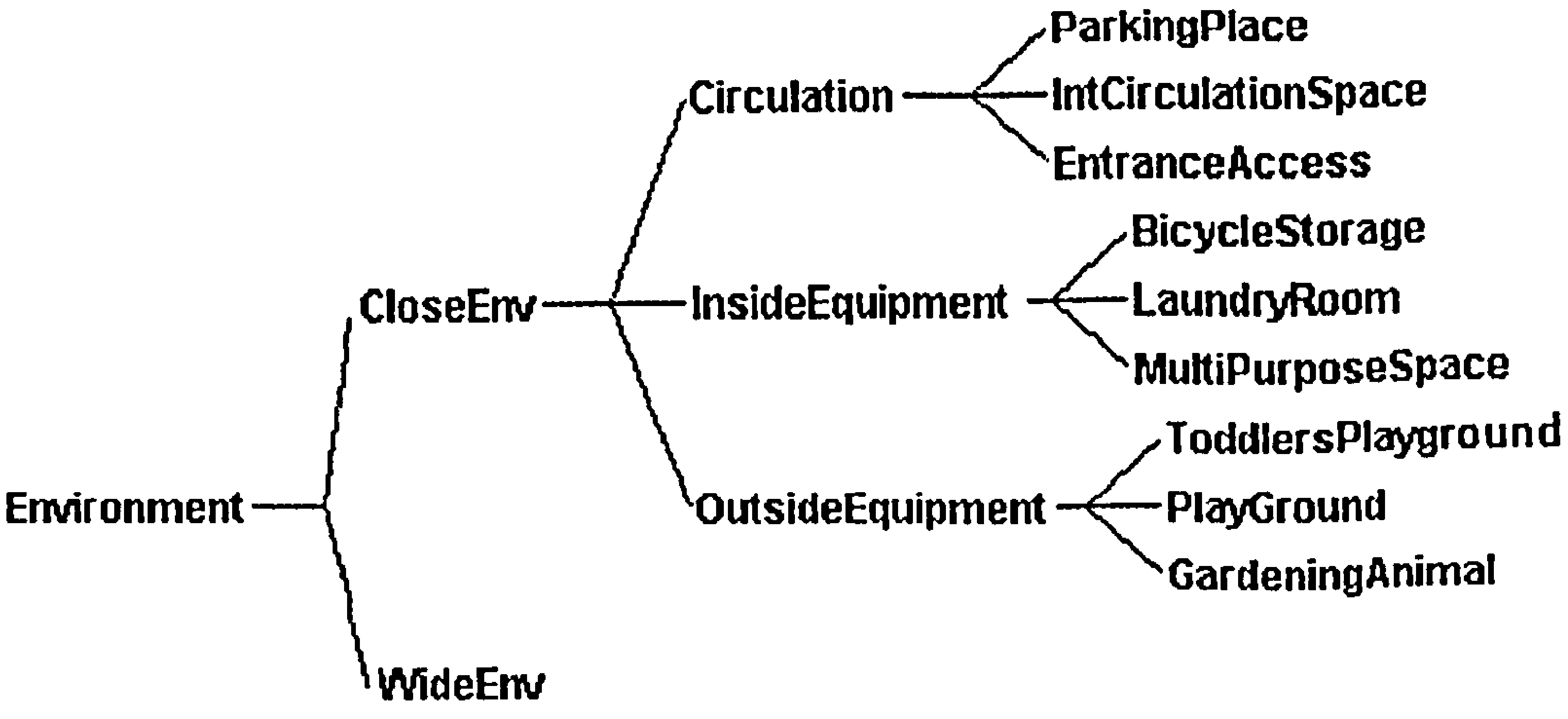


Figure 101 - DwellingElement hierarchy (Environment).

The **DwellingElement** hierarchy has as instances the different elements of the dwellings to be evaluated. As referred in section 6.3 (Figure 94) each instance of **Dwelling** "knows" the instances of **DwellingElement** of which it is composed and each instance of the **DwellingElement** "knows" to which instance of **Dwelling** it belongs. The association between Dwelling and DwellingElement has not been implemented using a separate class, because KAPPA has a direct implementation of lists of object pointers and this is sufficient to solve the problem.

The coexistence of several dwelling instances at runtime makes it easy to compare dwellings and their quality. The dwellings being compared may be different ones or design alternatives of the same dwelling. This could be useful to a dwelling buyer, because he can compare several dwellings and choose the more suitable one, as well as for a designer, because he can easily evaluate different design alternatives for the same dwelling.

Figure 102 presents an example of the structure of an external wall object (**Wall1**) as implemented in KAPPA. The structure is identical to the one presented in Figure 79. In this example only common (**Com**) and thermal (**Therm**) attributes and methods are found, because of the systems implemented (thermal, close environment and electrical fittings) only the thermal function is related to **Wall1**. When other systems concerning the external walls are implemented (e.g. acoustic system), their related attributes and methods will also be created.

Instance **Wall1** of class **CavityNonLoadExt**

Attributes	**Methods**
ComMyDwelling = HouseVilaR	ComCloseWindow
ComArea = 36.68	ComOpenWindow
ComOrientation = SW	ThermDTaCalcul
ComMaterial = "AirBrick11+15"	ThermDTCalcul
ComWeight = Heavy	ThermDTcCalcul
ThermInsulationMaterial = ExpandedPolystyrene	ThermDTrefaCalcul
ThermInsulationThickness = 20	ThermDTrefCalcul
ThermInsulationFillsCavity = FALSE	ThermFcEvaluateCalcul
ThermFc = 1.3	ThermFileGetK
ThermKref = 0.95	ThermKaCalcul
ThermKrefa = 45.2998	ThermKfcCalcul
ThermK = " .75"	ThermKKlimCalcul
ThermKa = 35.763	ThermKKmaxCalcul
ThermKmax = 1.45	ThermKlimCalcul
ThermKKmax = "According to Standards"	ThermKmaxCalcul
ThermFcEvaluate = 4	ThermKrefaCalcul
ThermDTref = 7.5	ThermKrefCalcul
ThermDTrefa = 122.30946	ThermLink
ThermDT = 6.5	
ThermDTc = 0	
ThermDTa = 83.68542	

Figure 102 - Attributes and methods of the instance Wall1.

It is easier to implement a complex system as a collection of interacting objects as **Wall1** than in the traditional way, i.e. by using functions which manipulate a set of data structures. The present implementation of the QDF prototype uses around 500 objects, depending on the complexity and number of dwellings being evaluated. The program has around 10,000 lines of code.

The program functionality will be explained in the following section.

6.5 Program functionality

Once the program has been activated the user is presented with the QDF main menu. This menu has the following options and sub-options:

- **File** - New, Open, Save, Save as..., Exit - Figure 103,
- **Dwelling** - Activate, Create, Delete, Open, Save, Duplicate - Figure 104,
- **Element** - Create, Delete, Duplicate - Figure 105,
- **Function** - Activate, Enter data, Evaluate - Figure 106,
- **Help** - About... - Figure 107.

Menu **File** is, as usual, about the application. An application is in this program a set of dwellings with the corresponding dwelling elements and other related information. In a typical session a user will open a new document (**File-New**) and create the dwellings and dwelling elements to be analysed. The other **File** options (**Open, Save, Save as...** and **Exit**) behave as is usual in any windows application. If the working version of an application is saved (**Save** or **Save as...**) before quitting the program, it can be loaded again using the Open command

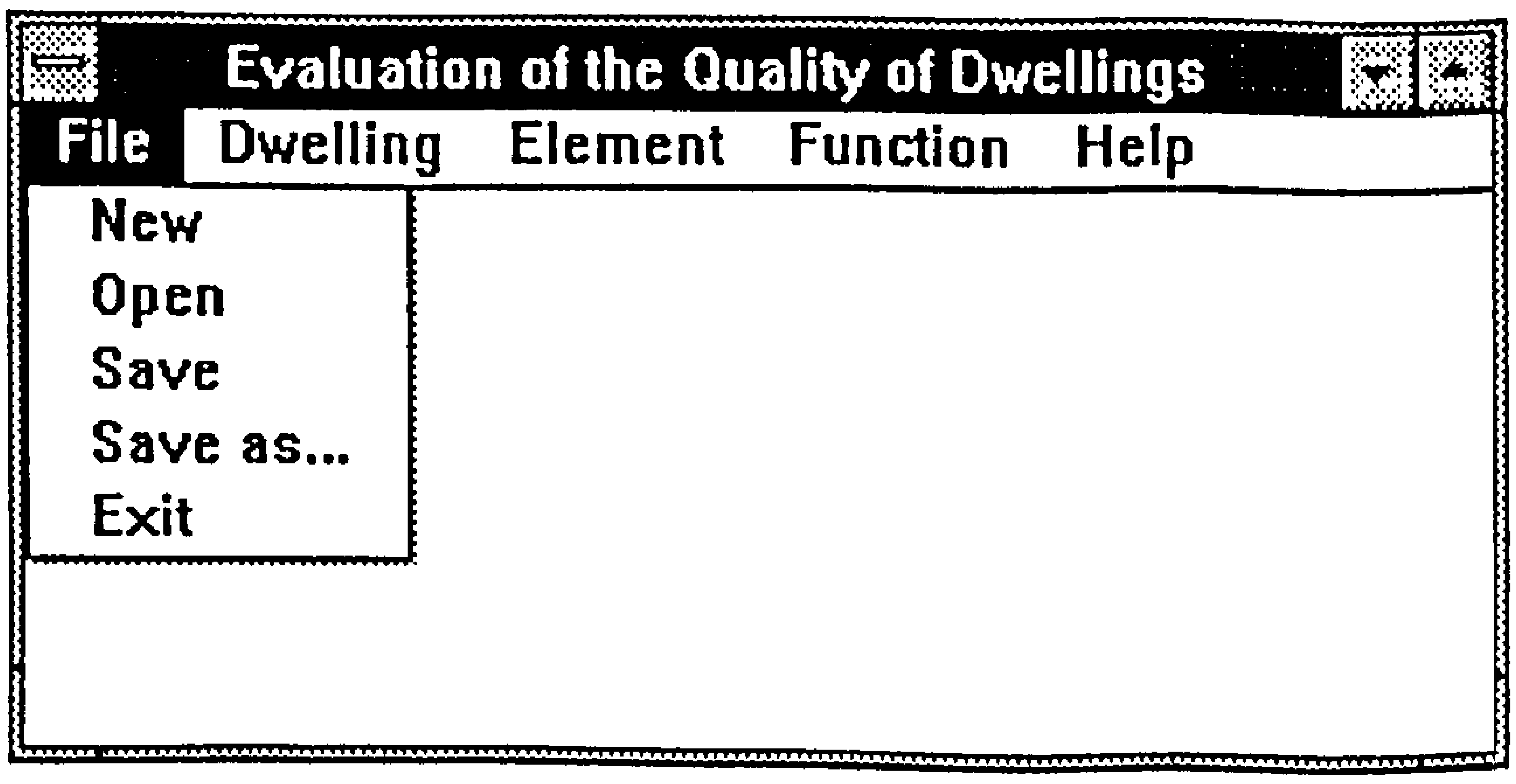


Figure 103 - QDF prototype main menu (File pop-up menu).

Dwelling menu gives six options to the user. **Dwelling-Activate** shows a list of the existing dwellings for the user to elect one as the active dwelling, the one to which all the program actions are associated. **Dwelling-Create** creates a new dwelling from scratch, asking for the dwelling name and type (house or flat). **Dwelling-Delete** shows a list of the existing dwellings for the user to select the one(s) to be deleted (all the object instances associated with the chosen dwelling(s) will be deleted). **Dwelling-Open** opens an existing dwelling which has been previously saved, loading all the object instances associated with the dwelling. **Dwelling-Save** saves the active dwelling and all the instances associated with it to a file. **Dwelling-Duplicate** creates a new dwelling, which is identical to the active dwelling but has a new name. The options **Dwelling-Open, Dwelling-Save** and **Dwelling-Duplicate** are useful when comparing alternative solutions for the same dwelling, because each alternative solution is modelled as a different dwelling. It also avoids introducing again all the data when creating new alternative solutions (it suffices to use **Dwelling-Duplicate** and change the relevant data).

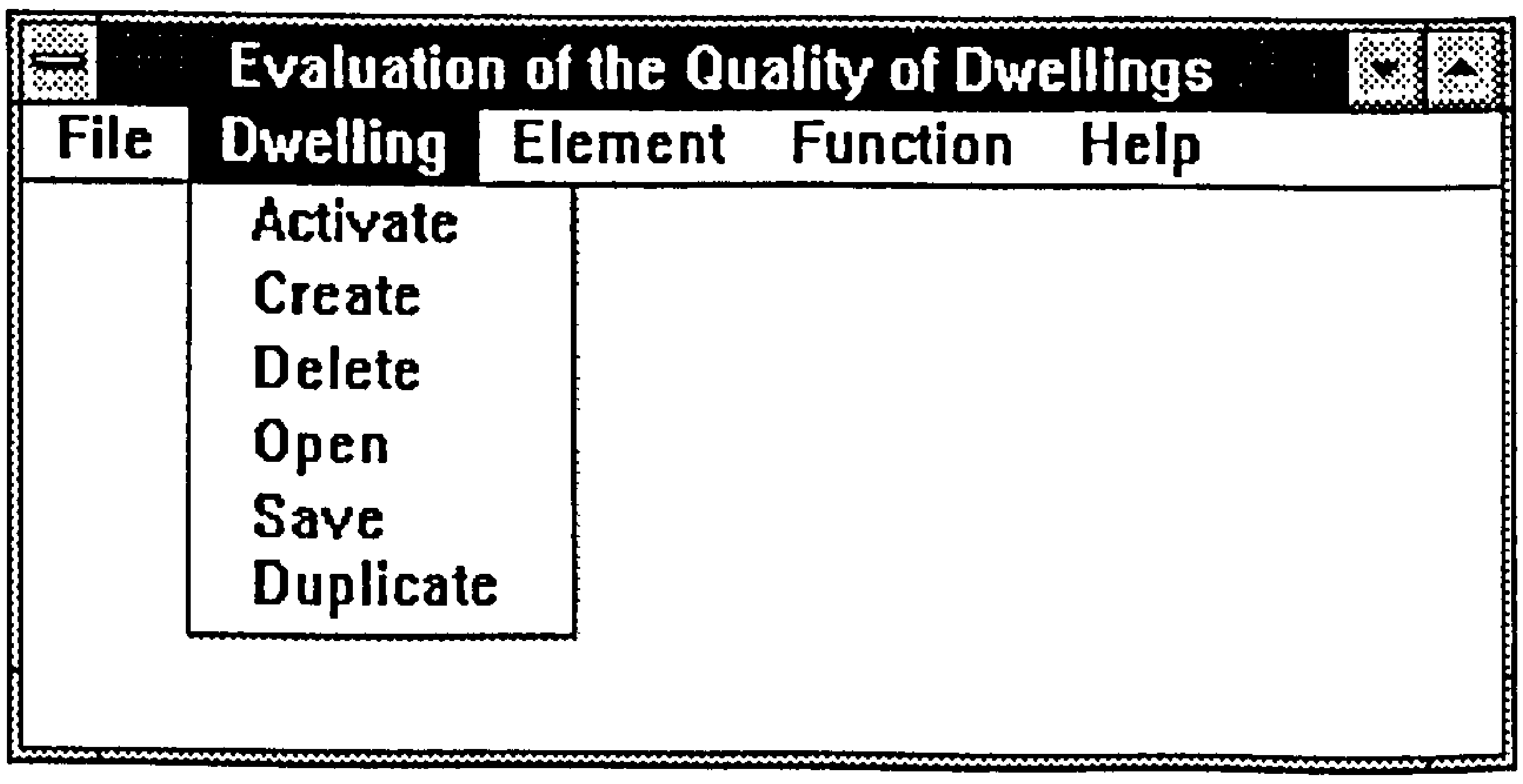


Figure 104 - QDF prototype main menu (Dwelling pop-up menu).

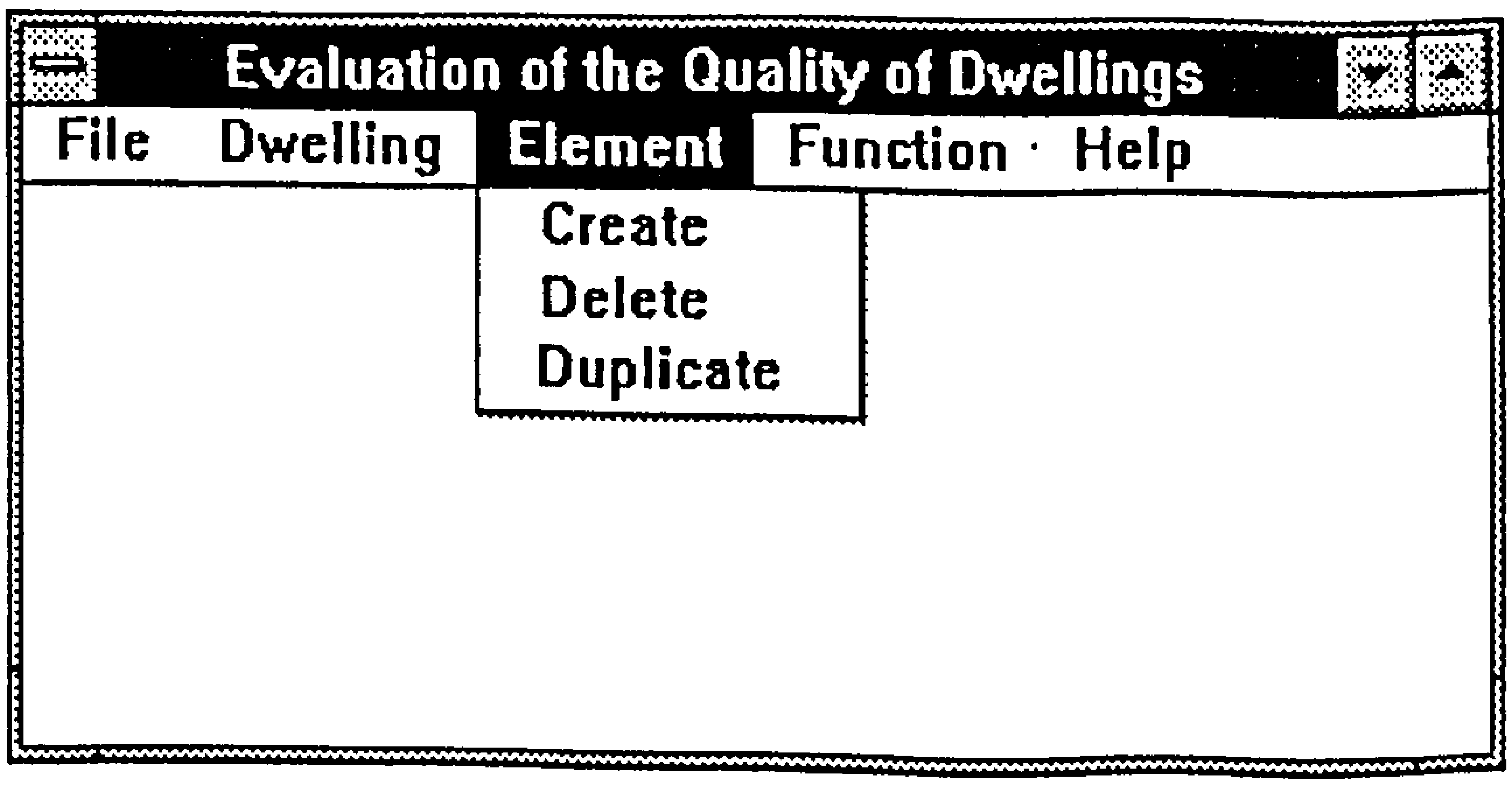


Figure 105 - QDF prototype main menu (Element pop-up menu).

Element menu has three options **Element-Create, Element-Delete** and **Element-Duplicate,** which allow new dwelling elements to be created (the user selects the class to which the new element will belong and its name), deleted (elements to be deleted are selected from a list containing the existing elements) and duplicated (a dwelling element is selected and the new name introduced).

Function menu has three options: **Function-Activate,** used to select the function to which all the program actions are associated (active function), **Function-Enter data,** that launches a set of data entry forms for the user to introduce in a friendly way the data related to the active function, and **Function-Evaluate,** that causes the active function to be evaluated and the results screen to be displayed.

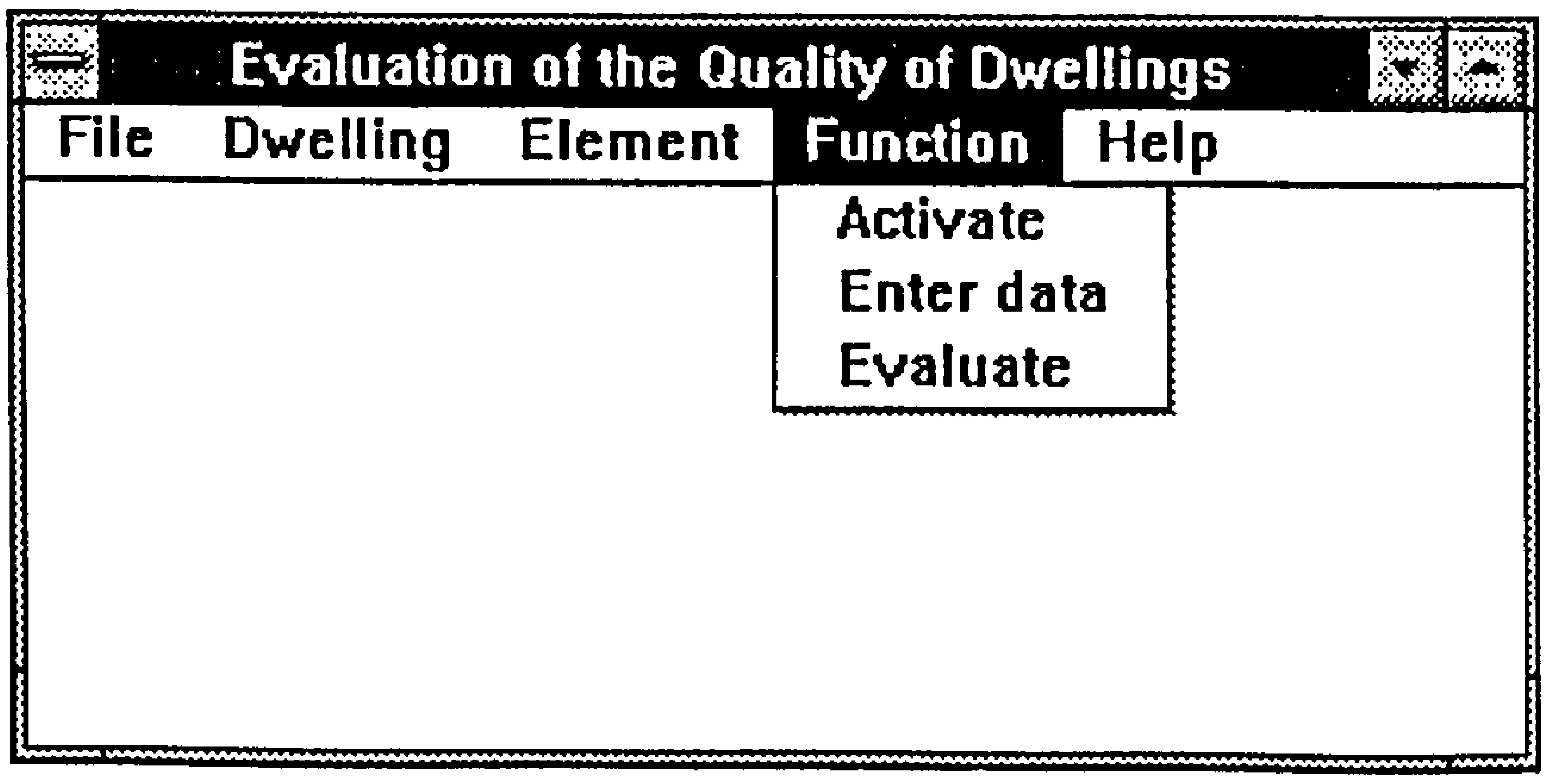


Figure 106 - QDF prototype main menu (Function pop-up menu).

Help menu is intended to provide access to a help utility, which will not be implemented in the present version of the system. At the moment **Help-About...** only prompts the user with the current version number of the QDF prototype (version 2.0).

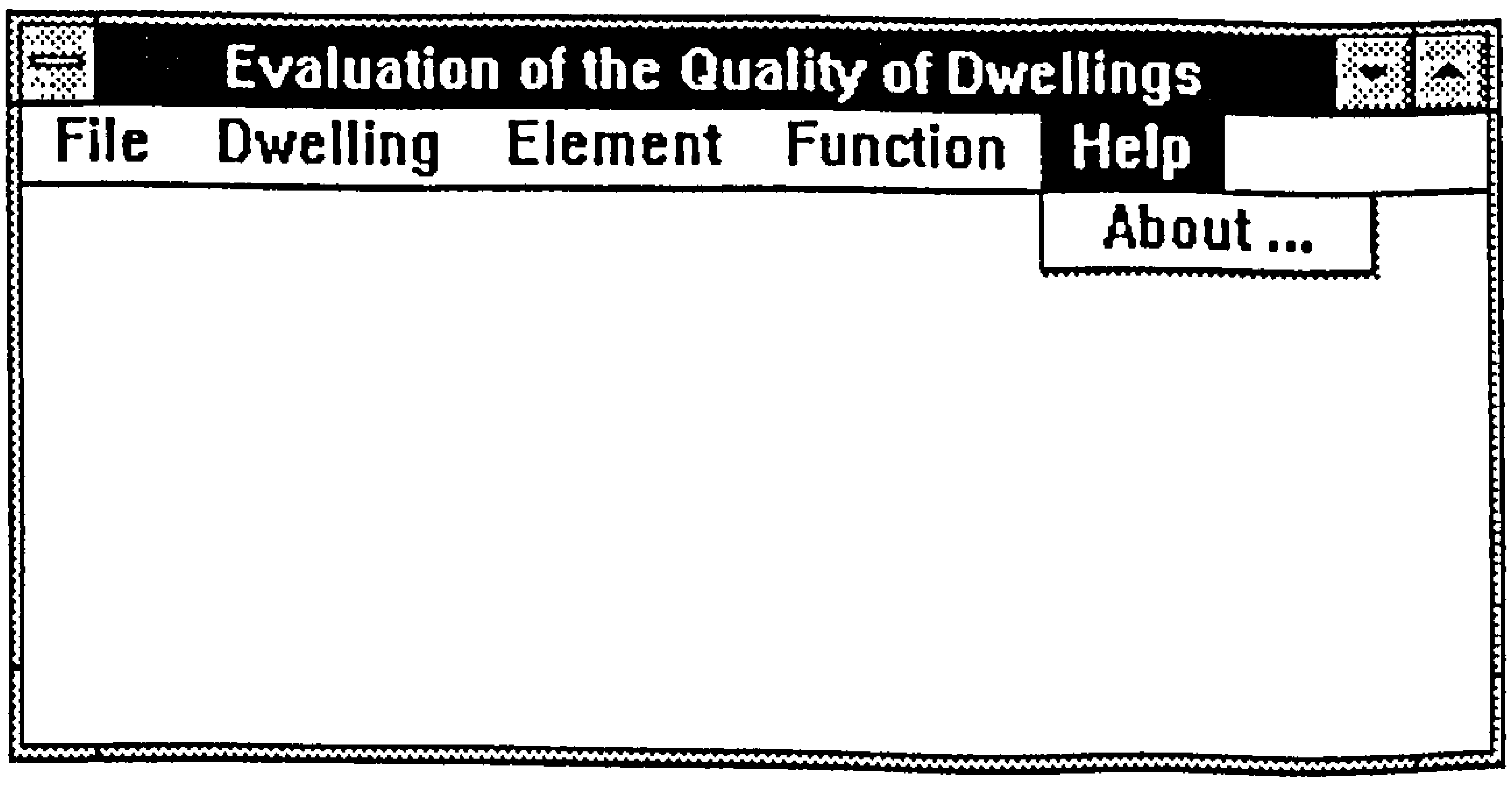


Figure 107 - QDF prototype main menu (Help pop-up menu).

No examples of the data entry forms and results screens are presented in this section, because they will be shown in Chapter 7 while testing QDF and the QDF prototype.

6.6 Summary

In this chapter an object-oriented design for a computer implementation of QDF has been developed, based on two main classes, Dwelling (whose instances are the actual dwellings being evaluated) and DwellingElement (whose instances are the elements of the dwellings). In the human body analogy drawn earlier Dwelling is equivalent to human body, while DwellingElement is equivalent to the human body components (organs, bones, veins, etc.).

A prototype of QDF using this design has been developed, implementing a thermal quality evaluation system (developed by the author and based on the Portuguese thermal regulations), an electrical quality evaluation system (from the Qualitel method) and a system to evaluate the quality of the close environment of a dwelling (from the SEL method). The developed prototype is very user friendly and provides a simple and effective way of evaluating the quality of dwelling designs, including the evaluation of alternative solutions for the same dwelling. Furthermore, the QDF prototype provides a test bed for evaluating QDF, as it will be shown in the next chapter.

7. Evaluation of QDF

7.1 Objectives

The objectives of this chapter are:

- to develop a strategy to evaluate QDF from different perspectives,
- to begin the process of evaluating QDF using this strategy.

7.2 Introduction

In this chapter a strategy to evaluate QDF is developed. The methodology used to develop this strategy is based on the philosophy of Karl Popper concerning the testing of scientific theories. The process of evaluating and testing QDF using this strategy is described. The evaluation includes a set of tests performed with the QDF prototype developed in the previous chapter. The prototype is used to evaluate the quality of four different dwelling designs and to help evaluate alternative design solutions for the same dwelling. A discussion of the similarities and differences between QDF and product modelling is also presented.

7.3 The strategy criteria

The view taken in this thesis about scientific knowledge follows the philosophy of Popper (1972a, 1972b, 1989). He argues that scientific knowledge differs from other kinds of knowledge (e.g. metaphysics) in that it is **falsifiable**, i.e. tests can be applied to try to refute it. If a statement which follows logically from a theory is tested and found to be false, then the theory has been falsified; if the statement is true then the theory is corroborated. Popper (1972b, page 32) suggested four different ways in which the testing of a theory can be carried out, as follows:

1. "The logical comparison of the conclusions among themselves, by which the internal consistency of the system is tested."
2. "The investigation of the logical form of the theory, with the object of determining whether it has the character of an empirical or scientific theory."
3. "The comparison with other theories, chiefly with the aim of determining whether the theory would constitute a scientific advance should it survive our various tests."
4. "The testing of the theory by way of empirical applications of the conclusions which can be derived from it."

Popper (Popper 1972a) refers to Tarski's theory of truth which is "a rehabilitation and an elaboration of the classical theory that truth is correspondence to the facts". He stresses that:

- "Any correspondence theory must be formulated in a meta-language; that is, a language in which one can discuss or speak about the expressions of some object languages under investigation."
- "In order to speak about any relation between the statements and the facts, we must have at our disposal descriptions of facts; that is to say, we must be able to describe, in our meta-language, all those facts which we can describe in the object language."

These ideas can be applied to the corroboration of QDF by saying that QDF should still be compared to the "facts" defined within a meta-system. By comparing a theory to the "facts" a measure of how well the theory explains the sub-system within an environment (the meta-system) is tested. QDF has to be used in the long term, because the "facts" to which it is to be compared are difficult to establish.

Theories are not verifiable, but they can be **corroborated** by testing. Corroboration of a theory is defined as the way the theory stands up to tests. A positive result can only temporarily support the theory, for subsequent negative decisions may always overthrow it. Theories may be more or less severely testable, i.e. more or less easily falsifiable. The **degree of testability** is of significance for the selection of theories. The amount of empirical information conveyed by a theory or its empirical content (class of its potential falsifiers) increases with its **degree of falsifiability**. So, the concepts of false or true as applied to scientific theories have meaning only in that it is an act of faith that the more corroborated is a theory (the higher the truth content) the more nearly it is true. A theory has a **degree of corroboration** and a degree of falsifiability (these concepts can be viewed as fuzzy concepts as opposed to Boolean concepts, which are either true or false). Every theory has classes of potential falsifiers and it is falsified if there exists at least one non empty class of basic statements which are forbidden by it, i.e. if the class of its potential falsifiers is not empty. In the words of Karl Popper (1972a) "... in the case of any particular theory proposed, it is the wealth of its content, and thus its degree of testability, which decides its interest, and the results of actual tests which decide its fate". Of course there needs to be a defined level of tolerance in order to decide whether there is agreement between the results of a theory and the "facts".

QDF is not in itself a scientific theory, but it is a piece of engineering knowledge (a model to evaluate the quality of dwellings), and can be tested using the ideas referred to above. In order to define the criteria to test QDF the four different ways presented above will be considered.

The first way is concerned with the internal consistency of the system. The methodology used to develop QDF was adopted precisely to obtain a good degree of internal consistency. This methodology was based on the human body analogy and on the systems approach (Chapter 5). A human body is a very sophisticated and highly developed form and provided a consistent basis for the development of the model. During the development of the examples (section 7.4.2) the results were examined for internal consistency.

The second way requires the model to have the characteristics of a scientific piece of knowledge, i.e. to belong to world3, "the objective world", in the sense of Popper (1983, 1992) and to be testable. In order to achieve this the following question has to be answered: "Is it possible to corroborate QDF by testing?". The answer is: **QDF can only be evaluated in the long term**, because the "facts" against which it is to be compared are difficult to establish, as mentioned earlier. The same is true of other areas of engineering, such as risk analysis (Blockley 1992b). Testing in these cases is a very complex process and can only be achieved by long term use in practice. In the case of QDF, users will use the system, make decisions, live in a house, provide feedback as to whether the evaluation turned out to be dependable or true (i.e. decisions correspond with the facts). This aspect has been already touched upon in Chapter 2, while discussing quality evaluation methods (Figure 15).

The third way implies the comparison with other theories. According to the published bibliography no other frameworks have been proposed for the evaluation of quality of dwelling designs. The closest work has been developed in the context of product modelling and so QDF will be compared with it in section 7.4.1. The fact that SEL and Qualitel are subsets of QDF also provides some evidence of the usefulness of the framework.

The fourth way states that the conclusions of the theory should be corroborated by applying it to real world situations. In the case of QDF this leads to the definition of the criteria proposed in section 7.4.2, which consist of modelling some real dwelling designs in order to evaluate its quality (section 7.4.2.1) as well as of the evaluation of alternative solutions for the same dwelling (section 7.4.2.2).

It is worth noting that quality has been defined earlier (in Chapter 2) as fitness for purpose. This interpretation is also valid when applied to the framework itself: QDF is a framework for the evaluation of the quality of dwellings and so it should be fit for this purpose. In more general terms this is equivalent to answering the following questions: "How good is a theory?" and "How good is the matching between the way we can use the theory and the problem we are trying to solve?". Popper has shown that probability is not a good measure to use to answer these questions. The problem is that a theory that has a low information content is highly probable, i.e. it says very little. The statement "this door is between 0.5 metres and 4 metres wide" concerning the width of a given door is highly probable, but contains very little information; on the other hand, the statement "this door is 0.85166662397 metres wide" contains a great deal of information, but precisely because of that it is less probable (it is more likely to be wrong). A measure of the degree of confirmation or corroboration of a theory must be defined so that only theories of high information content can reach high degrees of corroboration (Blockley 1980). Cui and Blockley (Cui 1990) further suggest an interval probability theory intended for use in problems involving sparse data and incomplete and possibly inconsistent knowledge (it enables system uncertainty as well as human based uncertainty to be considered). In order to achieve a high degree of corroboration for a theory not only extensive and severe tests should be used, but more importantly ingenious ones. Ingenious tests attempt at exploring any weaknesses of a theory in order to (try to) refute it.

In the following section the ideas explained above are used to initiate the process of corroborating QDF. The tests which are developed should only be seen as a preliminary evaluation of the framework. Only practical application of the framework will enable the achievement of a high degree of corroboration.

7.4 The evaluation

7.4.1 Comparisons

A comparison between QDF and product modelling will be presented in this section. This comparison is based on the qualities defined by Blockley (1992a) to evaluate engineering knowledge. The more relevant qualities for this purpose and their meaning are summarised in Figure 108.

Quality	Meaning
Function	Fitness for purpose
Form	Environmental impact, beauty, cost
Grounding	Dependability
Specification	Appropriateness
Applicability	Relevance, practicality
Expression	Calculation procedure models

Figure 108 - Meaning of the qualities of engineering knowledge.

Engineers take a pragmatic approach to knowledge, they are interested in truth only to the extent that it enables them to produce artefacts that have the requisite qualities. The rigour instead derives from the achievement of fitness for purpose. Knowledge has to be dependable. Truth is sufficient but not necessary for dependability. QDF and product modelling, as pieces of engineering knowledge, will be analysed (Figure 109) using the criteria set out in Figure 108.

Quality	QDF	Product modelling
Function	**Fit** for the defined purpose (to implement and develop **quality evaluation** methods for dwelling designs).	**Fit** for the initial purpose (to solve the problem of exchanging information between different application programs and CAD systems). **Not yet adequate** for the extended purpose (to express all the information related to a product in a common form, adequate for computer implementation)
Form	The framework was developed in a **hierarchical** way, dividing a dwelling into systems, subsystems and components. The methodology used to develop QDF was the **systems approach** and the **human body analogy**. The development of the framework was also based on computer implementation.	The building applications are being developed in a **hierarchical** way (RATAS, AEC building systems). **No methodology** for the construction of the model is referred in the available literature.
Grounding	Dependability.	Dependability.
Specification	The framework **is appropriate** to implement already defined methods like SEL and Qualitel as well as new ones (this has been corroborated by the tests shown in section 7.4.2).	**It is appropriate for the initial purpose**, exchange of graphical information (STEP). The extended purpose, due to its very large scope, is in a initial development phase. It remains to be seen how appropriate it is for this purpose.
Applicability	The framework is of great relevance to the evolution of quality standards. This idea is corroborated by the experiences of existing quality evaluation methods (e.g. Qualitel, SEL). It can be extended to other phases of the construction process and other purposes (e.g. obtaining bills of quantities, verify regulations standards and making general manufacturing processes).	Difficult to implement because of large scope. It seems to be more useful when applied to restricted areas with a well defined purpose. Some prototypes, in the case of the buildings, have already been developed, but no practical use is reported in the literature. Rather too abstract for easy application.
Expression (the language of the calculation procedure - models)	KAPPA	Express, NIAM, IDEF1X, etc.

Figure 109 - Comparison of QDF and product modelling.

The main differences which have been found are related to the form, expression and applicability. To develop the form of QDF the human body analogy and systems concepts like holons were used, while no methodology has been defined for product modelling within the published literature. Aspects related to the expression are also quite different: while QDF takes a "vertical" approach, going from modelling to design and implementation, product modelling is at the present stage more concerned with modelling and design. Finally, product modelling is based on a very broad view that makes it difficult to use in practice (it is rather abstract and requires much interpretation for practical use). QDF on the other hand is focused on the quality evaluation of dwellings (which implies dealing with a lot of information, but with a well defined purpose).

Attempts at the product modelling of buildings have been referred to in Chapter 4. The modelling of buildings in the RATAS and AEC building systems projects is based on a global approach which is similar to the one proposed in this thesis, i.e. a building is divided into systems and subsystems. In the RATAS model three types of systems are mentioned (space, structural and technical systems) but no specific classification is proposed, while in the AEC building systems model two alternatives for the classification of the systems of a dwelling are presented (passive, active and associative systems; space, services and fabric systems). Although the same approach has been taken in the three models, the way in which a dwelling is divided into systems is different. The classification proposed in QDF is the more comprehensive.

The purpose of QDF is to obtain a model which can be used for quality evaluation. This implies dealing with a lot of information, but with a well defined purpose. The models developed in RATAS and AEC building systems model, which have been defined without a specific purpose, tend to be too abstract for easy application.

SEL and Qualitel have been include in the present implementation of QDF as subsets. They had a strong influence in the development of this implementation of QDF, since they are the only methods available in the literature, for the evaluation of dwellings quality. QDF cannot be compared with these methods, because QDF is not in itself a quality evaluation method, but rather a model to implement and develop quality evaluation methods. The fact that SEL and Qualitel can readily be implemented within QDF increases its degree of corroboration, with respect to Karl Popper's third way (section 7.3).

7.4.2 Tests

7.4.2.1 Dwelling quality evaluation

This set of tests consists of using the developed prototype to evaluate the quality of four different dwelling designs:

- **D1** - design of a three bedroom house in Amarante (Portugal), designed by Architect Pedro Araújo.
- **D2** - design of a three bedroom house in Vila Real (Portugal), designed by Architect Eunice Salavessa.
- **D3** - design of a two bedroom flat (first floor) in Vila Nova de Gaia (Portugal), designed by Architect Pedro Araújo.
- **D4** - design of a two bedroom flat (top floor) in Vila Nova de Gaia (Portugal), designed by Architect Pedro Araújo.

A simplified description of the dwellings, including the more relevant information for the quality evaluation of the thermal system, electrical fittings and close environment, is given in the following tables. Simplified schematics of the dwellings are presented in Figures 110 to 115.

D1 - three bedroom house in Amarante - designed by Pedro Araújo	
General Information	
Winter climatic zone	I 2
Summer climatic zone	V 1
Country region	North
Thermal inertia	High
Altitude (m)	200.00
Useful area (m2)	225.00
Average headroom (m)	3.00
Type of central heating	Gas
Power supply (kW)	12
Number of persons living in the dwelling	5
Number of persons living in the block	Not applicable
Number of persons living in the close environment	24
Number of dwellings in the floor	Not applicable
Number of types of flats in the block	Not applicable

Number of flats in the block	Not applicable
Number of types of dwellings in the close environment	2
Number of dwellings in the close environment	6
Number of persons living in 1st floor of the block	Not applicable
Number of persons living in 2nd floor of the block	Not applicable

Primary Elements							
External Walls	**Wall1**	**Wall2**	**Wall3**	**Wall4**	**Wall5**	**Wall6**	**Wall7**
Area (m2)	29.60	8.40	57.00	5.40	60.60	39.30	35.10
Orientation	North	South	East	West	South	East	West
Type	Cavity	Cavity	Cavity	Cavity	Cavity	Cavity	Cavity
Material	Concr.+ Concr. block10	Concr.+ Concr. block10	Concr.+ Concr. block10	Concr.+ Concr. block10	Air brick11 + solid brick11	Air brick11 + solid brick11	Air brick11 + solid brick11
Insulation material	No ins.	No ins.	No ins.	No ins.	No ins.	No ins.	No ins.
Insulation thickness (mm)	0	0	0	0	0	0	0
Insulation fulfils cavity	Not app	Not app	Not app	Not app	Not app	Not app	Not app
fc	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Weight	Heavy	Heavy	Heavy	Heavy	Medium	Medium	Medium
External Roofs	**Roof1**						
Area (m2)	201.80						
Type	Pitched						
Material	Light slab cer. blocks						
Insulation position	On pitched slab						
Insulation material	Mineral wool						
Insulation thickness (mm)	60						
Ventilation	Strong						
Colour of protection	Bright						
Secondary Elements							
Vertical External Glazed	**Glazed 1**	**Glazed 2**	**Glazed 3**	**Glazed 4**	**Glazed 5**	**Glazed 6**	
Area (m2)	7.60	19.30	4.50	8.15	13.30	2.50	
Orientation	North	South	South	East	West	West	
Type	Double	Double	Double	Double	Double	Double	
Colour of glass	No colour	No colour	No colour	No colour	No colour	No colour	
Frame material	Timber	Timber	Timber	Timber	Timber	Timber	

Distance glazing (mm)	8	8	8	8	8	8	
Position of protection	Internal	Internal	Internal	Internal	Internal	Internal	
Type of protection	Slightly transpa. curtain	Slightly transpa. curtain	Timber portal	Slightly transpa. curtain	Slightly transpa. curtain	Timber portal	
Colour of protection	Bright	Bright	Bright	Bright	Bright	Bright	
Insulation of protection	Bad	Bad	Good	Bad	Bad	Good	
Services							
Radiators	**Radiat. 1**	**Radiat. 2**	**Radiat. 3**	**Radiat. 4**	**Radiat. 5**	**Radiat. 6**	**Radiat. 7**
Heating power (kW)	Not availab.	Not availab.	Not availab.	Not availab.	Not availab.	Not availab.	Not availab.
Spaces	**Dinning lounge**	**Kitchen**	**WC**	**Storage**	**Garage**	**WC/ bathr.**	**Bedr. 1**
Area (m2)	43.38	12.40	2.38	7.12	17.50	6.21	15.30
Perimeter (m)	31.35	13.90	6.20	11.20	17.00	10.00	15.70
Width (m)	5.50	3.50	1.30	1.50	3.50	2.30	3.60
Number of sockets	5	9	1	1	2	1	3
Number of light sources	2	1	1	1	1	1	1
Spaces (cont.)	**Bedr. 2**	**Bedr. 3**					
Area (m2)	12.32	15.45					
Perimeter (m)	14.30	16.40					
Width (m)	2.90	3.00					
Number of sockets	3	3					
Number of light sources	1	1					
Environment	**Park. place**	**Bicycle storage**	**Laund. room**	**Multi purpose space**	**Toddler playgr.**	**Playgr.**	**Garde-ning**
Area (m2)	Not applic.	Not applic.	Not applic.	Not applic.	Not applic.	Not applic.	Not applic.

D2 - Three bedroom house in Vila Real - designed by Eunice Salavessa	
General Information	
Winter climatic zone	I 3
Summer climatic zone	V 2
Country region	North
Thermal inertia	High
Altitude (m)	400.00
Useful area (m2)	115.48

Average headroom (m)	2.50
Type of central heating	Gas
Power supply (kW)	8
Number of persons living in the dwelling	5
Number of persons living in the block	Not applicable
Number of persons living in the close environment	468
Number of dwellings in the floor	Not applicable
Number of types of flats in the block	Not applicable
Number of flats in the block	Not applicable
Number of types of dwellings in the close environment	3
Number of dwellings in the close environment	60
Number of persons living in 1st floor of the block	Not applicable
Number of persons living in 2nd floor of the block	Not applicable

Primary Elements							
External Walls	**Wall1**	**Wall2**	**Wall3**	**Wall4**			
Area (m2)	36,68	47.46	52.88	45.1			
Orientation	South West	North East	South East	North West			
Type	Cavity	Cavity	Cavity	Cavity			
Material	Airbrick 11+11	Airbrick 11+11	Airbrick 11+11	Airbrick 11+11			
Insulation material	Expand. Polyst.	Expand. Polyst.	Expand. Polyst.	Expand. Polyst.			
Insulation thickness (mm)	20	20	20	20			
Insulation fulfils cavity	No	No	No	No			
fc	1.30	1.30	1.30	1.30			
Weight	Medium	Medium	Medium	Medium			
External Roofs	**Roof1**						
Area (m2)	75.69						
Type	Pitched						
Material	Light slab cer. blocks						
Insulation position	On flat slab						
Insulation material	Expand. Polyst.						
Insulation thickness (mm)	20						
Ventilation	Strong						
Colour of protection	Bright						

Semi Exposed Floors	**Floor1**						
Area (m2)	64.58						
Material	Light slab cer. block11						
Suspended ceiling	No						
Insulation material	No ins.						
Insulation thickness (mm)	0						
Secoudary Elements							
Vertical External Glazed	**Glazed 1**	**Glazed 2**	**Glazed 3**	**Glazed 4**	**Glazed 5**	**Glazed 6**	**Glazed 7**
Area (m2)	8.77	5.19	8.94	1.12	6.08	2.50	0.96
Orientation	South West	South West	North East	South East	North West	North West	North West
Type	Double	Double	Double	Double	Double	Double	Double
Colour of glass	No colour	No colour	No colour	No colour	No colour	No colour	No colour
Frame material	Metal	Metal	Metal	Metal	Metal	Metal	Metal
Distance glazing (mm)	8	8	8	8	8	8	8
Position of protection	Internal	None	None	Internal	Internal	Internal	None
Type of protection	Opaque Curtain	None	None	Opaque Curtain	Opaque Curtain	Very transp. curtain	None
Colour of protection	Bright	Not app	Not app	Bright	Bright	Bright	Not app
Insulation of protection	Bad	Not app	Not app	Bad	Bad	Bad	Not app
Services							
Radiators	**Radiat. 1**	**Radiat. 2**	**Radiat. 3**	**Radiat. 4**	**Radiat. 5**	**Radiat. 6**	**Radiat. 7**
Heating power (kW)	Not availab.	Not availab.	Not availab.	Not availab.	Not availab.	Not availab.	Not availab.
Spaces	**Dinning lounge**	**Kitchen**	**WC**	**Storage**	**Hall**	**WC/ bathr. 1**	**WC/ bathr. 2**
Area (m2)	39.12	11.20	2.40	2.10	6.45	6.90	3.12
Perimeter (m)	25.50	13.40	6.80	5.80	10.70	10.60	7.40
Width (m)	4.50	3.30	1.00	1.40	1.00	2.30	1.30
Number of sockets	9	11	1	1	2	1	1
Number of light sources	2	2	1	1	1	2	2
Spaces (cont.)	**Bedr. 1**	**Bedr. 2**	**Bedr. 3**	**Garage**			
Area (m2)	16.10	11.90	13.44	64.58			
Perimeter (m)	16.20	14.20	16.00	34.50			
Width (m)	3.50	2.70	2.40	7.50			
Number of sockets	4	4	4	2			

Number of light sources	1	1	1	1			
Environment	**Park. place**	**Bicycle storage**	**Laund. room**	**Multi purpose space**	**Toddler playgr.**	**Playgr.**	**Gardening**
Area (m2)	Not app	Not app	Not app	Not app	Not app	Not app	Not app

D3 - Two bedroom flat in V. N. de Gaia (1st floor) - designed by Pedro Araújo

General Information	
Winter climatic zone	I 2
Summer climatic zone	V 1
Country region	North
Thermal inertia	High
Altitude (m)	400.00
Useful area (m2)	90.73
Average headroom (m)	2.50
Type of central heating	None
Power supply (kW)	8
Number of persons living in the dwelling	4
Number of persons living in the block	16
Number of persons living in the close environment	60
Number of dwellings in entrance floor	0
Number of dwellings in the floor	2
Number of types of flats in the block	1
Number of flats in the block	4
Number of dwellings in the building	16
Number of types of dwellings in the close environment	4
Number of dwellings in the close environment	100
Number of persons living in 1st floor of the block	8
Number of persons living in 2nd floor of the block	8

Primary Elements							
External Walls	**Wall1**	**Wall2**					
Semi Exposed Walls			**Wall3**				
Area (m2)	16.10	6.80	4.80				
Orientation	West	East	Not app				
Type	Cavity	Cavity	Solid				
Material	Air brick 11+11	Air brick 11+11	Air brick 22				

Insulation material	Extrud. Polyst.	Extrud. Polyst.	No ins.				
Insulation thickness (mm)	20	20	0				
Insulation fulfils cavity	No	No	Not app				
fc	1.30	1.30	1.5				
Weight	Medium	Medium	Medium				
External Floors	**Floor1**						
Area (m2)	11.76						
Material	Light slab cer. block11						
Suspended ceiling	No						
Insulation material	Expand. Polyst.						
Insulation thickness (mm)	40						
Secondary Elements							
Vertical External Glazed	**Glazed 1**	**Glazed 2**					
Vertical Semi Exposed Glazed			**Glazed 3**				
Area (m2)	4.00	2.20	7.50				
Orientation	West	East	Not app				
Type	Single	Single	Single				
Colour of glass	No colour	No colour	No colour				
Frame material	Plastic	Plastic	Plastic				
Distance glazing (mm)	0	0	0				
Position of protection	external	Internal	Not app				
Type of protection	Plastic louver	Plate blind	Not app				
Colour of protection	Bright	Bright	Not app				
Insulation of protection	Bad	Bad	Not app				
Services							
Radiators	None						
Heating power (kW)							
Spaces	Dinning lounge	Kitchen	Storage	Laund.	Dwell. hall	Bedr. 1	Bedr. 2
Area (m2)	23.62	12.16	3.78	3.25	7.00	15.68	14.95
Perimeter (m)	20.5	16.50	7.80	7.70	10.60	16.16	15.70
Width (m)	2.50	1.70	1.8	1.25	2.10	3.25	3.25
Number of sockets	5	7	1	2	1	3	3

Number of light sources	2	1	1	1	1	1	1
Spaces (cont.)	**WC/ bathr.**	**Floor hall**	**Main Entran.**	**Open Entran.**			
Area (m2)	5.25	4.06	3.36	14.25			
Perimeter (m)	9.20	1.40	1.40	1.9			
Width (m)	2.10	8.60	7.60	15.38			
Number of sockets	1	Not app	Not app	Not app			
Number of light sources	1	Not app	Not app	Not app			
Environment	**Park. place**	**Com. storage**	**Bicycle storage**	**Laund. room**	**Multi purpose space**	**Toddler playgr.**	**Playgr.**
Area (m2)		20.00	0.00	12.00	4.80	48.00	120.00
Noise disturbance	No	Not app	Not app	Not app	Not app	Not app	Not app
Exhaust gas disturbance	No	Not app	Not app	Not app	Not app	Not app	Not app
Headlights disturbance	No	Not app	Not app	Not app	Not app	Not app	Not app
Distance to block entrance (m)	60	Not app	Not app	Not app	Not app	Not app	Not app
Disabled vehicle access	Yes	Not app	Not app	Not app	Not app	Not app	Not app
Environment (cont.)	**Gardening**						
Area (m2)	0.00						

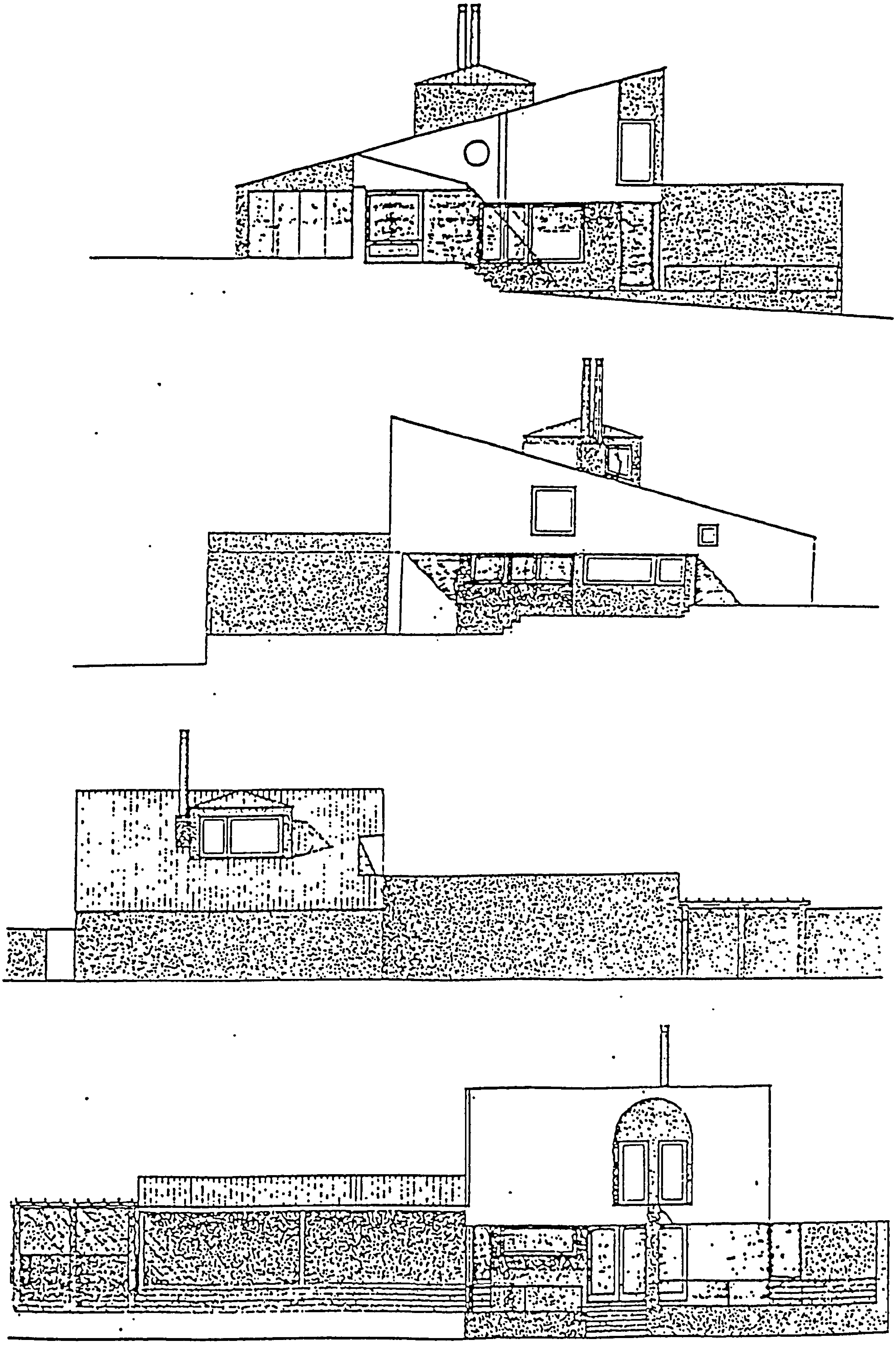
D4 - Two bedroom flat in V. N. de Gaia (top floor) - designed by Pedro Araújo

General Information	
Winter climatic zone	I 2
Summer climatic zone	V 1
Country region	North
Thermal inertia	High
Altitude (m)	400.00
Useful area (m2)	90.73
Average headroom (m)	2.50
Type of central heating	None
Power supply (kW)	12
Number of persons living in the dwelling	4
Number of persons living in the block	16
Number of persons living in the close environment	60
Number of dwellings in entrance floor	0
Number of dwellings in the floor	2
Number of types of flats in the block	1

Number of flats in the block	4						
Number of dwellings in the building	16						
Number of types of dwellings in the close environment	4						
Number of dwellings in the close environment	100						
Number of persons living in 1st floor of the block	8						
Number of persons living in 2nd floor of the block	8						

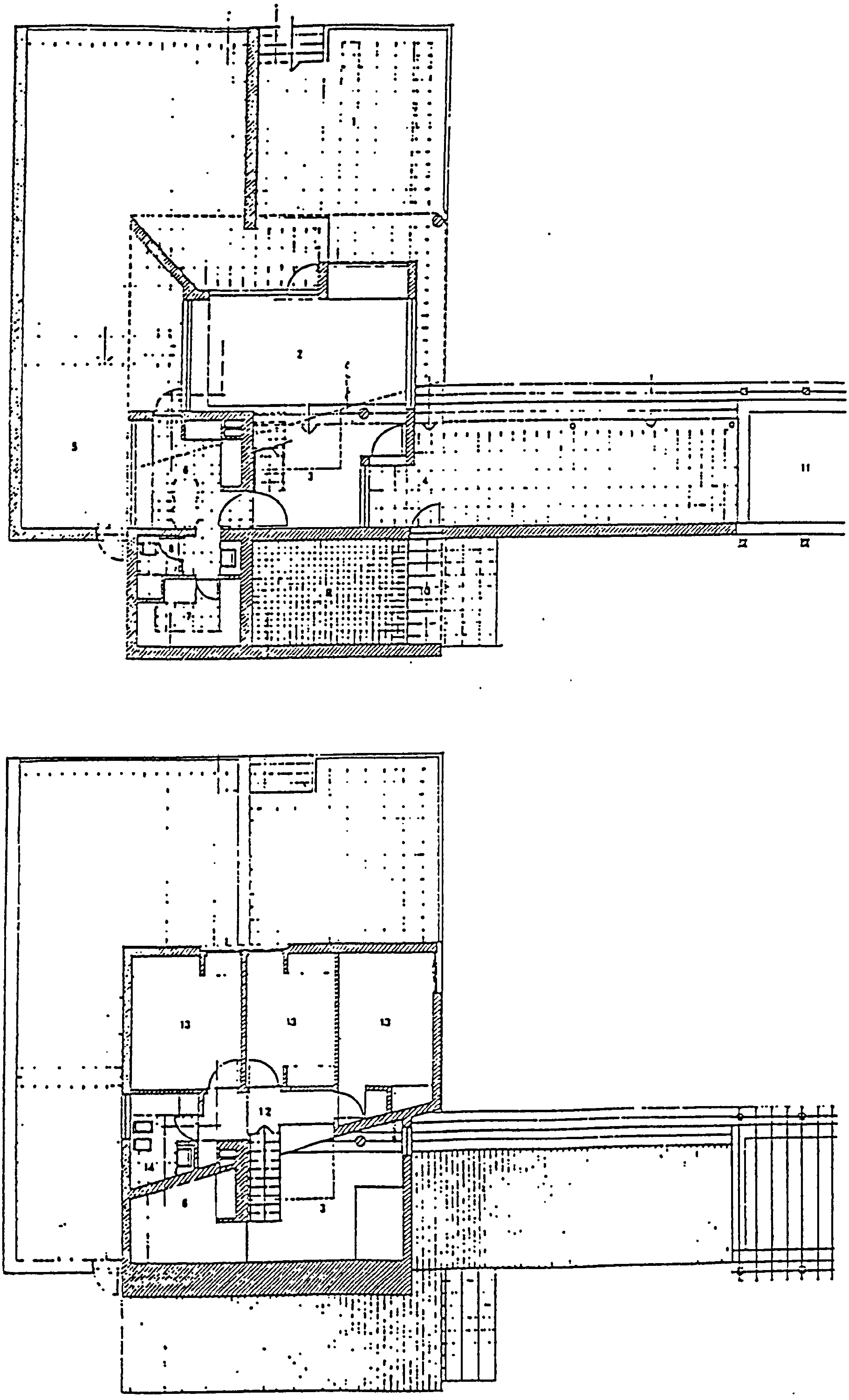
Primary Elements							
External Walls	**Wall1**	**Wall2**					
Semi Exposed Walls			**Wall3**				
Area (m2)	16.10	6.80	4.80				
Orientation	West	East	Not app				
Type	Cavity	Cavity	Solid				
Material	Air brick 11+11	Air brick 11+11	Air brick 22				
Insulation material	Extrud. Polyst.	Extrud. Polyst.	No ins.				
Insulation thickness (mm)	20	20	0				
Insulation fulfils cavity	No	No	Not app				
fc	1.30	1.30	1.5				
Weight	Medium	Medium	Medium				
External Roofs	**Roof1**						
Semi Exposed Roofs		**Roof2**					
Area (m2)	47.62	71.04					
Type	Flat	Flat					
Material	Light slab cer. block1	Light slab cer. block1					
Suspended ceiling	No	No					
Insulation material	Expand. Polyst.	No ins.					
Insulation thickness (mm)	20	0					
Type of protection	Heavy	Not app					
Colour of protection	Bright	Not app					
Secondary Elements							
Vertical External Glazed	**Glazed 1**	**Glazed 2**					
Vertical Semi Exposed Glazed			**Glazed 3**				
Area (m2)	4.00	2.20	7.50				
Orientation	West	East	not app.				

Type	Single	Single	Single				
Colour of glass	No colour	No colour	No colour				
Frame material	Plastic	Plastic	Plastic				
Distance glazing (mm)	0	0	0				
Position of protection	external	Internal	Not app				
Type of protection	Plastic louver	Plate blind	Not app				
Colour of protection	Bright	Bright	Not app				
Insulation of protection	Bad	Bad	Not app				
Services							
Radiators	**None**						
Heating power (kW)							
Spaces	**Dinning lounge**	**Kitchen**	**Storage**	**Laund.**	**Dwell. hall**	**Bedr. 1**	**Bedr. 2**
Area (m2)	23.62	12.16	3.78	3.25	7.00	15.68	14.95
Perimeter (m)	20.5	16.50	7.80	7.70	10.60	16.16	15.70
Width (m)	2.50	1.70	1.8	1.25	2.10	3.25	3.25
Number of sockets	7	9	1	2	1	3	3
Number of light sources	2	2	1	1	1	1	1
Spaces (cont.)	**WC/ bathr.**	**Floor hall**	**Main Entran.**	**Open Entran.**			
Area (m2)	5.25	4.06	3.36	14.25			
Perimeter (m)	9.20	1.40	1.40	1.9			
Width (m)	2.10	8.60	7.60	15.38			
Number of sockets	1	Not app	Not app	Not app			
Number of light sources	2	Not app	Not app	Not app			
Environment	**Park. place**	**Com. storage**	**Bicycle storage**	**Laund. room**	**Multi purpose space**	**Toddler playgr.**	**Playgr.**
Area (m2)	170	20.00	0.00	12.00	4.80	48.00	120.00
Noise disturbance	No	Not app	Not app	Not app	Not app	Not app	Not app
Exhaust gas disturbance	No	Not app	Not app	Not app	Not app	Not app	Not app
Headlights disturbance	No	Not app	Not app	Not app	Not app	Not app	Not app
Distance to block entrance (m)	60	Not app	Not app	Not app	Not app	Not app	Not app
Disabled vehicle access	Yes	Not app	Not app	Not app	Not app	Not app	Not app
Environment (cont.)	**Gardening**						
Area (m2)	0.00						



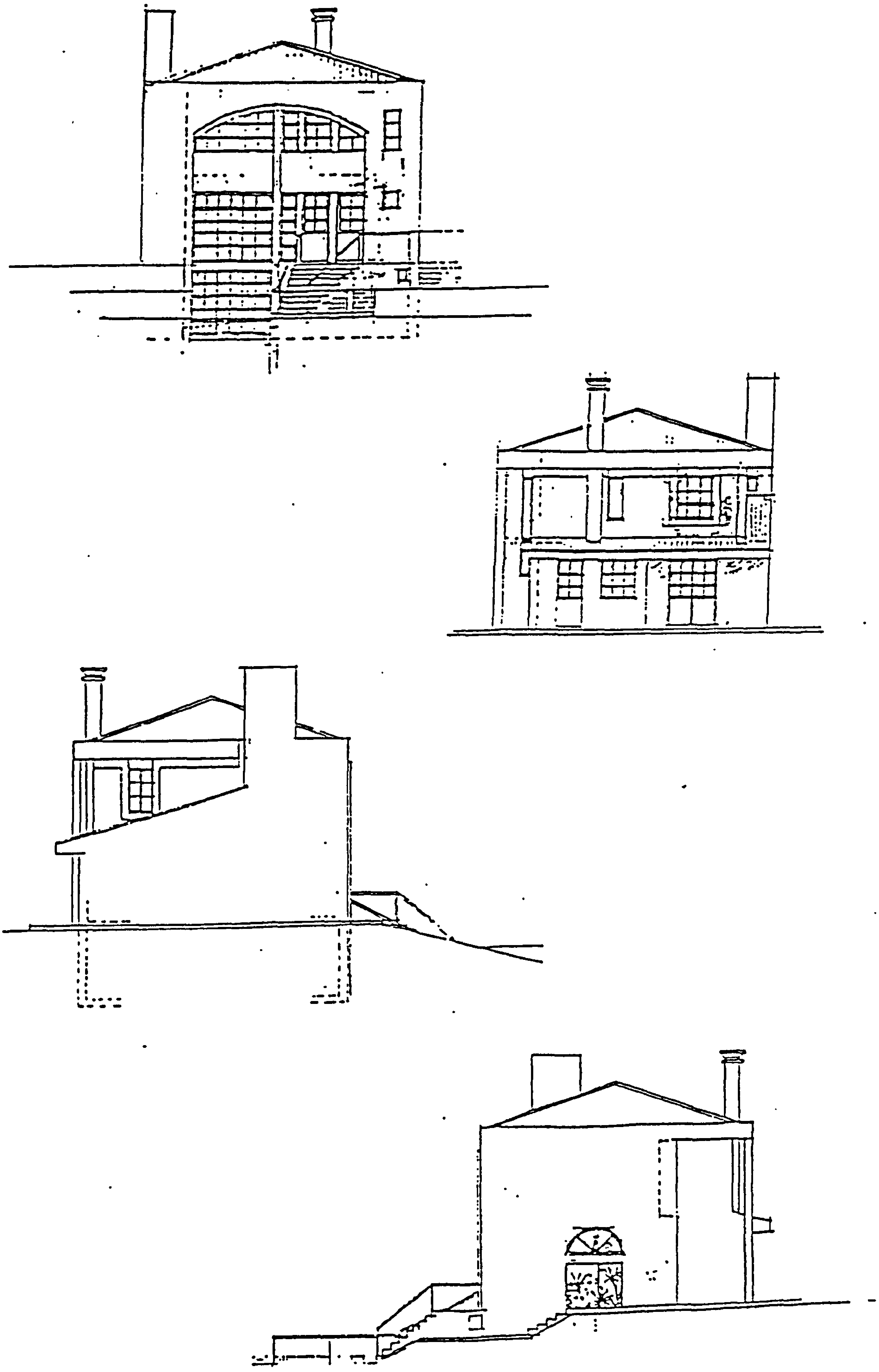
Legend: (from top to bottom) Southwest view, Northeast view, Northwest view and Southeast view.

Figure 110 - Dwelling D1.



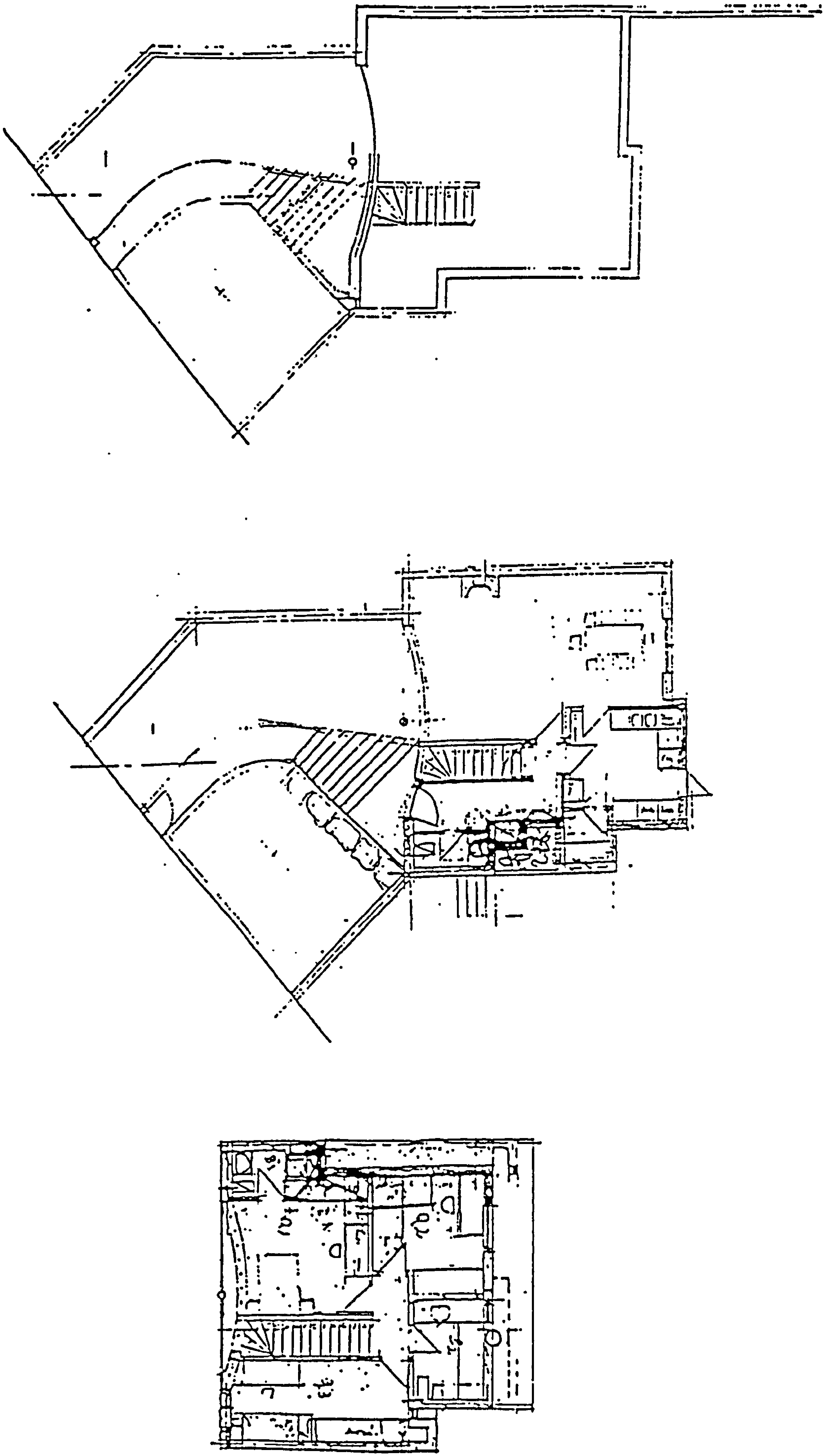
Legend: (from top to bottom) plan of the ground floor, plan of the first floor.

Figure 111 - Dwelling D1 (continued).



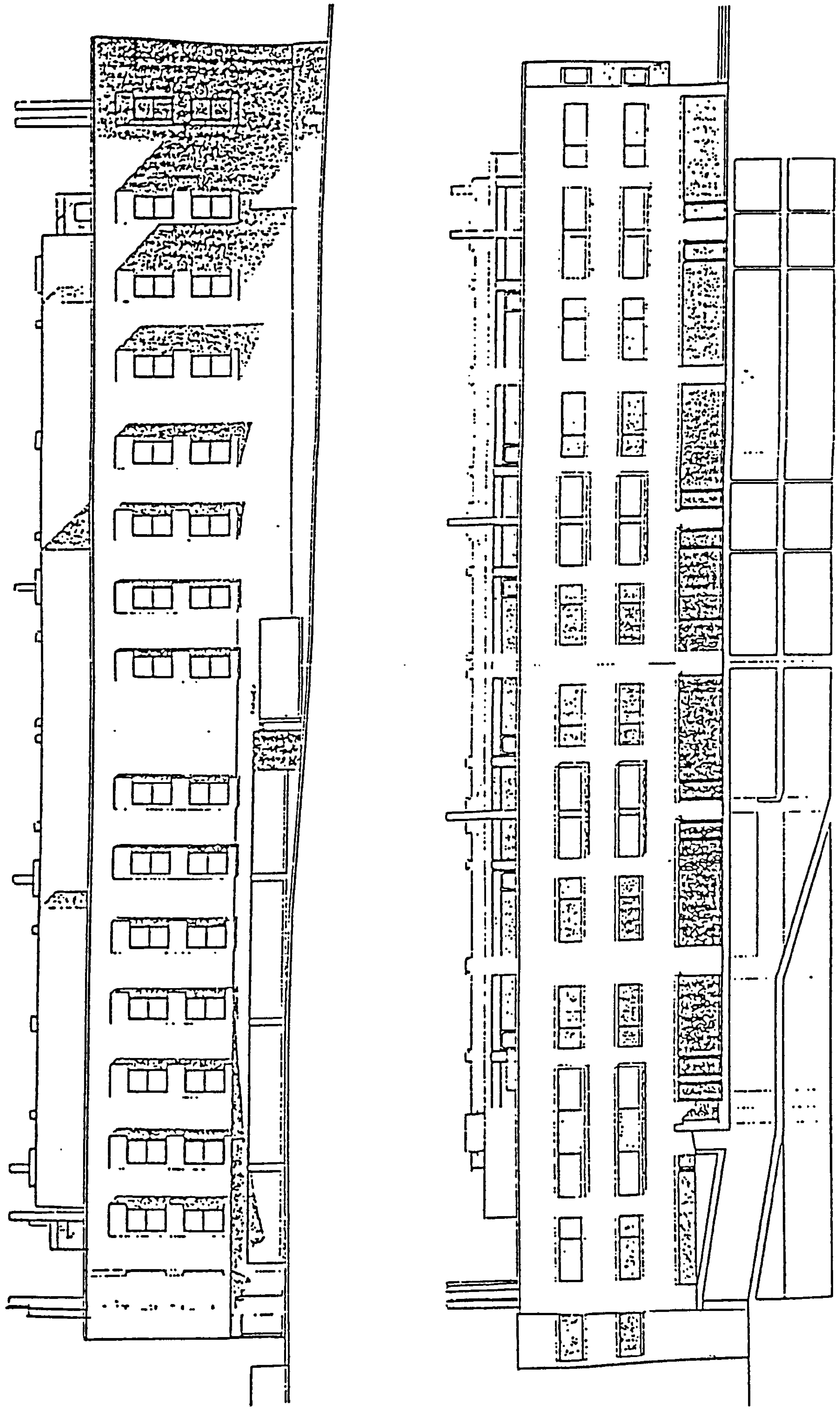
Legend: (from top to bottom) Southwest view, Northeast view, Northwest view and Southeast view.

Figure 112 - Dwelling D2.



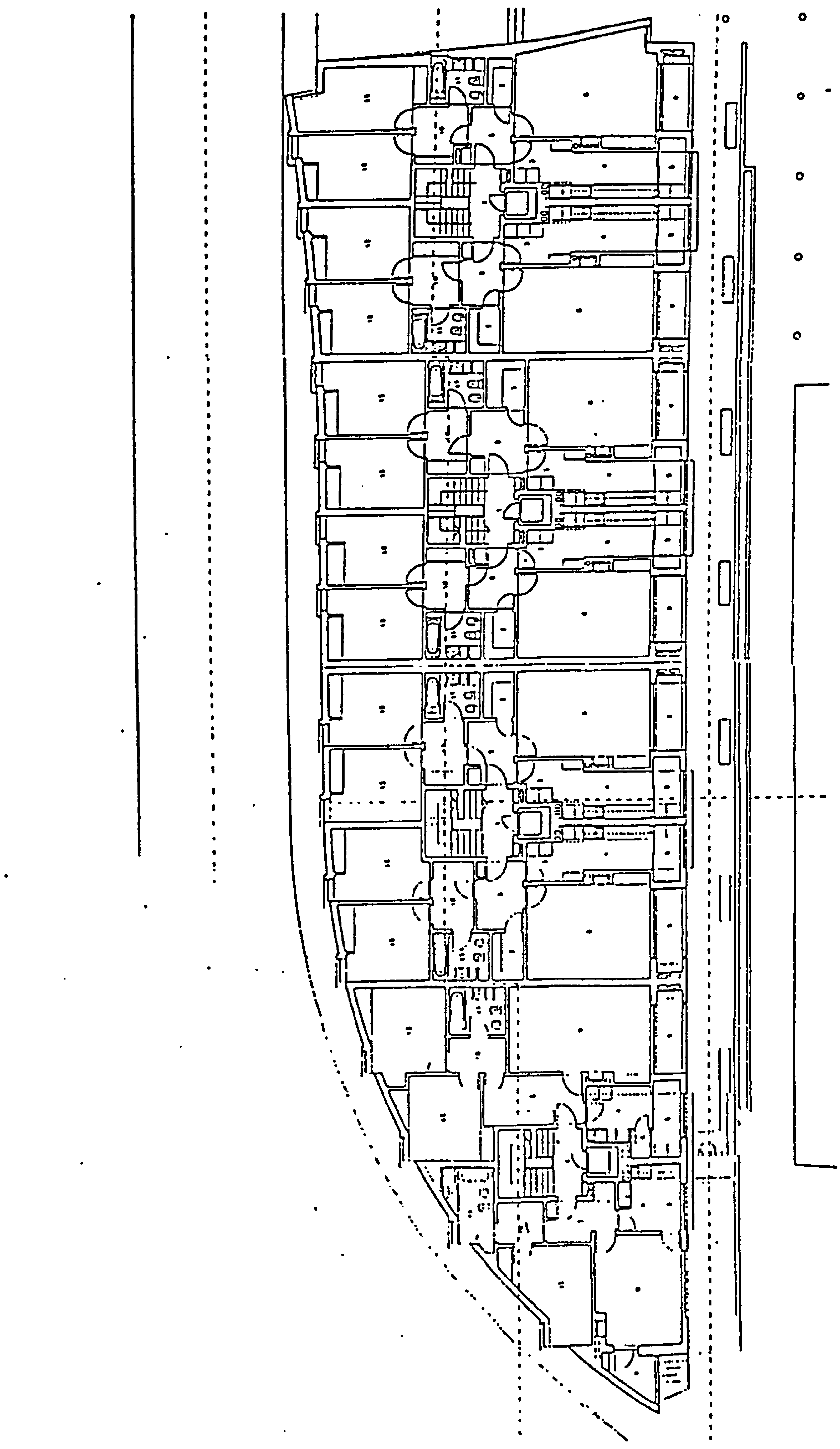
Legend: (from top to bottom) plan of the basement, plan of the ground floor, plan of the first floor.

Figure 113 - Dwelling D2 (continued).



Legend: east view and west view of the building.

Figure 114 - Dwellings D3 and D4.



Legend: plan of the first and top floors.

Figure 115 - Dwellings D3 and D4 (continued).

These dwelling designs were chosen so that they represent different classes of dwellings, namely houses (D1 and D2) and flats (D3 and D4).

D1 and D2 are different in that D1 is a two storey house located in Amarante (mild climate) while D2 is a three storey house located in Vila Real (severe climate). The construction solutions differ as well: D1 has no thermal insulation in the external walls while D2 has thermal insulation in the external walls (20mm expanded polystyrene). A lot of other less important details differ as well, as can be seen by consulting the tables and drawings.

D3 and D4 are flats in the same building, but located in different floors. While D3 is a first floor flat D4 is a top floor flat. This makes them very different from the thermal point of view, because top floor flats are heavily affected by the roof construction.

The houses (D1 and D2) have gas heating systems, while the flats (D3 and D4) have no pre-installed central heating (this heavily affects the electrical fittings system).

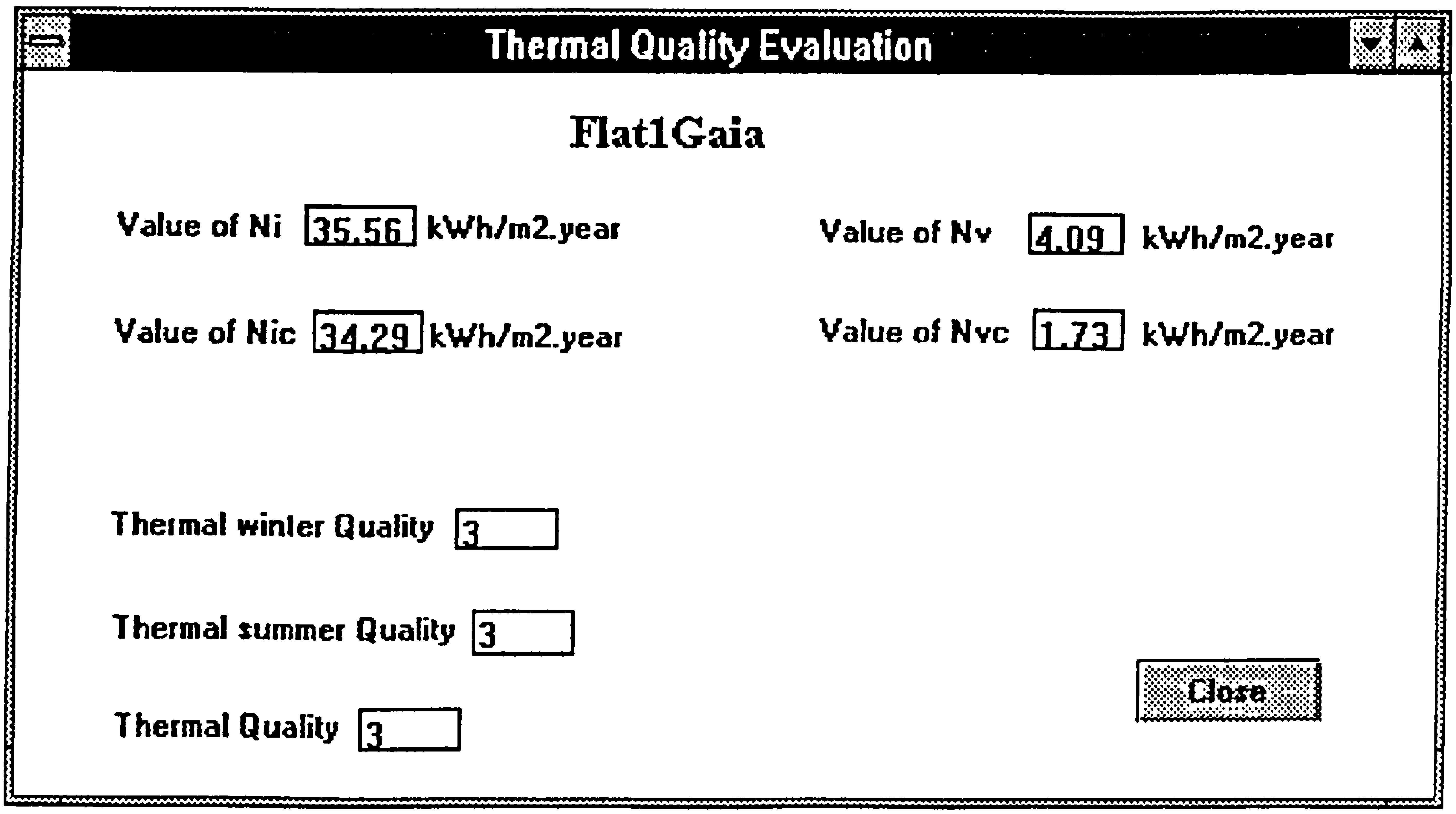
From the point of view of the close environment, the houses (D1 and D2) significantly differ between themselves (D1 is in the countryside, while D2 is in a residential development). The houses also differ from the flats (D3 and D4). It is worth noting, though, that the implemented prototype for the evaluation of the close environment, based in the SEL method, has been designed to be applied to flats; so, some of the criteria are not applicable to houses.

The screens with the results of the evaluation of the dwelling D3 are shown in Figures 116 to 118. These are shown to illustrate the interface of the prototype. The results for all the dwellings are presented in Figure 119. The evaluation of the thermal system and of the electrical fittings is expressed using a grade between 1 (poor) and 5 (excellent) for each criterion. The close environment criteria are evaluated using a grade between 0 and 4.

7.4.2.2 Comparison of alternative solutions

This set of tests consist of using the developed prototype to evaluate the quality of alternative design solutions for the a dwelling. The top floor flat in Vila Nova de Gaia presented in the previous section (D4) has been used for this purpose, using alternative solutions for the thermal system.

Five alternative solutions (S1 to S5) to the solution initially proposed (S0) have been studied. Figure 120 presents these solutions, in the aspects in which they differ from the initial solution (S0).



Flat1Gaia

Value of Ni 35.56 kWh/m2.year

Value of Nv 4.09 kWh/m2.year

Value of Nic 34.29 kWh/m2.year

Value of Nvc 1.73 kWh/m2.year

Thermal winter Quality 3

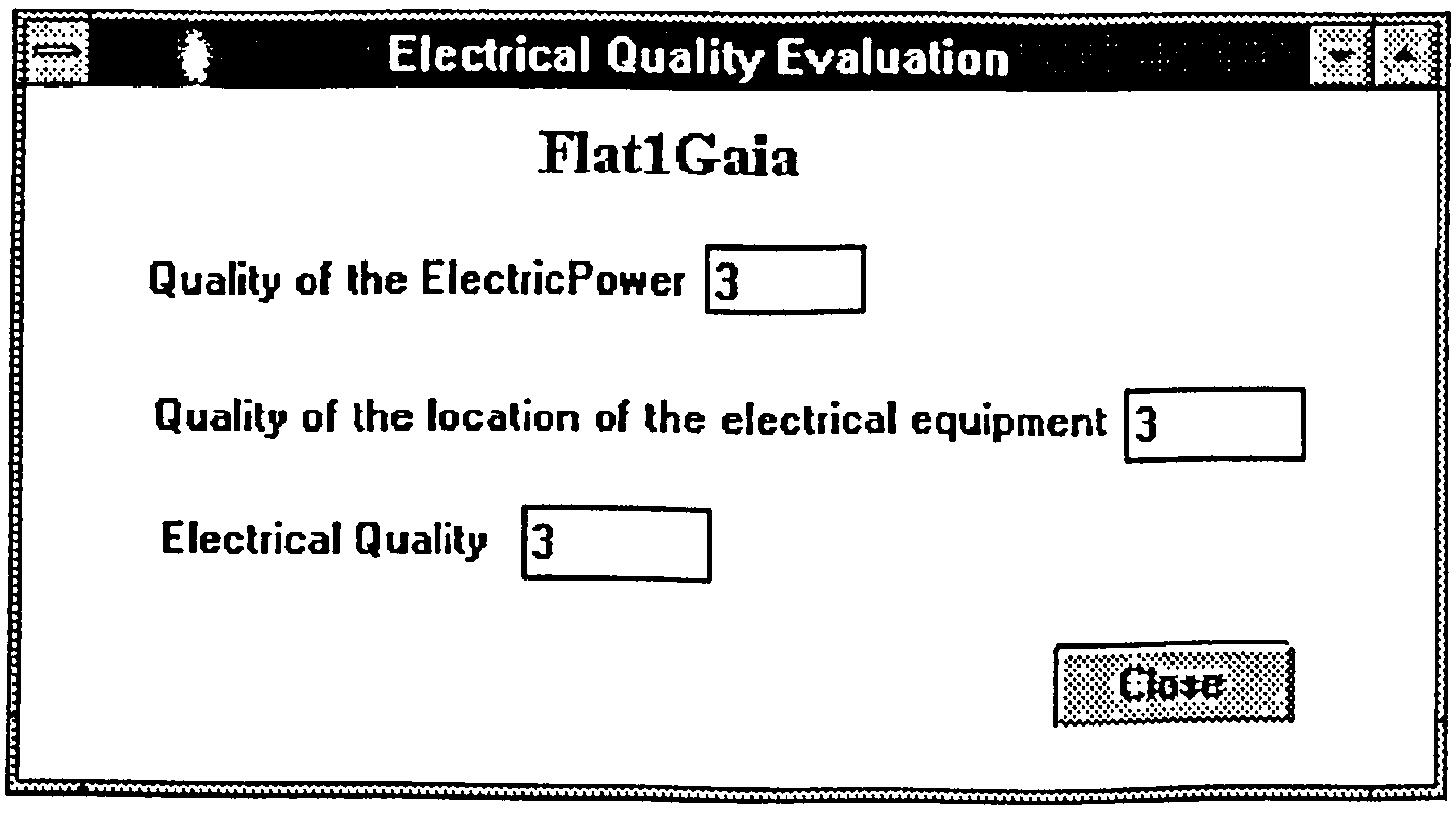
Thermal summer Quality 3

Thermal Quality 3

Legend:

Ni - reference value of the necessary energy per heating season per square metre of floor area;
Nic - value of the necessary energy per heating season per square metre of floor area;
Nv - reference value of the necessary energy per cooling season per square metre of floor area;
Nvc - value of the necessary energy per cooling season per square metre of floor area.

Figure 116 - Thermal system - first floor flat in Vila Nova de Gaia (D3).



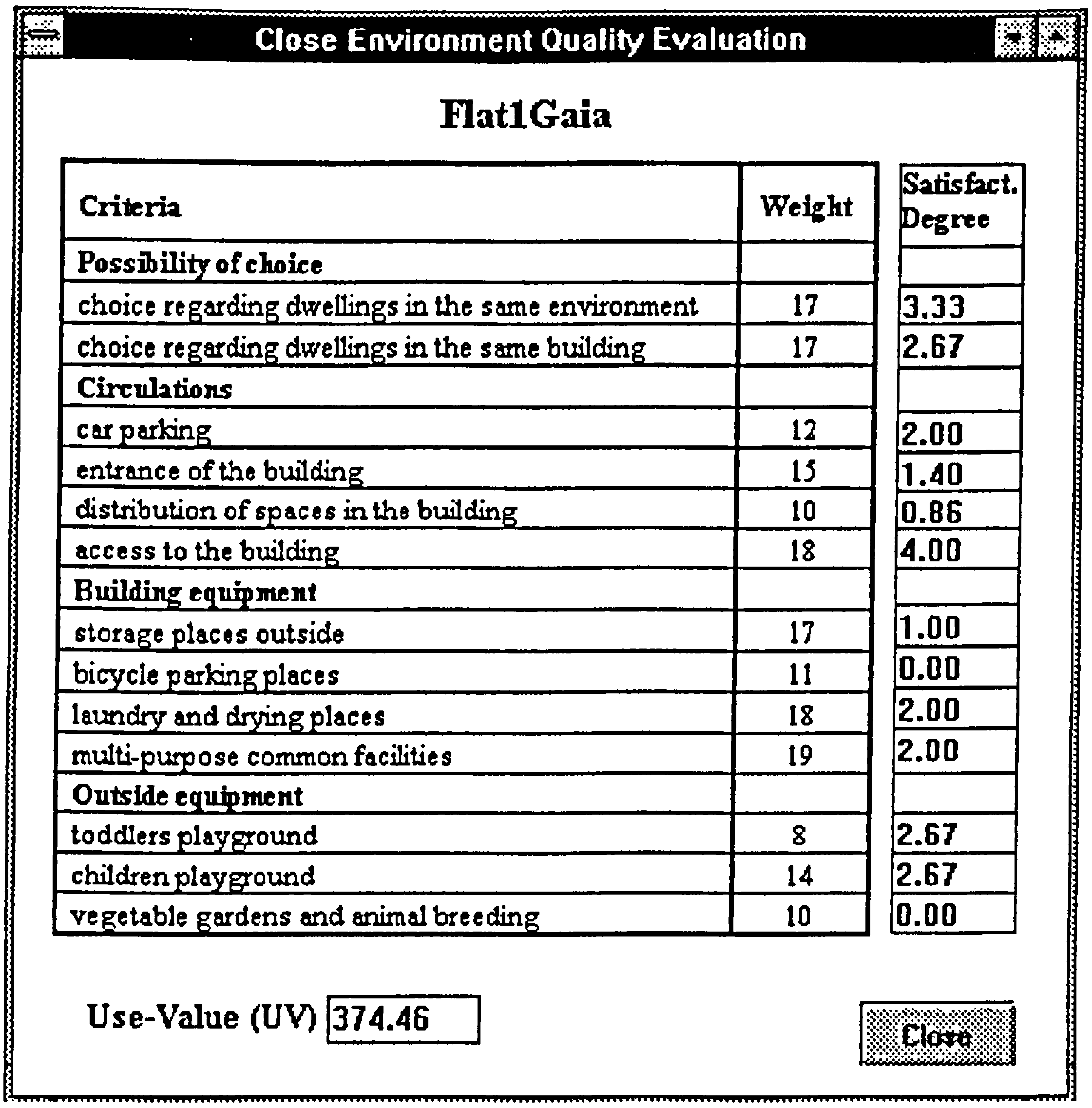
Flat1Gaia

Quality of the ElectricPower 3

Quality of the location of the electrical equipment 3

Electrical Quality 3

Figure 117 - Electrical fittings - first floor flat in Vila Nova de Gaia (D3).



Flat1Gaia

Criteria	Weight	Satisfact. Degree
Possibility of choice		
choice regarding dwellings in the same environment	17	3.33
choice regarding dwellings in the same building	17	2.67
Circulations		
car parking	12	2.00
entrance of the building	15	1.40
distribution of spaces in the building	10	0.86
access to the building	18	4.00
Building equipment		
storage places outside	17	1.00
bicycle parking places	11	0.00
laundry and drying places	18	2.00
multi-purpose common facilities	19	2.00
Outside equipment		
toddlers playground	8	2.67
children playground	14	2.67
vegetable gardens and animal breeding	10	0.00

Use-Value (UV) 374.46

Figure 118 - Close environment - first floor flat in Vila Nova de Gaia (D3).

Dwellings →	D1	D2	D3	D4
Thermal evaluation				
Ni (kWh/m2.year)	77.65	166.60	35.56	54.79
Nic (kWh/m2.year)	64.01	151.90	34.29	60.63
Nv (kWh/m2.year)	12.29	18.90	4.09	4.47
Nvc (kWh/m2.year)	10.78	22.90	1.73	2.05
Thermal winter quality	3	1	3	1
Thermal summer quality	3	1	3	3
Thermal quality	3	1	3	1
Electrical fittings evaluation				
electric power quality	5	3	3	5
electrical equipment location quality	1	5	3	3
electrical fittings quality	1	4	3	3
Close environment quality	not applicable	not applicable	see Figure 118	see Figure 118

Figure 119 - Quality evaluation of dwellings D1 to D4 using the QDF prototype.

Alternative solutions →	**S0 (original)**	**S1**	**S2**	**S3**	**S4**	**S5**
external walls	cavity wall with 20mm extruded polystyrene	cavity wall with 20mm extruded polystyrene	cavity wall with 20mm extruded polystyrene	cavity wall with 20mm extruded polystyrene	**solid wall with 40mm expanded polystyrene**	cavity wall with 20mm extruded polystyrene
semi-exposed wall	solid wall with no insulation	solid wall with no insulation	**solid wall with 20mm expanded polystyrene**	solid wall with no insulation	solid wall with no insulation	solid wall with no insulation
external roof	flat roof with 20mm of expanded polystyrene	flat roof with 20mm of expanded polystyrene	flat roof with 20mm of expanded polystyrene	flat roof with 20mm of expanded polystyrene	flat roof with 20mm of expanded polystyrene	**flat roof with 40mm of expanded polystyrene**
semi-exposed roof	flat roof with no insulation	**flat roof with 20mm of expanded polystyrene**	**flat roof with 20mm of expanded polystyrene**	**flat roof with 20mm of expanded polystyrene**	**flat roof with 20mm of expanded polystyrene**	**flat roof with 40mm of expanded polystyrene**
external glazed	single glazed with plastic frame	single glazed with plastic frame	single glazed with plastic frame	**double glazed with plastic unicellular profile**	single glazed with plastic frame	single glazed with plastic frame
semi-exposed glazed	single glazed with plastic frame	single glazed with plastic frame	single glazed with plastic frame	**double glazed with plastic unicellular profile**	single glazed with plastic frame	single glazed with plastic frame

Figure 120 - Alternative design solutions for D4 (thermal system).

The evaluation of the thermal quality of these solutions was obtained using the QDF prototype. The results are shown in Figure 121 and some comments on the results follow. Solution S0 is not in accordance with the regulation standards. If a designer is looking for a simple way of improving the solution in order to bring it up to the regulations standards, a simple change is to insulate the semi-exposed roof (because this element is not according to the regulations standards). This is alternative solution S1, which is in accordance with the regulation standards.

In order to obtain a better solution different improvements to S1 can be tried:

- **Insulate the semi-exposed wall**, solution S2.
- Change the **windows** from single to **double glazed**, solution S3.
- Change the construction solution for the **external walls** from cavity with insulation to solid walls with **external insulation**, solution S4.
- Improve the insulation of the **roofs** from 20mm to 40mm of **expanded polystyrene**, solution S5.

Alternative solutions →	S0	S1	S2	S3	S4	S5
Thermal evaluation						
Ni (kWh/m2.year)	54.79	54.79	54.79	54.79	54.79	54.79
Nic (kWh/m2.year)	**60.63**	**51.61**	**50.87**	**47.99**	**49.72**	**45.70**
Nv (kWh/m2.year)	4.47	4.47	4.47	4.47	4.47	4.47
Nvc (kWh/m2.year)	**2.05**	**2.05**	**2.05**	**1.88**	**1.77**	**1.95**
Thermal winter quality	1	3	3	3	3	3
Thermal summer quality	3	3	3	3	4	3
Thermal quality	**1**	**3**	**3**	**3**	**3**	**3**

Legend:
Ni - reference value of the necessary energy per heating season per square metre of floor area;
Nic - value of the necessary energy per heating season per square metre of floor area;
Nv - reference value of the necessary energy per cooling season per square metre of floor area;
Nvc - value of the necessary energy per cooling season per square metre of floor area.

Figure 121 - Results of the alternative design solutions for D4 (thermal system).

The results for these solutions are presented in Figure 121. For the thermal winter quality, the solutions can be ranked S5, S3, S4, S2. The best alternative (S5) is to increase the thickness of the insulation of the roofs. For the thermal summer quality the solutions can be ranked S4, S3, S5, S2. The best alternative solution (S4) is to change the construction of the external walls to solid walls with external insulation. The overall rating of solutions S5 and S4 is not very good, because they are not well balanced, i.e. only some of the elements have very good quality.

As mentioned before, a solution with a good quality needs to be well balanced. The following solutions are better balanced:

- Semi-exposed wall insulated with 20mm extruded polystyrene, 40mm expanded polystyrene in the roofs and double glazed, solution S6.
- As S6 but change the construction of the external walls from cavity with insulation to solid walls with external insulation, solution S7.

These solutions are presented in Figure 122, and the results in Figure 123.

The analysis of the results indicates that to achieve high standards of quality well balanced solutions are required.

Alternative solutions →	S0 (original)	S6	S7
external walls	cavity wall with 20mm extruded polystyrene	cavity wall with 20mm extruded polystyrene	**solid wall with 40mm expanded polystyrene**
semi-exposed wall	solid wall with no insulation	**solid wall with 20mm expanded polystyrene**	**solid wall with 20mm expanded polystyrene**
external roof	flat roof with 20mm of expanded polystyrene	**flat roof with 40mm of expanded polystyrene**	**flat roof with 40mm of expanded polystyrene**
semi-exposed roof	flat roof with no insulation	**flat roof with 40mm of expanded polystyrene**	**flat roof with 40mm of expanded polystyrene**
external glazed	single glazed with plastic frame	**double glazed with plastic unicellular profile**	**double glazed with plastic unicellular profile**
semi-exposed glazed	single glazed with plastic frame	**double glazed with plastic unicellular profile**	**double glazed with plastic unicellular profile**

Figure 122 - More alternative design solutions for D4 (thermal system).

Alternative solutions →	S0	S6	S7
Thermal evaluation			
Ni (kWh/m2.year)	54.79	54.79	54.79
Nic (kWh/m2.year)	60.63	41.82	39.93
Nv (kWh/m2.year)	4.47	4.47	4.47
Nvc (kWh/m2.year)	2.05	1.77	1.49
Thermal winter quality	1	4	5
Thermal summer quality	3	4	5
Thermal quality	1	4	5

Legend:

Ni - reference value of the necessary energy per heating season per square metre of floor area;
Nic - value of the necessary energy per heating season per square metre of floor area;
Nv - reference value of the necessary energy per cooling season per square metre of floor area;
Nvc - value of the necessary energy per cooling season per square metre of floor area.

Figure 123 - Results of the solutions S6 and S7 for D4 (thermal system).

7.4.3 Future tests

As referred to earlier, any theory can be falsified at any time. Positive results of the evaluation process carried out up to the time can only corroborate it. So, QDF will continue to be evaluated by the type of tests presented earlier.

There is however another set of tests, which are particularly relevant and which can only be performed in the long term. The process consist of different parties using the system, making decisions and providing evidence as to whether the evaluation turned out to be dependable or true, i.e. decisions correspond with the "facts".

These tests can be carried out by the different parties involved in the construction process, namely users, builders, architects, engineers, property developers, bankers, building societies, state agents and politicians. All these parties will use the system, base their decisions on the evaluation provided by the system and provide evidence to whether the evaluation corresponds to the "facts", i.e. turns out to be in accordance with the reality (as seen from their point of view). This is a long term process, because the delay between the use of the system and the corroboration (or not) by the "facts" may take several years.

Of special importance is the corroboration by the users. Quality is fitness for purpose and the purpose of a house is to be fit for people to live there. How fit has it been judged by QDF and how fit do the users, living in the house, find it to be? Are the "opinions" of QDF and of the users very different? In the view of the author this is the crucial test QDF has to stand for, in order to achieve a high degree of corroboration.

7.5 Summary

A strategy for the evaluation of QDF has been presented, based on the theory of scientific knowledge developed by Popper. The strategy has been used to perform a preliminary set of tests which corroborate that QDF is appropriate for the evaluation of quality of dwelling designs, as well as for comparing and selecting alternative design solutions. Only the use of the framework in the long term will provide the feedback needed for achieving an adequate degree of corroboration.

QDF has been compared with product modelling and with some models proposed in this context for buildings, the RATAS model and the AEC building systems model. It has been stated that these models, which have been defined without a specific purpose, tend to be too abstract for easy application. QDF is concerned with the evaluation of the quality of a dwelling. This requires a lot of information to be analysed, but with a well defined purpose.

A prototype QDF has been implemented. Tests have been run which indicate that QDF is general enough to cope with different quality evaluation methods and metrics. This makes QDF easily adaptable to different climate and social realities.

8. Conclusions and future work

8.1 Conclusions

1. A new approach for the evaluation of the quality of dwelling designs named **QDF** (Quality Dwelling Framework) has been proposed. In order to develop QDF a parallel between a form of a dwelling and a form of a **human body** was drawn. This is justified by the fact that the human body is the most sophisticated and highly developed form known. The methodology behind QDF is the **systems approach**. In QDF knowledge about a dwelling is organised in a hierarchical way, into systems, subsystems and components. Each of the elements in the hierarchy is both a system and a part of a larger system, i.e. a **holon**. Holons are modelled as **software objects** which interact with each other through an exchange of messages. In QDF the software objects contain models of quality.
2. QDF is an **important contribution to the raising of dwelling quality standards** (quality is used here in the sense of **fitness for purpose**). It provides a comprehensive framework to implement and develop different quality evaluation methods, specific to different countries and cultures. It is hoped that this will help all parties involved in the residential building industry, namely users, builders, architects, engineers, property developers, bankers, building societies, state agents and politicians, to agree upon quality standards tuned to the national or regional realities.

3: A strategy for the **corroboration of QDF** has been proposed, based on Popper's philosophy of scientific knowledge and on an extension of this theory proposed by Blockley in the context of risk analysis. QDF can only achieve a *high* degree of corroboration by testing it in **practice** in the **long term**, i.e. users will use the system, make decisions, live in a house; and then provide feedback as to whether the evaluation turned out to be dependable or true (i.e. decisions correspond with the facts). The process of evaluating QDF has been initiated by using a **prototype system** to evaluate different dwelling designs as well as different alternative solutions for the same dwelling design.

4: The **prototype system** has been developed using the programming environment KAPPA. The quality evaluation has been implemented for a thermal system (the metrics have been developed by Paiva and are based in the Portuguese thermal regulations); an electrical system (the metrics used are defined in the Qualitel method); and a close environment system (the metrics used are defined in the SEL method). The development of the prototype shows that QDF is suitable for implementing new evaluation methods, as well as methods which have already been developed. It also indicates that the complexity of modelling a dwelling in a comprehensive way can be further developed using advanced computer techniques which provide high storage capacity and fast processing. This can be achieved by using parallel computer architectures since QDF is naturally parallel. The developed model is based on the object-oriented paradigm where a collection of software objects interact with each other through an exchange of messages.

5: In order to develop QDF existing quality evaluation schemes have been identified and critically evaluated, namely the French method Qualitel, the Swiss method SEL, the NHBC warranty scheme in the UK and the Portuguese scheme, which is still in a development phase. The analysis of these schemes helped in identifying some important aspects of quality evaluation which were relevant for the design of QDF, namely the aspects to be evaluated, the evaluation criteria and the evaluation procedures to produce a partial or a global rating.

6: Modelling and design techniques and tools adequate for computer implementation have been studied and critically evaluated in order to develop QDF in a way which would be suitable for computer implementation. **Object-oriented** analysis, design and implementation techniques have been adopted, following closely the method proposed by Rambaugh and co-workers.

7: Recent developments in **product modelling** have been identified and critically evaluated, with more emphasis on the attempts at modelling buildings. Product modelling has been developed for the definition of a standard for the exchange of graphical and other product related data. Examples are the RATAS product model and the AEC building systems model. These models, which have been defined without a specific purpose, tend to be too abstract for easy application. QDF is concerned with the evaluation of the quality of dwellings. This requires the analysis of a lot of information but with a well defined purpose.

8.2 Future work

The framework has been developed having in mind the evaluation of quality of designs of dwellings (or other artefacts). This will enable designers to test the quality of different design solutions and choose them accordingly. A future development would enable a computer system to assist designers by giving automatic guidance in how to improve a given solution. Expert systems can be used for this purpose. Also machine learning schemes can be investigated.

The proposed framework is a methodology for the development of quality evaluation methods. When developing a method based on this framework for the evaluation of quality of dwellings in a given environment, e.g. country, the views of users on what attributes are important for quality evaluation in that environment must be taken into account. This will lead to the definition of a set of weights for the different attributes, according to their importance.

The framework can be extended to evaluate the quality of dwellings after construction, new and refurbished. This dimension would lead to **quality assurance**, which is of major importance to raise quality standards.

Economic aspects would be included, so that quality standards would be compared with the cost to obtain them.

The approach can be extended to other types of buildings, such as schools, industrial buildings and hospitals. It can be developed for any system, e.g. Elorduy (1995) is using it for evaluating the quality of water in cities.

QDF is a framework which can be instanciated with different methods. Further applications of this kind would enable the framework to be further tested and improved.

QDF provides a good way of structuring quality information concerning dwellings to develop databases of large numbers of dwellings. Such large databases would be useful for all parties concerned with building and would enable a quality selection mechanism (evolution system) to be more effective in the assessment of the quality of new solutions and in the refinement of the existing ones.

Finally, QDF could be extended for process quality evaluation, i.e. it could allow for the temporal dimension to be taken into account. The quality of a dwelling would be evaluated through its life cycle, from design until demolition and taking into account the evolution of the environment (e.g. construction of new roads, shopping areas, leisure areas, etc.). The methodology would be based on the synthesis of QDF with the IOPM (Interacting Objects Process Model) (Agarwal 1994). The IOPM consists of software objects which represent holons of physical processes and enable simulation of these processes.

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