Graphical Expression and Designing:

Cognitive Aspects of Drawing Operations in Design and Implications for Computerised Drawing Environments

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I hereby declare that I am the sole author of this thesis.

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Abstract

The thesis focuses on the relations between design drawings and design activity. It develops an approach to conceptual processes employed during designing and their impact on drawing operations, and examines the implications of this approach on the systematic representation of drawings in computerised environments.

The implementation of most computerised drawing systems relies on approaches that treat drawings as symbolic structures determined mainly by geometric knowledge. The thesis takes the view that drawing is an integral part of designing and it looks at: the role of drawn descriptions within conceptual activity aimed at design information; representational schemes developed for the formation and interpretation of graphical representations; and qualifications that such schemes exhibit during the accomplishment of design tasks. It argues that the ways in which design drawings are used reveal much of the knowledge used in designing, and it is this knowledge which determines the structure of drawings.

A theme throughout the thesis is the discussion of a case study concerning the development of a design project by students of architecture using a computerised drawing system.

Although emphasis is placed on drawing systems, the contribution of the thesis lies in its global understanding of the effects of design processes on drawings, and this understanding might be of interest to future advanced design systems incorporating graphical representations.

Prologue

The act of drawing has always been considered as an important component of design activity. Designers, through the centuries, have been firstly expressing their ideas about designed objects in drawings, in order to explore and evaluate them, before attempting to manifest these ideas in an actual built form.

However, the analysis of the features of drawings has not been the subject of many studies. Studies of drawings in design literature mostly concern techniques for the accomplishment of drawings,[1] methods for the effective use of drawings,[2] or perhaps the consequences that the use of drawings entails for designing,[3] rather than the qualities of drawings themselves.

Computer applications, aiming to facilitate the production of drawings, give us an incentive to consider design drawings and drawing operations. Precise accounts of the features of drawings are needed, upon which their systematic representation in computers should be based.

This thesis sets out to investigate the effects of design processes on drawing operations. It considers the constituents of design drawings, their structure and their attributes, and the qualifications on them that arise during the progress of design tasks. It is grounded on the assumption that computerised drawing systems have to take into account the manner according to which drawings are used, so as to provide drawing environments that match the expectations of designers. Considerations about the use of drawings do not seem to be involved in the implementation of the majority of

1 See, for example: Fraser Reekie, R., 1969.
2 As in: Porter, Tom, 1979.
3 For example: Laseau, Paul, 1980.

current drawing systems. These mainly confront drawings as distinct objects, disconnected from designing and conditioned by issues internal to themselves, such as geometry.

The thesis looks at drawings and drawing systems, but its main objective is to provide an understanding of the *relation* between drawing behaviour and design activity. Various aspects of this relation are discussed ranging from issues about the cognitive manipulation of drawn representations, and schemes developed for their interpretation, to functions of signification that drawings serve during designing, and qualitative aspects of techniques for executing drawing operations. Effectively, the thesis is an interdisciplinary study.

Background material occurs mainly in the first parts of chapters on distinctive issues affecting the making of drawings. Some emphasis is given to cognitive theories of representation, presented in the fifth chapter, and to the conditions that characterise the making of drawings in existing computerised drawing systems, in the sixth chapter.

The focus on the relation between drawings and designing entails certain implications for both the approach undertaken and the layout of the thesis. The thesis takes a descriptive approach to the constituents of this subject. It does not aim to put forward a new account of designing, neither does it introduce a new way of making drawings, in the form of a novel drawing system. This descriptive approach is exemplified by the examination of a case study of a design project by students of architecture using a computerised system. The case study provides a point of reference throughout the thesis.

Also, the above focus brings some inevitable circularity into the discussion. So we have aspects concerning designing discussed in relation to their manifestation in drawings, and drawing operations discussed in relation to designing. The case study helps to reduce possible difficulties arising from circularity, when reading the thesis.

The thesis progresses along a general direction from accounts about designing and the cognitive manipulation of graphical representations, to aspects of the systematic representation of drawings in computerised systems, and finally to the qualifications on structure that use of drawings entails. This progression is manifested in the arrangement of chapters.

The thesis consists of ten chapters. **Chapter 1** opens the discussion by examining early attempts at clear understanding of designers' modes of thinking. The description of these efforts is followed by observations of design practices. **Chapter 2** outlines the assumptions underlying the thesis and specifies its objectives and expectations. It also introduces the case study. The grounds for an approach to designing are set, taking into account drawings. **Chapter 3** estimates the factors that characterise the accomplishment of design tasks and the use of knowledge in design activity, by looking at behaviour manifested by designers. **Chapter 4** provides a characterisation of design processes in terms of cognitive operations. The role of representations within cognitive activity is related to the importance of drawings in designing. **Chapter 5** is a central discussion on representation and interpretation. Cognitive aspects of schemes of representation are presented, and the character and structure of graphical representation is discussed. Implications from this discussion begin to indicate how we should view computerised drawing systems. **Chapter 6** is a critical description of drawing systems. Issues on the features and use of computerised drawings are discussed and evaluated. **Chapter 7** presents an examination of the particular computerised system as used in the case study. The impact from the use of computerised drawings in the development of design tasks reveals some limitations of the system: imposition of mode of thought unconnected with designers' explorations of solutions. **Chapter 8** returns to the role of drawings in designing, with emphasis on spatial composition. This concerns the application of conceptual knowledge to spatial forms, and views drawings as intermediate stages between conceptualisation and realisation of spatial objects. **Chapter 9** examines how the use of drawings in designing determines their features. It looks at the functions that drawings serve for spatial composition, and the qualifications that these imply for their structure. **Chapter 10** relates conclusions back to the systematic representation of drawings in computers. It concludes the thesis with a discussion of possible directions in the development of future systems, to take into account the needs and expectations of designers.

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Contents

1. Early Accounts of Designing

Looking at early attempts towards the clarification of designers' modes of action, one can observe that the majority of them are characterized by designations of processes from requirements to optimum solutions, and specifications of objectives, variables, and criteria. The most courageous of these attempts also offer maps or sequences for moving from one state to the next and eventually to the design solution. A possible connotation is that designers work in a scientific problem solving manner, spending most of their time in studying and testing theories and methodologies, extracting tables and charts from analysed data, and estimating and rejecting alternatives, before they finally specify an ultimate solution which satisfies the requirements and expectations of their clients.

Yet, another look at the activities of practising designers leads to a rather different image. Designers hardly ever select methods that are going to be used in the accomplishment of their specific task before any attempt to accomplish it. They do not try to find objective criteria for testing their proposals. They superimpose their subjective agendas over the expressed requirements. Instead of examining tables and charts of carefully analysed data, they reflect utterances of thought in rough and sketchy graphical expressions. These expressions occur even before explicit specifications of problems. Designing stops not when optimum solutions are reached, but when designers run out of time or they judge that it is worthless to push matters further, in relation to their perceptions of given circumstances.

This chapter briefly examines early studies of processes and methods in designing, as well as efforts on employing computational techniques in design tasks. Through a comparison between these approaches and actual design practices, it attempts to provide some hints about their inadequacy in accommodating or modelling design activity. The chapter tries to establish a basis for discussion about design thinking that will be further developed in subsequent chapters.

1.1. Design Methodology

Over the past thirty years the activity of designing has attracted the attention of dedicated professionals who tried to make explicit the private thinking of designers, on the assumption that designers could thereby be made more efficient in addressing the purposes for which designs are made, and design outcomes would be more effective. By bringing designing into the open, other people and professions could contribute information and knowledge that lies outside the individual designer's experience.

Black-box Design Methods

Among the several approaches that appeared at the beginning of this trend, a small minority took the view that the most valuable part of designing is that which goes on inside the designer's head and out of the reach of conscious control. Designers, like other professionals, are capable of producing outputs in which they have confidence without always being able to say how exactly these outputs are obtained. Actions towards those outputs can be explained by the assumption that they are largely governed by a skilled nervous system without the intervention of conscious thought.

These theories were usually referred to as 'black-box' design methods. The main principles of these methods are summarised by Jones:

> 1. The output of a designer is governed by inputs received recently from the problem and also by other inputs received from previous problems and experiences.
> 2. His output can be speeded up, but made more random, by [periodic relaxation of] social inhibitions.
> 3. His capacity to produce outputs relevant to the problem is dependent upon his being given time to assimilate and to manipulate within himself images representing the structure of the problem as a whole. During a long and seemingly fruitless search for a solution he may suddenly perceive a new way of structuring the problem so that conflicts are resolved. This pleasant experience is the "leap of insight."
> 4. Intelligent control over the forms in which the problem structure is fed into the human black box is likely to increase the chances of obtaining outputs that are relevant to the design problem.[1]

[1] Jones, Christopher, 1970, p.5.

Glass-box Design Methods

Because of their 'mystical' position these approaches were discarded by the majority of theorieticians who, instead, became more concerned with externalised thought based on rational assumptions. The idea behind rational approaches was that designers work in a fully explicable manner, and the resulting theories were referred to as 'glass-box' design methods. They were viewing designers as human computers, persons that operate only on information that is fed to them, and follow specific sequences of analytical, synthetic, and evaluative steps towards the attainment of solutions.

Such methods were based on the assumption that design problems can be well defined and divided into smaller sub-problems that can be solved either in parallel, where sub-systems could be independent to each other, or in series, where the output of one system is used as an input to another. As indicated by Jones, 'glass-box' methods accept that in design tasks:

> 1. Objectives, variables, and criteria are fixed in advance.
> 2. Analysis is completed, or at least attempted, before solutions are sought.
> 3. Evaluation is largely linguistic and logical (as opposed to experimental).
> 4. Strategies are fixed in advance; these are predominantly sequential but often include parallel operations, conditional operations, and recycling.[1]

Early Computer Applications

By clarifying design processes, design methods, in particular 'glass-box' methods, were making the introduction of computers in design practice possible. Indeed, the relationships between a number of methods and computational accounts of problem solving were apparent. Thus, a variety of computer applications to design appeared, ranging from programs calculating and analysing quantitative tasks to systems generating layouts on the basis of area requirements.[2]

The development of computerised tools for the designer, while initially based on descriptive accounts of design activity, very early began to show an emphasis on prescriptive methods. In order to make the use of computers in design more effective, there was a concern about: the cutting down of the context within which design problems occur by theoretically determining its constituents; the hierarchical organisation of the components of design tasks; the introduction of strict maps of

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1 Jones, Christopher, 1970, p.6.
2 Examples of such applications can be found in: Mitchell, William, 1977.

sequences of operations in designing; the explicit definition of objectives to be fulfilled and criteria for evaluating alternatives.[1]

As a whole, the majority of these approaches were referring to the search for ultimate solutions within strict contexts which were assumed fully explicable, lacking accounts about general patterns of designing. Based largely on theories adopted from other disciplines, computer applications and corresponding design methods might have illuminated and helped the accomplishment of certain design tasks, but generally they failed to capture the essence of design activity and, more importantly, the relation of this activity and the objects that it produces to society and people that interact with them.

Design Methods and Designers

As a possible consequence of these weaknesses neither design methods nor early computer applications to design were fully embraced by the majority of practicing designers, particularly in the field of architectural design. A very small number of buildings were built following principles of design methods as they were originally introduced.[2]

Design methods might generate a concern about issues studied by scientific disciplines, and in particular the social sciences, related to how people perceive, use and feel about designed artifacts. Yet, these methods were incorporated in designing in individual, idiosyncratic ways, rather than 'participation programming' and 'behaviour modelling' as the advocates of design methods would have expected. Design practice still continues to work outside the enterprise of rationalisation and computability of design decisions. Similarly, so does the main stream of design education and criticism.

1.2. Design Practice

In order to access the mode of action which characterises designers, it would be interesting to examine how the issues that were primarily addressed by design methodology are reflected in design practice. Indications about the purpose for which design objects are produced, about the intentions of designers to make valid

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1 See the criticism of early attempts towards the modelling of design processes in computers in: Archea, John, 1986.

2 One of the most notable examples of attempts to directly apply principles of design methodology to the designing of actual buildings can be found in the case of Eugene Campus of the University of Oregon. This case is described in: Alexander, C., et al, 1975.

contributions to people who interact with them, will provide some clues about the nature of design tasks and the role of established knowledge and information in the accomplishment of these tasks.

Tasks and Problems in Design

Designers, in contrast to scientists, are not asked to develop methods for the description and analysis of phenomena and the conditions that determine them, but primarily to produce solutions. For a particular designer what matters is not so much the process towards an output but the output itself. Problems emerge during the evolution of designed objects, and they do not exist as such beforehand. They are closely related to the conditions insinuated by a specific object, and distinct objects within particular design fields are often associated with distinct problems. Accordingly, different design disciplines are not distinguished by differences in the processes that are applied to the evolution of design tasks but by differences in the kinds of objects they produce. Thus, a product designer is differentiated from an architect by the artifacts they produce and the efficacies achieved.

The conditions which are associated with a particular class of objects direct the approaches that distinct design disciplines follow in order to handle them. Objects produced by designers engaged in a specific design field are recognisable for some distinctive knowledge that is exploited in their development. This knowledge is often associated with technology or the use of materials; an architect, for example, would have a different way of handling timber in a building, compared with the way that a furniture designer handles timber in the case of a chair.[1]

It is generally assumed that a shared body of knowledge characterizes distinctive disciplined fields and marks the actions performed when it is applied to the procedures for moving between different states within design tasks. However, when knowledge is connected with actions towards solutions, the intentions of individual designers and disciplines have to be taken into consideration.

Innovative and Evolutionary Design

Design fields do not all share common intentions for the designed artifact. In product design, for example, the interest is usually much more concentrated on the appearance of objects, rather than radical changes in the functionalities they offer and

1 See the discussion on the components of design problems and their relation to design disciplines in: Lawson, Bryan, 1980, pp.38-43.

the technology they encompass. In engineering design, on the other hand, the emphasis is given principally to function and technology. A distinction that can be drawn, in terms of the kind of activity in which a design field is engaged, might concern *evolutionary* and *innovative* design. Evolutionary design relates to the development of new products evolving from existing ones, while innovative design has to do with fundamental changes in the creation of objects, in the area of the functional suggestions, the technological achievements, the aesthetic propositions, and so on.

In some respects, design disciplines can be seen as employing both modes of action. In product design, for example, which is largely prescribed by the standards that previous products set and is usually characterised as evolutionary, there is the case of the Walkman by Sony, an innovative design that has gained public acceptance.[1]

Yet, for some design fields, innovation seems to be far more apparent in leading design intentions. Architectural design, in particular, concerns buildings which can never be well defined as they are determined by the people who live in or otherwise use them. People's changing perceptions and needs entail new expectations and demands that buildings have to satisfy. Innovation, within this domain, plays an important role in orientating designers to perceive unspoken demands and express them in buildings. In architectural design, innovation is made up "of a sense of purpose, a route to a solution that is unexpected and unrepeatable, and a result that is ... recognised as valid".[2]

Reflective Practice

Architects work in a domain largely influenced by the information of some specific context. They act according to the circumstances presented by the given client, at a given point in time.

The ability of architects to perceive and translate demands is largely based on their integrated response and their insightful judgement. Schon draws a parallel between the attitudes employed by an architect and those of a psychotherapist. Although the former deals with place contexts and the second with person contexts, both attempt to discover the circumstances presented by single cases. Both focus on the conditions existing here and now, including instances from the past and

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1 See the discussion on evolutionary - innovative design and the use of computers in: Tovey, Michael, 1989.

2 Bijl, Aart, 1989, p.63.

anticipations for the future. They negotiate acceptable interpretations and courses of action by juxtaposing them with the circumstances of the given context.[1]

Architectural Education

The specific spatio-temporal context, within which architectural objects occur, involves social, political, organisational or psychological issues, individualised as they are addressed by particular clients. The demand on architects to respond and contribute to these individual issues implies sensitivity and ability to cope with a wide range of uncontrolled variables.

Correspondingly, in architectural education, studio work promotes these sensibilities by addressing design tasks through a form of role-playing, instead of articulating how design presumably occurs. It encourages students to develop their own point of view about architecture, by stimulating them to use the information from explored temporary or historical proposals on the peculiarities of their specific context.[2]

Established Knowledge, Intuition and Design Activity

We come now back to our earlier assumption that a shared body of expert knowledge supports and demarcates the actions performed by distinctive disciplines and professionals.

Established knowledge, developed mainly by theorists in contrast to practitioners, can be seen as a body of theories, methods, scientific propositions, extracted from analysed cases of past experience and largely neutralised and normalised to take account of the conditions of a great number of different occasions. When knowledge is applied to actions directed at specific situations it is rigorously specified to meet the issues underlying them.

Furthermore, as we have seen, the innovative character of architectural design places great significance on the subjective intentions of individual designers, which play a leading role in the execution of actions. Designers, becoming amenable to people's demands and concerns, are obliged to contribute to valid and persuasive answers. Their actions, grounded in aims and intentions, cannot be normal and

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1 Schon, Donald, 1983, pp.128-167.

2 A survey into current problems in architectural education in relation to the changing role of the architect within society can be found in: Gutman, Robert, 1985.

neutral. They are intrinsically oriented towards the future, confronting uncertainty. They involve much more than definite established knowledge from the past.

The dynamic state of designing converts generalised and even consistent knowledge into a forceless base for verifying practices. It is a state of mind where knowledge is in fact derived from actions rather than supporting them, where designing becomes a form of learning: "The kinds of knowledge we develop and the ways in which we develop it are very much the product of our interests and our activities."[1]

To cope with the uncertainty, designers are directed to embrace less objective and explicit but more attentive and compelling means of speculation in order to confirm their attitudes. We can refer to such kinds of inner and implicit thought as intuition.

Intuition is essential to human functioning. It relies on beliefs and sensibilities and cannot be fully explicated, or assimilated to the model of discursive reasoning. It operates beyond the limits of rational thinking.[2] As it involves emotional persuasion, it takes into account ethical values and increases designers' sensitivity in perceiving hidden preferences and unexpressed demands of people at whom designs are addressed.

Intuitive responses refer to actions whose relationships with the presented circumstances cannot be explained rationally and verified by objective knowledge, but still might be justified by silent agreements within people. They provide the connections between general established knowledge and the issues underlying the circumstances, or better, they transform existing knowledge into new forms of self-knowledge applicable to the specific conditions from where it is derived: "Even though professionalized, we are still fundamentally human; we develop theories as part of being rather than mere knowing."[3]

Correctly then, architectural education promotes these sensibilities by stimulating students to develop their own view on architecture instead of just supplying them with accurate objective knowledge. The success of architects, and practitioners of any discipline which interacts with people, is importantly dependent on

1 Bolan, Richard, 1980, p.261. For a discussion on knowledge as a result of interests and activities see: Habermas, Jurgen, 1972. Also: Barnes, Barry, 1977.

2 See: Kaplan, Bernard, 1970.

3 Bolan, Richard, 1980, p.264.

their responsible use of intuition to supplement established knowledge and skills in operating with this knowledge.[1]

1.3. Summary

Early approaches on designing, and computer applications that have followed them, have established an era of thought about designers' mode of thinking. Yet, their ambitious effort to fully clarify and model design processes was based on the externalisation and rationalisation of design knowledge and prescriptive accounts of design activity. By generalising and neutralising design actions, they underestimated the time and context specific conditions within which design objects occur and failed to realise the delicate relations between design actions and people.

A look at the practices of design disciplines suggests that knowledge in design cannot be objective but is necessarily in a state of continuous change. This is related to the specific contexts within which design occurs and to the changing perceptions of people who interact with design artifacts. Designers have to answer to the human needs of people to whom they address their objects and this responsibility leads them to rely on more sensitive modes of response than rational thinking according to established knowledge.

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[1] Bijl, Aart, 1989, p.62.

2. An Example from Architectural Design

The examination of early approaches to designing and their comparison with design practices, motivates us to move away from deterministic accounts about design activity. Yet, since our interest is in computerised systems that support designing, it seems that some account of the way designers address design tasks cannot be excluded.

This thesis attempts to develop a descriptive view of the processes developed during the evolution of design tasks by focusing primarily on the examination of the externalised utterances of thought in designing, principally in the form of graphical expressions. Assumptions about the design knowledge that supports the accomplishment of design tasks, and the operations by which it is applied, are construed on the basis of observations of design expressions. Similarly, the computerised systems upon which we place emphasis are mainly those which support the realisation of design descriptions.

In order to avoid formal restrictions on the context within which design tasks occur, the discussion about designing and its relation to graphical expressions develops on the basis of empirical investigations of a real design situation, a case study that attempts to incorporate most of the factors that underlie the actual designing of objects. The case study has as field of reference architectural design and involves design projects completed by four fourth year students of architecture.

This chapter describes the methodology used in the investigation and the conditions underlying the case study. It also discusses its relation to the issues addressed by the main approach of the thesis, the assumptions upon which generalisations are based, and the expectations about the results.

2.1. Towards an Account of Designing

Design Expressions

Most of the exploratory activity in designing towards the solution of a given design task is realised through the use of drawings and other graphical or textual expressions. In fact, design expressions are the most profound manifestation of this activity, and they are so inseparably bound up with it that drawing becomes equivalent to designing.

The thesis makes the assumption that the realisation of design expressions, the means of their accomplishment and the manner according to which they organise information, reflects much of the conceptual activity in designing. Design expressions serve as a means for the external representation of knowledge and information, and as a vehicle for reviewing and transforming this information into spatial forms. Based on this assumption, the thesis focuses on the examination of design drawings and their role in designing and suggests that an account of the operations that underlie their accomplishment effectively and comprehensively describes design activity.

The emphasis on design expressions is also increased by our general concern about computerised systems that can help designing. Linguistic or graphical expression seems to be dependent on certain theories and rules that we employ for their accomplishment and interpretation. As the technology of computers relies on logical and systematic structures, considerations about the logic behind expressions describing design will contribute to accounts that can be applied to the development of systems that support their formulation.

Information Processing

Based on the general assumption that drawings are the manifestation of design activity, designing is regarded as a progression through different states of knowledge and information as these are represented in design expressions.

The emphasis on processes concerning information and knowledge is motivated by recent research in Artificial Intelligence and Cognitive Science on human cognitive behaviour encountered in problem solving operations. One of the most comprehensive studies on the subject is the work of Newell and Simon, which provides an information processing theory as an abstract model to understand, measure and represent human behaviour.[1] Their ideas, especially on ill-structured tasks and problems, departing from the orthodox view of problem solving, have been found relevant to design tasks, and influence a number of approaches to design activity.[2]

Design, under an information processing model, can be seen as the task of transforming an initial, partial and incomplete description of an object into a more accurate, full and complete one. This transformation is accomplished by the application of information and knowledge.[3] The generality of the definition does not compare designing to problem solving activity any more than to thinking activity behind other human behaviour. Furthermore, as it recognises design descriptions as fundamental components of designing, it can form a basis for further discussion. However, it does not specify the substance of the transformation process, and more importantly this transformation from linguistic descriptions into spatial ones which seems to absorb essential effort in designing. It will be suggested that drawings in particular, as representations of states of information, provide a powerful environment for the accommodation and activation of operations aimed at the transformation of conceptual entities into spatial forms, the task which differentiates designing from other abstract thinking activity.

It has to be noticed that the concentration on design expressions suggests an approach that will be descriptive in itself, in the sense that the thesis will try to offer a plausible account of processes that might or could have been employed, and not all-inclusive, in the sense that it will not try to predict all possible attitudes, in different cases. However, the descriptive approach promises wider applicability in contrast to the prescriptive accounts of the early approaches on design methodology.

2.2. The Case Study

Assumptions and Description

Architectural design is usually referred to as a rather complicated activity in which an often large team of professionals collaborate to develop design proposals. Yet, in studies of design processes the common attitude is to decompose this activity

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1 Newell, Allen & Simon, Herbert A., 1972.

2 See, for example: Heath, Tom, 1984; Akin, Ömer, 1986.

3 Lansdown, John, 1986, pp.120-121.

and focus on parts, stages, or tasks, in order to make contact with experiments or simply to study particular aspects independently, and later estimate their importance and relation to design as a whole.[1] As such, they go deeply into problems concerning those aspects and contribute to some understanding of their internal mechanisms and implications.

Without denying the validity of such approaches, this thesis adopts the less common attitude of looking at the overall design activity and focusing on particular aspects of it occasionally.[2] The reasons for this attitude are a) it concerns design expressions, and especially graphical expressions, which are evident throughout design practice, and, in consequence, b) considerations about how the factors that apply to particular constituents of designing might negatively influence further ones which relate to design expression.

The principle objective behind this choice is based on the assumption that an integral and comprehensive approach to design drawings should focus on the role of drawings in designing, rather than considerations of their production. The intention is to contribute to the global understanding of the connections and relationships between different aspects of graphical expression.

According to this objective, a case study was conducted concerning the design of a small research centre on an island. The case study was accomplished with the help of four students of architecture in their fourth year, as part of an educational programme of the university, undertaken over four months. The students were asked to complete the project using computerised tools, drawing and modelling systems, but when these tools were found to be inappropriate they could use the traditional drawing board.

The brief presented to the students can be seen in *Figure 2.1* and the map of the island (~1:3000) in *Figure 2.2*. The brief, together with the map, describes the needs of a hypothetical client and provides some information about the client's practices and about the island. However, more than merely describing, it stimulates the students to think about the presented situation and aspects that relate to it.

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1 Examples of such approaches can be found in: Eastman, Charles, 1970; Freeman, P. A. & Newell, A., 1971. For a series of several experiments examining specific aspects of designing see: Akin, Ömer, 1986.

2 An approach which describes designing in its broadest sense can be found in: Krauss, R. I. & Myer, R. M., 1970.

A Brief for an Environment Centre on Cramond Island

While public interest in green issues is high it is worth thinking about what will happen after media attention has shifted elsewhere. One thing is certain: the need to preserve and nurture our natural environment is here to stay. But to sustain high levels of awareness and to promote increased understanding of the environment requires a commitment to continuous study and education. This is a brief for an education and research centre which would demonstrate an investment in built form to continued repair, maintenance and preservation of the earth's most precious resource.

For this design exercise we have chosen the environmental trust Greenpeace, who are at the forefront of the green movement, as notional clients for the building. Greenpeace will be principal tenants of the building, and will be responsible for operating and managing it. However, since they will be unlikely to use the whole building all year round we can expect them to make the facilities available to other organizations with similar interests. The brief, therefore, is to design a medium-size building which will enable Greenpeace and others to publicise their work in exhibitions, and through talks, conferences and seminars, and to conduct small-scale research projects.

The site is on Cramond Island in the Firth of Forth. Normally the island can only be reached on foot at low tide, but it is assumed here that a single-track road will allow vehicular access from Cramond foreshore to the proposed development at the same times.

The table below is a schedule of accommodation. Areas, where specified, should be taken as rough guides.

	Space	Area (m2)	Notes
	Lecture theatre	150 people	raked seating
	Exhibition space	100	
	Café/catering facilities	50 people	but occasionally for as many as 150 people — other spaces may be used to accommodate overspill
2	Laboratories	each 35	
	Library	40	
2	Seminar rooms	each 15	
4	Administration rooms	each 20	
20	Bedrooms + facilities	each 12	
	Warden's flat		
	Reception		
	Toilets and Cloakrooms		
	Workshop/garage	40	

The development should also include a landing stage or jetty to allow access by boat.

The building presents a challenge insofar as it will seek to celebrate nature and Greenpeace's work, and yet should not diminish the trust's reputation for caring for the environment through insensitivity to the natural beauty of this prestigious site — Cramond Island is a popular local beauty spot and a favourite route for walkers. Obviously the building should reflect concern for natural resources through energy-efficient design and careful choice of materials.

Figure 2.1

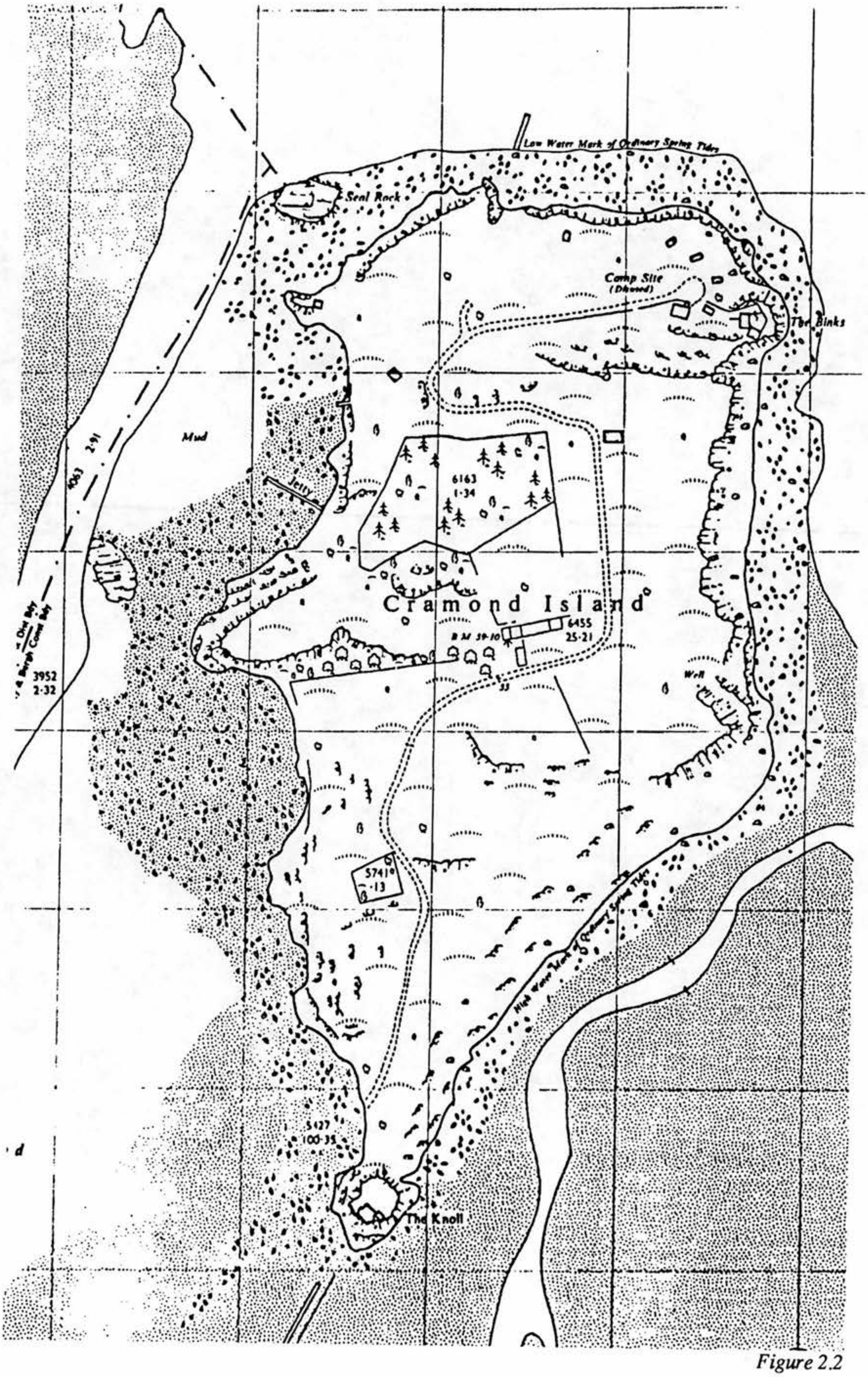
Low Water Mark of Ordinary Spring Tides
Seal Rock
Camp Site
(Disused)
The Binks
Mud
Jetty
6163
1·34
Cramond Island
6455
25·21
Well
3952
2·32
5741
·13
High Water Mark of Ordinary Spring Tides
5427
100·35
The Knoll

Figure 2.2

As indicated by the brief, the case study was chosen to be a real design situation, involving most of the conditions that underlie the development of design tasks. As such, the students, being in their fourth year and having training experience with practitioner architects, have gained sufficient knowledge of designing. Also, they had to face a brief addressed by Greenpeace, an institution with well known views about the environment, as strong as the views often imposed by individual clients. It was assumed that these views included a bias towards energy efficient design.

However, there were some conventions, similar to the conventions met in design projects in schools of architecture, which had to do with the fact that the project would not have to go through the phase of construction, and the corresponding stage concerning production information. There was some freedom given to the students: there were no particular building regulations, they could interpret the given requirements, they could choose the type and the location of the building on the small island site. These were found acceptable for the case study as they would allow the observation of individual responses and attitudes to the presented information. The major differentiation from the majority of actual design practices was the involvement of computerised systems.

Expectations

The students were asked to use computerised tools in the accomplishment of drawings in order to observe the impact of formal techniques in design expression. When they undertook the project they had sufficient training in using computers and the particular systems. In consequence, their choice to fall back on handmade drawing was expected to be directed by complications in the use of the computerised environments in particular design situations, rather than by difficulties in the apprehension of their functionalities. The study of these situations would lead to conclusions about the application of computerised techniques for particular drawing operations.

However, the thesis does not primarily aim to discuss the functionalities of computerised drawing systems and compare them to traditional environments, although parts of the thesis will do this incidentally. It rather tries to develop an account of graphical expression in designing in general. As such, drawings by the students, made either in the traditional manner or using computers, are used as distinctive examples in discussions concerning particular issues about design expression. For the same reason such discussions are also enriched by examples of drawings by other designers.

The primary expectations are to observe modes of exploring given information, ways of reviewing existing knowledge, and means developed for the organisation and representation of information. The thesis is expected to contribute towards a comprehensive account of the operations that underlie the accomplishment of drawings, as they are prescribed by design, leading on to consequences about the use of computerised modelling environments within design activity. As such, it attempts to develop a mapping between different theories related to the issue of representation, from such fields as cognitive psychology, semiotics, computer science, geometry, etc., brought into the context of design and graphical expression.

Method of Investigation

In accordance with the objectives just described, the data collected include the whole series of textual and graphical expressions from each of the students, and written records, resulting from close attendance to the whole episode, of the actions undertaken. Because of the extended length of the case study, the whole range of activities was found difficult to record objectively, as the students used also to work outside the design studio (home, libraries, etc.) and beyond the specified period of time for each day. As such, the records of activities are largely based on discussions with the students. However, as will become apparent later, primary emphasis is given to the textual and graphical expressions.

Notes, texts, drawings, etc. are not initially distinguished from each other but they are generalised as 'instances' of design expression. They are organised into 'sequences of instances of expression'. Similarly, activities are organised into 'sequences of actions'. An abstracted and summarised extract from student A's sequence of actions can be seen in *Table A.1* of Appendix A. Textual or graphical expressions are also indicated as 'instances' on the table. A representative part of the textual and graphical expressions of the students can be found in Appendix B.[1]

Sequences of expressions and activities are used for observations on trade-offs between drawings and design intentions, knowledge, and information. As such, the content of each particular drawing is placed into context and is connected to the

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1 The captions of particular drawings are numbered in correspondence to their occurrence in the sequence of instances of expression rather than their sequence in the presentation.

conditions that underlie its accomplishment. This results in 'maps of design expressions' which can be regarded as the reflection of the design activity as a whole in the drawings by the students. The diagrams corresponding to maps of design expressions are shown in *Table A.2*, *Table A.3*, *Table A.4* of Appendix A. *Figure 2.3* is an extract from student A's map of design expressions.

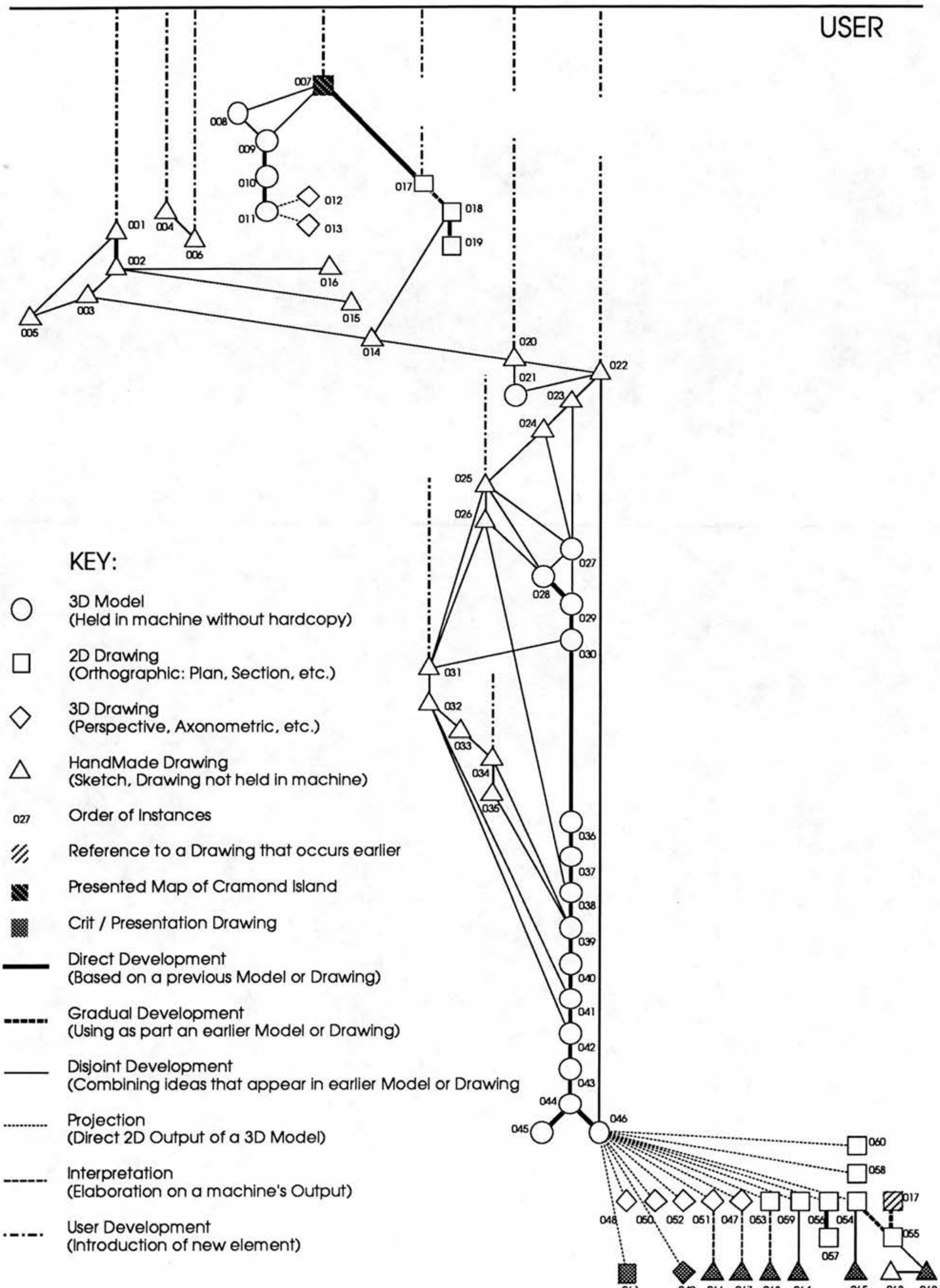
Drawings are differentiated in the diagrams according to whether they were made using the computerised systems or in the traditional manner. Handmade drawings are not differentiated and include sketches, diagrammatic drawings, and textual notes. Computerised drawings are distinguished into three dimensional models, two dimensional orthographic drawings, and three dimensional drawings which are in fact two dimensional drawings conveying three dimensional information, such as perspectives and axonometrics.

There is some distinction with respect to the computerised drawings, which relates to the specific way according to which the particular modelling system used organises drawings and models. Thus, three dimensional models exist only in the memory of the computer. Drawings can be either outputs of the three dimensional model (most of the three dimensional drawings fall into this category) or distinct drawings not directly connected to the models. In both cases, they have to be firstly separate computer files, keeping the information for the drawing, and then hardcopies. For this reason, while all instances of handmade drawings refer actually to individual sheets of paper, none of the computerised drawings refers to hardcopies. Instances of computerised models or drawings refer to individual files.

Computer files, for both models and drawings, are treated by the students like sheets of paper. In other words, the students were advised to use a new copy of a file when they wanted to introduce a major change in the development of the project, just as they would have to use a separate sheet of paper if they were using a drawing board. Consequently, it is possible to have in the diagrams several three dimensional models in a sequence without the presence of two dimensional drawings.

All individual instances of computerised models or drawings in the maps of design expression are files that the students decided to treat separately without any intervention by tutors (and the author of this thesis). Work with particular files is recorded, for reasons of both analysis and presentation, by means of 'screen-dumps'.[1]

[1] Snap-shots of the screen that capture all the information that is currently displayed.



USER
KEY:
3D Model
(Held in machine without hardcopy)
2D Drawing
(Orthographic: Plan, Section, etc.)
3D Drawing
(Perspective, Axonometric, etc.)
HandMade Drawing
(Sketch, Drawing not held in machine)
027 Order of Instances
Reference to a Drawing that occurs earlier
Presented Map of Cramond Island
Crit / Presentation Drawing
Direct Development
(Based on a previous Model or Drawing)
Gradual Development
(Using as part an earlier Model or Drawing)
Disjoint Development
(Combining ideas that appear in earlier Model or Drawing
Projection
(Direct 2D Output of a 3D Model)
Interpretation
(Elaboration on a machine's Output)
User Development
(Introduction of new element)

Figure 2.3

Screen-dumps were performed periodically, approximately every twenty minutes. Hardcopies of computerised drawings are ignored if there is no evidence of manipulation of them. In other words, they are treated as displays on the screen. If there is some manipulation, this would be by means of manual editing and effectively they become instances of handmade drawing. It should be noted that the diagrams include as an instance the map presented to the students, but not the brief. This was decided because there was evidence of elaborations directly based on the information of the map, while the brief was taken to be stimulative and the students interpreted the requirements of the brief in their own textual notes.

Distinctions with respect to the processes by which different drawings are related to each other are kept to a minimum and they result from analysis of the information conveyed by the drawings, and connections to corresponding activities as indicated earlier. These processes are namely: a) 'direct development', in which a copy of an immediately previous file or a handmade drawing is used as a basis for further elaborations; b) 'gradual development', in which a part of information existing in an earlier file or handmade drawing is transferred into a new one; c) 'disjointed development', when a new file or handmade drawing takes into account and elaborates information that appears in an earlier instance but does not directly transfer it into the new one; d) 'projection', which occurs only for computerised drawings and is the direct two dimensional output, including drawings of a three dimensional model; and e) 'interpretation', which signifies the manual elaborations and the handmade editing of a computer's output, such as sketching on the top of a hardcopy of a computerised drawing. The processes also include the 'user development', that indicates the introduction of a new piece of information in the development of the project, met mostly at the first stages of development. This distinction takes into account only very profound elements, such as a completely new spatial distribution.

Peak points in the development, such as presentations and crits, are indicated in the diagram with differentiation in the representation of the instances of design expression that take part in them. Crits are conventionally treated by the case study as analogous to meetings with the client in an actual design project.

As indicated by the description of the case study, the analysis of the activities and the drawings of the students is empirical, based largely on observations. Statistical analysis or other scientifically oriented methodologies were not found to be appropriate because of the generality and the abstractness of the issues that the case study attempts to describe, the extended period of time, and more importantly because they would involve strong and definite assumptions about designing.

The developments of the projects of the students, in relation to the use of computerised systems, are extensively discussed in Chapter 7.[1] However, specific parts of the case study are used as examples throughout the thesis to illustrate the theoretical discussions, and are further analysed. On most occasions, discussions arise from observations of the case study and conclusions are reflected back to them. As the thesis attempts to relate different accounts of representation to design activity, the case study offers a plausible way to connect these accounts to evidence of designing and drawing operations.

2.3. Summary

In contrast to early approaches on design methodology that were based largely on prescriptive accounts, the thesis attempts to develop a descriptive approach to designing by focusing on the externalised aspects of it, design expressions. The model of design activity upon which this approach is based is motivated by studies on cognitive behaviour encountered during ill-structured problem solving. Under this view, designing is encountered as a continuous process of transforming partial and incomplete descriptions of states of information towards a more final and complete one, in the form of a spatial object, by the application of knowledge. Graphical expressions in particular hold a central role in this process as they offer a vehicle for the representation of information and allow transformative operations. This objective focuses interest on computerised systems that support the production of design descriptions.

To observe how these operations emerge, a case study was conducted with the help of four students of architecture who were invited to develop a design project that involved most of the factors that underlie the accomplishment of design tasks. The students were asked to use computerised systems, in order to examine the activity that relates design expressions to processes involving knowledge and information, and the role of computers in supporting this activity.

Being a realistic example, the study gains in generality by incorporating conditions that characterise the making of drawings in different stages of design activity. It is anticipated that the examination of the attitudes of students in design

[1] 7. Example of the Use of Computers in Design.

situations would lead to valid arguments with respect to particular issues about the accomplishment of drawings, but more importantly would contribute towards a global understanding of the role of graphical expression in design activity.

3. The Design Episode

It was mentioned, in the previous chapter, that designing is confronted by this thesis as a task of transforming partial and incomplete information about an object into a more stable and complete description, in a spatial form, by the application of knowledge. This view does not differentiate designing sharply from other kinds of problem solving activity. However, in contrast to well defined problem solving activity, which is characterised by pre-specifying effects as explicit performance criteria and testing alternative solutions until an outcome is obtained, design activity is accomplished as a search for the most appropriate effects that can be attained in the unique context of specific circumstances. We have also seen earlier that knowledge towards the accomplishment of design tasks cannot be regarded as being stable and objective, based on established theories and methods, as in the case of well defined problems. Designers, being responsible for contributing valid answers to human needs expressed in varied and unrelated ways, have to rely on less neutral but more attentive means of contemplation, involving intuitive thinking.

This chapter discusses the dynamics of the design episode and looks at the mode of thinking that characterises design activity. It focuses on those aspects of designing which relate to the use of knowledge and information. By examining the individual and idiosyncratic ways according to which designers approach design tasks, it attempts to identify their attitude towards the presented information. It also discusses the relations between existing knowledge and the conditions implied by specific design situations.

The chapter seeks to provide an account of the nature of design tasks and clarify their differences to other kinds of problems. It will be suggested that elements of design consciousness specify the character of the interaction between designers and external information, and lead to the emergence of different kinds of conduct within the design episode. Problems and paths for their solution are recognized within the context of these views, and existing knowledge is re-structured and converted into new forms of knowledge in order to be applied to them.

The chapter offers a basis for an approach to the cognitive operations by which transformative processes are exemplified in designing, which will be discussed further in the following chapter. It also indicates a qualification on the formulation of design concepts, generalised under the notion of 'models of discourse', that will become dominant in our discussion on drawings later.

3.1. The Framework of Discourse

Having set in the previous chapter the general objectives upon which the case study is based, let us attempt here to identify the aspects that underlie the attitude of the students towards the presented project. We will concentrate on the information that is provided by the brief and the map of the island, and we will examine some of the first attempts of the students to organise this information as they are expressed in their initial textual notes and drawings. In addition to the brief and the map shown at *Figure 2.1* and *Figure 2.2* respectively, consider the notes *Instance 001*, and *Instance 002* of student A that can be found in Appendix B.

Presented Information and Response

As was described in the previous chapter, the design project that the students were asked to develop is a small conference, research and exhibition centre for Greenpeace on Cramond island. According to a first observation, the information given by the brief relates to: a) Greenpeace's interests, activities, and needs, b) Cramond island, its wider area, and its physical conditions, and c) functionalities, requirements, and specifications in area that the building has to encounter. The brief also indicates: a) emphasis on the relation between the building and the physical environment, and b) concern about the natural resources through energy efficient design and choice of materials.

A look at the sequence of activities of student A, shown in *Table A.1* in Appendix A, demonstrates his first reaction. The designer considers a first location for the building but finds inadequate the information given about the island so he looks for a more accurate map and visits the island. In his visit to the island, he estimates that his first choice for the location of the building is inappropriate and considers a new one. Then he produces the first series of notes and sketches.

An examination of the first two expressions reveals:

a) gathering and considering of selected information from the brief (specifications in space and area - *Instance 002*);
b) interpretation and modification of the given requirements ('must be green', but also 'might be self build', 'might be "scottish"', etc. - *Instance 001*);
c) consideration of spatial distribution and organisation (*Instance 002*), arrangement ('U shape' - *Instance 001*), and topological ordering ('facing S' - *Instance 001*);
d) identification of properties in some facilities ('accommodation: relatively private'), and attribution of spatial features in others ('education: large hall' - *Instance 001*);
e) questions on further properties of the building ('harmonising with surroundings?' - *Instance 001*).

This, taken together, indicates that there is already a lot of transformative activity over the description in the brief, with parallel exposure of subjective intentions, and imply some support from existing knowledge.

Abstractions: Self-Knowledge and Knowledge-in-Use

The framework of the example just illustrated can be seen as consisting of elements of consciousness that the designer carries in practice and elements of information about the specific episode. Design consciousness involves a complex array of knowledge, experience and design responsibility, which intermix as the designer attempts to measure the situation.

Established institutional knowledge for a design discipline, in contrast to a knowledge discipline, incorporates not just scientific propositions but also aspects of professional conduct. Thus, it is concerned additionally with issues of sanction, legitimacy, setting, methods and procedures of practice, and theories of intervention. This is the knowledge that usually comes through training and professional protocols and is assumed to be normative in character. In a stable environment these features of knowledge can be seen as predictable and controllable.

Institutional knowledge, however, is filtered, even from the time of education, through overt intentions, personal interests, modifications due to past experience, redefinitions from the influence of practices of other designers, awareness of professional competition – factors very important within the design discipline. It ends up as a form of *self-knowledge*, which can be seen as an individual's adaptation of established knowledge through the involvement of idiosyncratic procedures and methods of intervention, personal preferences, ethical and symbolic codes, and design awareness. While for some knowledge disciplines (as in science) any divergence from established knowledge is usually characterised as misunderstanding and is assumed inadmissible, for design disciplines it is strongly encouraged by education. It is often considered as the key factor on which the innovative mediation of a designer is based. This form of self-knowledge, and not established knowledge, can be thought of as the background with which a designer is equipped when she or he enters the framework of the episode.[1]

Yet, design consciousness, responding to the information of the specific episode and its unique circumstances, leads to the emergence of conceptualisations that depart even from self-knowledge. They can be considered as constituting *knowledge-in-use* where only some features of existing knowledge are encountered, others are judged as inapplicable, and others take new importance under the elements of the episode. We can refer to such conceptualisations as *abstractions*.

Abstractions signify the ways through which existing knowledge and past experience is decoded, reclassified, and restructured in order to meet the conditions insinuated by the information of the episode. They are the key means by which knowledge-in-use is constituted.

Abstractions are not comparable to those modes of thought which often are referred to as rational thinking. They include beliefs, norms, and expectations derived from different and diverse domains of meaning. They might stem from the sphere of scientific contemplation and theorizing, but also from the sphere of art, faith and introspection, the sphere of dreams and imagination, the sphere of play and everyday life confrontation.[2] In short, they can be thought of as the schemes developed when the context of some individual intellect interferes with the context introduced by some specific incident. When they refer to knowledge, they reflect the internal and external influences to which existing knowledge becomes exposed under this interaction. Consequently, knowledge-in-use cannot be encountered as stable and solid. It is susceptible to continuous changes as presented information about the episode is uncovered and new information is discovered under the dynamic state of the intervention.

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1 See the discussion on the dynamics of the professional episode in: Bolan, Richard, 1980.

2 Schemes by which we develop theories are discussed in: Bernstein, R. J., 1976, pp.146-152.

Abstractions: Designers and Information

The other major part of the discourse framework in the example consists of elements of information about the specific episode. It can be assumed that this comes from the brief and the conditions that it specifies. On the other hand, paradoxically, the brief itself stimulates designers to search for further information and apply their own view to it.

The episode is better defined as including all of the people involved and the settings within which actions take place. These can be conceived as constituting a series of scenes or situations where the interrelations between people and settings, under the focus of the specific task, are also taken into account.[1] Presented distinctive requirements correspond to small parts of the episode as they are magnified under the strain of the confrontation.

To illustrate this point, the need for a small research and exhibition centre on Cramond Island, in our example, is extended into the major task of interposing a human built form into a natural environment and is accomplished with effort which goes beyond the putting together of a library, an exhibition hall, and some laboratories. This is clearly demonstrated in the expressions of the designer (*Instance 001*, *Instance 002*). Settings, such as physical attributes of the site (e.g. flora, geology), geographical characteristics (e.g. being by the sea, exposed to winds), historical features (e.g. part of the island was used as a battery during the second world war), ethnological aspects (e.g. Scottish culture), etc., interrelating with people who are going to use the building, such as administrators, researchers, visitors, walkers etc., correspond to various situations each accompanied by different problems under dissimilar conditions.

The role of the designer within the episode is to locate different scenes, to uncover the information that is related to them, to estimate the conditions that determine them. The designer's attitude in relation to the scenes can be defined as interaction. Interaction describes the vigorous relationship between the designer's consciousness and the design episode. This is not a one way relationship in which knowledge is simply applied to information, but a dialectical and cyclical one in which self-knowledge guides examination of information, presented information provides

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1 See: Bolan, Richard, 1980, pp.264-271.

hints according to which knowledge-in-use is acquired, related information is searched, new knowledge is attained, and so on.

Entering the design episode, designers are relatively free to evaluate which scenes compose the episode, which are worthwhile considering, which have to be carefully accomplished. There is no ultimate determinism implied as some of the scenes may have diverse characters in relation to others. The designer is responsible for defining her or his own actions and considering their implications.

An interesting example from the survey on the island in the case study was the idea of one of the students that the building should have a nicely distributed plan to be attractive from the air, as a lot of aeroplanes pass over the site landing on an airport nearby. Of course, such observations do not often define requirements but illustrate the awareness that characterizes the approximation of design information. Still, there are cases from architectural practice where observations like this give direction in the development of a project and contribute to recognisable and innovative buildings. Consider, for example, Spreckelsen's Arc de la Défense in Paris whose central axis, composed from itself and the Arc de Triomphe, shifts by some degrees to meet the Louvre, constituting in this way a triangle between the three important monuments in the cityscape of Paris.[1]

Abstractions are the key features of consciousness through which the interactive relationship between designer and episode is achieved. Due to them, the connections between self-knowledge and information are maintained, and moreover judgements of the character of such connections are made. There are cases where information from the episode calls for expert knowledge, as in our example knowledge about energy efficient design. Expert knowledge, by definition, is assumed to be knowledge directly applicable to particular situations. However, the evaluations of its appropriateness and efficacies according to which it is adopted and adjusted, are subject to assessments of individual designers who place it into the context of the whole design episode.[2] In this sense, even expert knowledge, under the dynamics of the episode, becomes a form of knowledge-in-use. The modes of its application are approached and identified on the basis of design abstractions.

More crucially, abstractions, existing essentially in virtue of human conduct, provide the patterns on which estimations of the relations between people and settings

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[1] See: Davey, Peter, 1989.

[2] See the discussion on expert knowledge and expert systems in: Bijl, Aart, 1986, pp.132-133.

are based, and on which judgements of the applicability of actions directed at these relations are construed.

Errors in these estimations seem unavoidable since any one of us cannot ever really know what other persons think. Often, theories are conceived to help us observe and understand people's behaviour. However, the specific conditions under which this behaviour is manifested seem usually to be outside the boundaries of detached theoretical models. Judgements in design seem extremely complex as they are addressed in several ways: to relations between people and settings, to demands entailed from these relations, to actions that correspond to these demands, to their effectiveness, and back to people's responses to these actions.[1]

In other words, designing becomes a form of social intercourse, between the designer and groups of people or sometimes the whole society, involving psychological, social, economic, even political issues.[2] Discussions of designs often continue a long time after they were first presented. The contradictions evolving from this intercourse imply a designer who is sensitive to a very wide range of uncontrolled variables. The designer is responsible for the correct perception of the unsteady and usually unrelated messages that information transfers, and for the right reply to them. In accordance with this responsibility, the designer does not primarily have to solve problems but has to comment on this information. She or he has to put her or his own idiosyncratic mark on the culture that creates this information.[3]

Design abstractions operate on this level. In relation to them, particular problems which can be distinguished from the framework of discourse, together with the specific processes that are employed for their accomplishment, are related and evaluated against the widest context of the design episode which takes into account all the conceivable consequences. Their importance within design activity has not to be looked for in the exemplification of solutions that refer to isolated factors but in the

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1 Accurate methods of measurement, and criteria that attempt to assign absolute values of design effectiveness, may fail to give a meaningful result even for scientific constituents of designing such as thermal analysis and daylight illumination in buildings. See the discussion on judgement in design in: Lawson, Bryan, 1980, pp.48-62.

2 The Grand Projects, which are currently under construction in Paris, are just a single example.

3 This view on designing is consistent with recent approaches in architectural theory which extend practical views on architecture, as for example the production of physical entities, to more speculative ones, that is as the production of meaning. In this sense, every building, by carrying meaning for other people, is seen as a medium of communication between its designer and the people to whom it is addressed, and designing becomes essentially human expression. See: Jencks, C. & Baird, G. (ed.), 1969. Also: Broadbent, G., Bunt, R. & Jencks, C. (ed.), 1980.

identification of the interrelations between these factors. The composition of these relationships into an overall infrastructure is the essence of the design activity.

3.2. Models of Discourse

The discussion on design abstractions just presented suggests that designing actually progresses through different kinds of conduct between designer and the design episode. It can be conceived that each kind is characterised by the specification of distinctive tasks, and is accompanied with related information and knowledge that can be applied for their accomplishment.[1]

We can refer to these different accounts as *models of discourse*. They can be thought of as scenes which can be distinguished from the framework of the episode or multiple views which can be applied to the development of the building. Models are approached by locating particular contexts to which the presented information is related, together with reference to existing knowledge. Within models problems are identified, specific information and knowledge is searched, and actions for the solution of problems are considered. In our example, a case of a model might be defined under the aspects concerning green issues or the aspects implied by the relation between visitors and the building.

Evidence of this differentiation is demonstrated in the expressions of designers. In *Instance 001*, for example, there are distinctions in the character of the building ('green', 'self build', '"scottish"', '"sea"ish') with a parallel identification of properties of the building or parts of it in relation to these distinctions ('local materials', 'small elements', 'stone render', etc.). The dissimilarities that appear between them ('harmonising with surroundings' - 'stand over water') or at least their dissociations ('mineral insulation' - 'standard sizes') suggest that they are entailed by different states of mind, related to variant views about the building.

Models of discourse can be seen as distinct conceptualisations of the relationships within the design episode. Their role is to facilitate an understanding of separate relationships and of connections between them, to serve as a medium for the definition and exploration of the continuously changing structure of such relationships, and to contribute to a global approach to the building, incorporating diverse factors. None of them can be regarded as more real than any other but all of them are more or less useful for some purpose.

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[1] A similar approach can be found in: Logan, Brian, 1988.

The formation of models is unique to a particular designer and maintains this individuality throughout design activity. Models reflect both the perception of information and its interpretation through knowledge, interests and intentions. They evolve as the designer proceeds in the development of the project and considers the implications of her or his actions. There is some evidence of particular attention to some aspects of the building,[1] which strengthens the view that various degrees of importance are given to different models which are directed by design intentions. Yet, we can assume that the designer tries to express and satisfy in the built form what she or he conceptualises under models each time. In anticipation, richness in the conceptualisation of models contributes to comprehensive approaches to the building. Richness is seen in terms of number of models but also in terms of variables that are considered under distinct models.

Models might be hierarchically related so that the definition of a model in one level could lead to the emergence of models in lower levels, or, the other way round, distinct models can be organised into higher level models which contain them. If we consider, for example, a functional model that confers possibilities of function on the building, this can be thought of as constituted by other models at lower hierarchical levels which in correlation to each other specify it. For a functional model such lower level models could be a model of circulation, a model of ergonomics, and so on.

Distinct models, considered isolated from each other, could be internally consistent. Their connection however to others, in order to define higher level models, might render them mutually inconsistent in respect to specific attributes of the object. For example, the location of a door in a building might be justified in relation to some circulation model, but it may be inappropriate in relation to some thermal performance model.

In this sense, designing can be conceived as progressing through multiple levels of interaction and its most important aspect with regard to the conceptualisation of models is the interrelationships between them and their structuring. Designers are not usually asked to specify solutions within distinctive models and, when they have to do so, they need specific knowledge or advice from experts. In contrast, more usually they are asked to propose solutions which correspond to distinct and multiple views taking into account varied models. The building becomes a plane on which the

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1 See: Akin, Ömer, 1986, pp.86-87.

majority of designer's models are realised, and, respectively, from the user's point of view, it can be organised under of a variety of possibly conceivable models.

Abstractions, as we defined them above, function above these models or, more precisely, at the higher level of interaction. They maintain the consistency of processes emerging in lower levels, and take care of their interdependencies. The control over these processes is preserved through the exercise of a kind of "meta-knowledge"[1] such that implications in operations involving knowledge at one level are used for considerations and designations of knowledge at another level. While specific knowledge that is used on distinctive tasks is dependent on the task, but may be independent of the episode, meta-knowledge is always closely dependent on the episode.

Meta-knowledge is seen as knowledge-in-use. However, this should hold also for specific expert knowledge since, even if it could be independent from the episode, its application is not irrelevant to that. This does not appear to be controversial in regard to the ways through which specific knowledge is selected. Consider, for example, the case in which a designer thinks about the structure of the windows in a building. The knowledge about timber, metal, or plastic construction of frames is independent of the episode. Yet, her or his decision to use a particular material, and accordingly to specify the appropriate knowledge, is not. Quite often, even within the boundaries of the specific technology used, important judgments are made, mainly through the exercise of meta-knowledge, which bring a decision into agreement with further aspects.

3.3. Models and Design Tasks

On the basis of the discussion above on the interaction between designer and the design episode, we shall focus now on the character of design tasks as they appear during design activity. We have already characterised the operations towards the accomplishment of design tasks as transformation processes and indicated some similarities between design tasks and problem solving. Yet, we have seen that design tasks emerge by virtue of partial conceptualisations of the overall interaction, which we have defined as models of discourse. Before continuing in the next chapter to discuss in detail transformation processes in designing, it seems worthwhile to examine some

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1 Coyne, Richard, 1988, p.5. The term is used here to describe the knowledge that we have about operations on knowledge.

attributes of design tasks on the basis of our approach to abstractions and models of discourse.

Problem solving is traditionally used to describe behaviour that is characterised by well-structured tasks where the constraints of the problem and the resources of the problem solver are explicit. In comparison to problem solving: design tasks can be thought of as having also initial states that are described in the brief or are specified by the designer through estimations about information; they go through different states which are manifested in design expressions; it can be assumed that each state is transformed into other states by operations which are based on knowledge; search strategies are used to minimise the number of transformations; the final set of drawings which is proposed by the designer can be thought of as a description of a solution state.[1]

On the other hand, designing cannot be thought of as composed from states in the form of sub-problems, since there is no part of the designed object which serves only one purpose. Problems which can be distinguished from the overall design activity are interrelated to each other so that parts are differentiated according to interests from different models of discourse. States in design solving activity can be seen as current estimations on the available information categorised under models. As individual abstractions operate upon the various aspects of perceived information to formulate models, states in design activity do not logically follow each other but usually intermix. Discriminations in states are imposed by the designer as she or he attempts to size up contrasting factors, and, correspondingly, their boundaries are fluid and constantly redefined as the designer proceeds in structuring relations between models.

Transformation processes in well-defined problems are usually known beforehand as rules or methods, and redefinition of these rules is not necessary and even not allowed. In contrast, designing proceeds by discovering and redefining common interpretations of the artifact, where the imposition of idiosyncratic processes is desirable and usually characterises a creative designer. Transformations in design attempt to link perceptions entailed by different models with the effect of reducing abstract solution spaces for the problems in hand, or directing the overall design task to a class of satisfying solution states. The use of these links as transformation rules is

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1 Akin, Ömer, 1986, pp.20-21, 24.

not logically determinate. It indicates a search for a solution rather than mappings between states and criteria.

Solution states are never specified at the outset as goals or criteria. It is rare for a design problem to be comprehensively stated in a manner which allows some logical derivation of a solution, and there are no explicit evaluation functions which guarantee correct results. Solutions to partial sub-problems are likely to be disturbed or at least distracted when other aspects, under different models, are considered. The evolving overall design task reflects the designer's conceptualisation of the dependencies between models, and it is these dependencies which form a basis of relationships between states and criteria. In this sense, criteria are embodied in the proposed solution rather than being inherent in the design task itself, or otherwise, in contrast to orthodox problem solving, the designer sets criteria for the problems in the proposed solution.[1]

3.4. Summary

The discussion of design tasks so far suggests that in fact what absorbs the greatest effort in designing is the location of design problems under different models of discourse, which can be thought of as different kinds of conduct between the designer and the design episode. In other words, problems are not defined by presented requirements, or even the description in the brief, but they emerge as results of individual abstractions about information, as contradictions between dissimilar perceptions under different models, or as implications of actions for the fulfilment of earlier encountered problems in the same or different domains. The identification of links between distinctive problems, and the structuring of such links are often more important than their solution.

This view of design processes is radically different from most of the early accounts of methodology in design and the analysis – synthesis – evaluation hypothesis. There is no meaningful distinction between analysis and synthesis as problems and solutions emerge in parallel under the impact of structuring relationships within the overall design task.

Designing proceeds as a sequence of actions with the purpose of joining different states of information, and the effect of diminishing multiple

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1 See the discussions on problem solving and designing in: Bijl, Aart, 1989, pp.66-69; Also in: Logan, Brian, 1986, pp.158-159.

conceptualisations under discrete models into an acceptable proposition which combines them. It can be thought of as a search for a consistent fit between conceptual models and a spatial object that manifests them. What propositions satisfy as solution states are exactly the assumptions under these models.

4. Objects in Mind

Our developing approach to design tasks confronts designing as a highly conceptual activity in which the direct application of external components of knowledge, in the form of rules, methods, maps of sequences, etc., effectively does not exist. This is because there are no explicit descriptions of states of information upon which existing rules can act, but instead perceived information is filtered through individual conceptualisations and abstractions of designers. If however this is the case, how do designers proceed in the accomplishment of design tasks, and what form can processes that transform information have?

The thesis takes the view that the ways through which information in initial design descriptions is transformed and a final description is obtained as solution has to be looked for exactly in the mental exertions which constitute the conceptual activity of designers. This chapter looks at primary cognitive operations that act upon information and examines the ways according to which existing experience and forms of self-knowledge are applied to states of information. These operations concern the acquisition, projection, confirmation, and representation of information and the regulation of flow of these operations.

The chapter will not explicitly concern itself with the problem of the transformation of concepts into spatial objects. However, it indicates the manner according to which cognitive operations can qualify for a description of the overall design activity and more importantly to specify the role that representations, such as drawings, can have within it. Also, it will further clarify distinctions that have been put forward earlier to describe the diversity of conceptualisations that occur during designing, as with the notion of models of discourse.

4.1. Design Actions, Transformations of Information, and Cognitive Operations

The design actions that can be observed in the sequence of activities of the designer in our example (*Table A.1* in Appendix A), such as questions and declarations, examinations of the site, recordings in notes, drawings, or photographs, enquires for detailed maps, design working drawings, etc., are all reflections of conceptual design activity which aims to transform information with the purpose of proceeding to a subsequent stage in the development of the project. Design actions, as transformations of information, can be described, under an information processing model, as combinations of primary cognitive operations on information. Such operations might be guided during design activity by search strategies which result in a reduction of their number.

Akin defines a series of general categories of operations on information as: acquisition of information, projection of information, confirmation of information, and representation of information. Acquisition refers to the selection of information from the environment, projection to the application of knowledge to it, and confirmation to the comparison between different states of information. Representation, either in memory or externally, can occur after acquisition or projection. There is also some sort of regulation of flow of the rest of the operations.[1]

In the following, we will try to apply this view to the context of our case study, but we will further develop it by relating it to our approach so far and by looking at evidence from the expressions of the designers and other studies in the field of human problem solving, as indicated. Particular focus is given to representation, because of the interest in design drawings, and as such the discussion on cognitive operations can be seen as an account of the activity that supports their accomplishment and manipulation, rather than a comprehensive theory of cognition. To this extent, the discussion on representation departs from Akin's view, principally with the distinction between representation in memory and externalisation, and forms the grounds of a theory about design representations that will be specifically encountered in the following chapter.

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1 Akin, Ömer, 1986, pp.48-50. A different terminology for similar operations is used by Newell. He proposes selecting, applying, and comparing for the operations of acquisition, projection, and confirmation respectively. See: Newell, Allen, 1969.

Yet, it is assumed that cognitive operations can qualify for a description of the overall design activity, as it was mentioned above. The emphasis on cognitive operations, in contrast to external procedures that modify information, is consistent with a view that confronts designing as a conceptual activity carried out by individual designers. It is important to realise, that cognitive operations are determined by implicit or explicit design *intentions* upon information, which aim to synthesize it into a spatial object. To see how cognitive operations are reflected on design expressions and what they involve, consider also an additional drawing by student A, *Instance 005.a-005.b*, shown in Appendix B.

Acquisition and Projection of Information

In acquisition, pieces of information are selected from the external environment (e.g. notes, sketches and photographs of the site, presented information in the brief), and instances of experience are recalled from the memory (e.g. 'trusses span up to 15-18m', 'pitches - 45-60°' - *Instance 005.b*) constituting the data which enable the activation of the other operations.

The means through which external information is obtained could be visual scanning, through photographs, maps, sketches, or directly the site; verbal inquiry, through questions, texts, meetings with clients, etc.; or search of memory. Designers always prefer direct contact with the sources of information. When this is permissible, they do not replace it with examination of secondary sources as this involves perceptions and interpretations of information by bodies external to the design intervention. They visit the site usually more than once, as is shown on the sequence of activities in our example, and meet their clients regularly to exchange information.

Projection of information is the process in which acquired information forms associations with knowledge, in relation to particular aims or intentions. During projection, existing knowledge is added to a given piece of information, resulting in new or modified information (e.g. in relation to the 'pitches' of the previous example: 'i.e. rooms in roof' - *Instance 005.b*, in relation to information from the site: 'faces W. generally to sun levels' - *Instance 005.b*, 'going against contours to use hillside as a wall' - *Instance 005.a*, in relation to instances of experience from memory and according to the overt intention of 'being scottish': 'stone render', 'large slates or thatch' - *Instance 001*).

Projections differ from each other in terms of their source, the knowledge that is applied, the intentions according to which it is applied, and the level of confidence associated with them. This differentiation results in a varied degree of stability which the new or modified information obtains within the overall design task. This stability is reduced even more when this information is related to new contrasting information.

Additionally, as is clearly demonstrated in the expressions of the student, each projection draws from areas of knowledge that are relevant to specific domains or even from expert knowledge. In other words, they are construed within discrete models of discourse which might have to do with occupancy (e.g. 'lecture theatre row for 150 ...' - *Instance 002*), structure (e.g. 'suggests timber frame' - *Instance 001*), materials (e.g. 'minimum metal concrete' - *Instance 005.b*), feasibility (e.g. 'rooms in roof' - *Instance 005.b*), programming (e.g. 'contrast exterior + interior?' - *Instance 005.a*, 'roof twice as high as it is wide' - *Instance 005.b*), distribution (e.g. '... curved maybe' - *Instance 005.a*), organisation (e.g. 'progression of privacy ...' - *Instance 005.b*), access (e.g. 'route should lead you to centre' - *Instance 001*, 'enter exhibition' - *Instance 005.b*), etc. It can be said that each projection produces a new piece of information with the purpose to declare the validity of a concept in the current state of a model.

It should be clear that the role of abstractions during the projection of information is very important, as they determine how knowledge-in-use is obtained. However, abstractions are much more important during the acquisition of information. It is not conceivable that the selection of information from the environment can be a blind mechanistic process in which pieces of information are loaded into the memory of a designer. Interests and intentions direct the designer during the survey of information; awareness and consciousness ensure its correct perception. External information is filtered through abstractions forming internal individual interpretations of information on which projections are actually directed.

It can be said that acquisition and projection work in parallel in the sense that every selection of a piece of information, even in the very first phases of design, is done in respect to some projection that is to follow. Acquisition is important in structuring a problem; however, projection is seen as substantial progress, even if it is later rejected, as it has a crucial role in proceeding to the next state in the development of a model.

Confirmation of Information

Confirmation is a critical process in which information that is newly acquired or projected is related to existing information to verify its consistency with that existing. During confirmation cross relationships between pieces of information relevant to a model or different models are construed. This may result in the enforcement of the stability of a piece of information – either an existing piece of information or one that was just projected – its rejection, or the emergence of an alternative direction in the overall task that is re-examined in detail later.

Generally, it can be assumed that in the first phases of design greater emphasis is placed on retaining discrete and possibly unrelated pieces of information, rather than their concrete examination, so that they will not be rejected superficially without the consideration of additional information. However, instances of confirmation occur implicitly after a new piece of information is acquired or projected.

Confirmations can be thought of as internal to design task evaluations. Their role is crucial in developing the structure of interrelationships between discrete models on which the overall design task is based. An explicit example of confirmation, which demonstrates this aspect, can be seen in *Instance 005.b*: 'consider thermal response of heavy structure ...'. While projections are drawn through the application of specific knowledge, confirmations are seen as relying mainly on forms of meta-knowledge.

Representation and Externalisation of Information

Representation of information occurs either after acquisition or after internal processing. According to Akin, representation refers to "all overt or covert behaviors aimed at encoding of information, such as writing, drawing, marking, learning, memorising, and so on"[1], and instances of representation could be concepts, images, states of information, etc. Examples of representations constitute all the expressions of the designer.

Representations, in this context, can be thought as the results of acquisitions or projections of information which are either stored in memory to be recalled later or are realised externally on paper to be permanently stored and assist internal storage through rehearsal. However, external representations, being actually the only realisations of the mode of thinking in designing, demonstrate also a shift from

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[1] Akin, Ömer, 1986, p.49.

abstract processes on information, that the rest of the operations suggest so far, to organisational schemes with clear reference to spatial forms through the use of graphical expressions.[1]

Because of the specific importance of design expressions and the complexity of processes in representation, we shall distinguish between representation in memory, as the implicit encoding of information, and externalisation, as the process of accomplishing an external representation in respect to some internal state of knowledge in memory. Design expressions, as a term that we have used to generally describe drawings, notes, and other physically realised encodings of information, refer to external representations. While representation of information in memory after acquisition or projection can be seen as the formulation of new or the re-formulation of existing but possibly discrete design concepts, externalisation aims at the organisation of such concepts into spatial configurations.

Representation in Memory

The representation of information and knowledge in memory is a process which is only partly understood. Current theories, originating from the fields of artificial intelligence and especially cognitive science, accept the view that knowledge consists of units or packages, so that detailed structures of knowledge exist even for single concepts which are organised together in one functional unit relating to the concept in question. Different levels of knowledge play different organisational roles with higher order units adding structure to lower order ones. Knowledge for one concept can be applied to other concepts which may lead to instances of inconsistent knowledge when default values substitute information for a concept that is not known explicitly.[2]

What this view suggests for our approach to the encoding of design tasks is that the representation of a state of information in memory entails the formulation of a number of associative units of knowledge or the modification of a respective existing

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1 It is anticipated that the particular ways through which external representations are realised accommodate the fundamental conversion of information and knowledge into spatial arrangements, and constitute a major task in designing. As such, we will contribute a subsequent chapter on the transformation of concepts into spatial forms (Chapter 8). In the context of this chapter, however, in order to understand the relations between representation and the rest of cognitive operations, it seems appropriate to introduce some first distinctions.

2 These theories rely on the view that knowledge is represented as highly structured configurations of symbols with associated procedures for interpreting these symbols (see: Rumelhart, David E., & Norman, Donald A., 1985). Some of them are described in more detail in the following chapter.

one. These joint structures of knowledge are very closely connected to our notion of models of discourse.

In order to make this point clear, it seems useful to consider human memory as consisting of long term memory, which is the relatively permanent repository of knowledge worth remembering, and short term memory, which serves as an interface between the long term memory and the external environment and as a temporary repository of information on which the cognitive operations that manipulate information are primarily applied.[1] A current piece of information, stored in the short term memory, is decomposed and interpreted according to associative structures of knowledge held in the long term memory. This state of information, irrespectively of whether it will be rejected, modified, or preserved, implies adjustments in the coordinating structures of knowledge in order to incorporate it.

While the main feature of short term memory is that of limited storage capacity, for long term memory the central issue does not concern space but principally organisation, so that knowledge relevant to the information can be efficiently retrieved when needed. In this way, information in the short term memory can be easily and quickly manipulated. The organisational patterns upon which the storage in long term memory is based are exactly what we referred to earlier as models. While the formulation of new structures of knowledge in the long term memory is a lengthy process on which there is no evidence of direct control,[2] different organisational patterns might occur simultaneously which could interchange rather fast according to interests and intentions.

A salient characteristic of designing is that distinctive pieces of information currently held in the short term memory might refer to more than one organisational pattern in long term memory, since information in design might occur within various contexts. This accordingly suggests that different aspects of knowledge are eligible to be applied to single pieces of information. It is conceivable, also, that for a specific piece of information no organisational pattern could be easily attained, which might lead to problems of insufficient projection or no projection at all, or of rejection of the information. Such cases may usually occur in the early stages of designing. Generally, it can be assumed that single models are acting upon single pieces of

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1 The two kinds of memory are described by: Newell, Allen & Simon, Herbert A., 1972, pp.792-796. Elsewhere, they are also referred to as working memory and memory, respectively. As a critique of conceptual design, Heath incorporates additionally working drawings as the external memory. Heath, Tom, 1984, pp.122-123.

2 Newell, Allen & Simon, Herbert A., 1972, p.794.

information during some specific period of time, due to limited space in short term memory.

The importance of representations in designing is central. Designers do not deal with design tasks directly, in that they generally do not execute or build their proposals. They deal instead with representations of tasks. Assuming that there is a mapping between things in mind that stand for objects in the physical world, the whole range of cognitive operations act upon representations. In fact, an entity like the physical world cannot be conceived irrespectively of a mind that looks on it. This is why we do not realise that we are actually dealing with representations until we explicitly think about it.

Another aspect, which seems very important from the point of view of designing, is a distinction that appears in relation to the modes in which a representation in memory can occur. These are the verbal-conceptual modes and the imaginal modes. Verbal-conceptual refers to the structures that form a representation of a concept which can have a series of imaginal correspondents. Conversely, imaginal refers to a mental image that similarly can have a series of verbal-conceptual correspondents.[1] If we consider, for example, the symbol 'door', we can associate a larger number of mental images equivalent to the concept 'door'. On the other hand, a picture of a specific door would provide only one imaginal mental entity, but it might have a series of verbal-conceptual structures that could be associated with it. For example, a place to enter a building, a separation between the public and the private, an opening element that keeps the wind out of a house, etc.

Our discussion on representations so far, including models as organisational patterns of knowledge, refers mainly to the verbal-conceptual structures. However, imaginal models and representations can also occur and be manipulated through cognitive operations. What differs is the nature of the information and the modes of its manipulation, but more importantly its use within the overall design task.

Designing, much more than any solution of distinctive problems, involves the synthesis of a spatial entity which obviously does not yet exist in any form to generate corresponding mental images. Still, there is a range of visual representations which

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1 There is no clear account of how precisely images occur in memory. There are approaches which suggest that they exist as such, i.e. distinct imaginal representations, (e.g. Kosslyn, Stephen M., 1980) and others which accept them as instances or epiphenomena of conceptual symbolic representations (e.g. Palmer, Stephen E., 1975). Here, we will refer to them as imaginal representations, but we will discuss these approaches later.

contribute to the emergence of a very rough and obscure, at the beginning, spatio-imaginal model of the building. These usually come from everyday knowledge about the nature and the behaviour of physical objects, experience from previous projects, analysis of build settings, etc. The main agent under which visual information is accumulated and gradually formulates spatio-imaginal models is not conceptual knowledge but intuitive thinking. The development of intuition is also supported by studio work and survey exercises during architectural education. Architects, entering the design episode, already have a sketchy image of how they want the building to look. Some preliminary 'images' of parts of the building in our example are shown in *Instance 005.a.*

As the mapping between a concept and an imaginal equivalent of it is not determined by a one to one correspondence, the greatest proportion of the design activity is concentrated on the exploration of effects of manipulations from cognitive operations on the spatial form of the object. This is performed by distinguishing and separating the spatio-imaginal model (or the models, if there are alternatives[1]) from other conceptual models, and by clarifying and developing it under the tendencies, stabilities, and dependencies that emerge within the context of single conceptual models or from their interrelations. Much of this exploratory activity, if not all, is accomplished by the use of external representations.

External Representations

Representations in memory are realised as external representations in some physical medium, like paper, air, cathode ray tube, through externalisation. This process involves the mapping of concepts, components of concepts, or attributes of concepts into sets of abstract and, in some sense, arbitrary symbols, like words, lines, sounds, which stand for them. The process includes also rules composing symbols into structured configurations, usually referred to as syntax or syntactics. Central to external representations, and in some respect to corresponding internal ones, is the notion of *decomposition*. According to this, representations are made up by symbols, which, in turn, are constructed by primitives. Primitives are parts of symbols which do not stand for other things. For example, 'a', 'b', 'c' are primitives, and 'cat' is a symbol. The accomplishment and the interpretation of the representation can be

[1] Usually there are not many spatio-imaginal models as they are not precise enough to be distinguished. The case of alternative spatio-imaginal models often relates to the adoption of particular morphological styles.

obtained in a compositional fashion. All the expressions of the designer in our example are examples of external representations.

Generally, an external representation is an expression from an internal state of information and of knowledge relevant to it. As a consequence of this function, external representations can serve as a kind of external memory that acts as a repository of elements that are no longer manipulated in the short term memory but can be reached later by recall mechanisms. Recalling might concern both the state of information that used to be in the short term memory and the knowledge that was interacting with it. Accordingly, previous stages can be reviewed, alternatives or early solutions of particular problems can be re-considered.

An interesting feature of recalling is that it always involves also an acquisition of the previously made external expression. This means that external memory is not simply an extension of the internal memory that is permanently connected to it and conditioned by the same state of mind, but implies further activation of the cognitive operations, under another state of mind (or 'clear mind' as problem solvers indicate). This might lead to the recall of further, lesser, or usually different aspects of knowledge determined by the organisational patterns which are contemporary to the acquisition.[1] In effect, as a discrete reading of external information actually takes place, the state of information resulting from the interpretation of the external expression can be seen as partial, in respect to the information by which it was made, but supplementary, in respect to the information that is processed through cognitive operations in total. This phenomenon occurs also when a re-acquisition of already selected information from the external physical or other environment is drawn.

In other words, the designer sees additional things every time she or he looks at the expressions that were earlier produced. In practice, this suggests that external representations offer her or him a means of accessing further aspects of the design task. This facility by itself emphasises the importance of external representations; yet, their contribution in designing is far more than simply for storage and retrieval.

In principle, externalisation is an implicit or explicit *organisation* of elements of a design task. As the production of a written and, especially, drawn expression usually takes some time, other cognitive processes also operate on elements of information that are currently being represented externally – such as projection and

[1] Newell and Simon go further to describe such aspects of knowledge as 'extended knowledge state'. Newell, Allen & Simon, Herbert A., 1972, p.585-587.

especially confirmation – developing a system of relations between these elements. Models, being essentially organisational patterns of knowledge, provide the framework within which these relations occur and, correspondingly, the modes according to which the symbols of the external representation are interpreted.

This aspect of externalisation is most apparent in partial or inclusive descriptions of the *effects* of manipulations of the designed object through a sequence of cognitive operations. These descriptions are almost always realised in graphical forms. In contrast, expressions which refer to the selection of information or the manifestation of operations on discrete pieces of information might also be realised in graphics but mainly occur in text.

This differentiation is very well illustrated in the expressions of the designer in our example. The first aspect of organisation of the effects from the manipulation of information in the case study is shown at the top of the *Instance 002* and occurs in a diagrammatic form. The differentiation between descriptions of effects of operations on the spatial form of the object and expressions relating to the execution of specific operations characterises to a great degree the use of graphics in designing, and relates directly to the distinction between verbal-conceptual and spatio-imaginal models.

Regulation of Flow

Regulation can be seen as a need to control the flow from one operation to the next in order to decrease the search space for specific problems or for the overall task. It is a function at some higher level above the rest of the operations but dependent on the current state of the design task. It can be thought of as the detachment of the demanding effort of accomplishing a particular task and the contemplation of the direction of the overall activity. It might concern problems of dealing with an alternative, considering a task that has been left unfinished in an earlier state or reconsidering a supposedly finished one, the identification of a desired solution state, the examination of new external information in relation to a previous confirmation, and general strategies that can facilitate the design activity. Regulation deals directly with the question 'what to do next'.

Regulation of flow cannot be explicitly observed in particular expressions of the designers in our example, as it is assumed that it occurs at a higher level directing the activation of particular cognitive operations. To this extent, specific patterns developed from the connections between expressions in the maps of design expression, *Table A.2*, *Table A.3*, and *Table A.4* of Appendix A, can be seen as reflections of the activation of regulation of flow. Thus, for example, the decision of two of the students to proceed to the development of a new alternative after the second crit, *Instance 112* of *Table A.2* and *Instance 163-166* of *Table A.3*, can be regarded as a result of regulation of flow. In contrast, student C continues developing the same alternative after the crit, *Instance 107-110* of *Table A.4*. Similarly, regulation of flow might underlie the decision of student B to incorporate two relatively distinct developments, one in two dimensional drawings, *Instance 182-189*, and another in three dimensional models, *Instance 190-213*, into a final one, *Instance 204-219* of *Table A.3*.

Obviously, regulation of flow relies on meta-knowledge or knowledge that can be independent of the particular episode, as instances of self-knowledge. This is indicated by the preference of individual designers for dealing with discriminating aspects in designing first, in the development of idiosyncratic procedures for advancing the task, and in estimations about particular models or problems which, on the basis of experience, are seen as more difficult to attain and which have to be approached carefully.

This aspect of designing might look similar to some of the early approaches to designing,[1] as it implies a kind of methodology for the design activity. However, regulation of flow, as a function applied to the rest of the cognitive operations and not to the overall design task, suggests that any considered method in design cannot be rigorous and restrictive.

There is a general categorisation of weak methods, which appear to be used in the accomplishment of ill-defined tasks, under the term of heuristics. Heuristics are ways of searching for a solution which serve more to indicate or stimulate an investigation rather than to offer a guarantee of success. They help a problem-solver to focus her or his attention on a portion of the search space which is likely to contain a solution. As processes, they involve trial and error in the absence of a precise path to a solution.

In the context of design, heuristic search methods have to do with the familiar process of generating and representing solutions in the form of drawings or models,

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[1] See the discussion under: 1.1. Design Methodology; Glass-box Design Methods.

and estimating later their consistency and effectiveness.[1] However, a number of considerations in design, such as these which we have seen above, relate to weak search methods, directed mainly by experience. Estimations like: 'the ideas that come first to mind are often the best'; judgements of the current state of a particular task like: 'let's leave it as it is and we may find a better solution in relation to something else'; rules of thumb like: 'it is better to have all of the information in front of you before you start thinking of a solution'; or procedures like: 'make several photocopies of this drawing and explore them individually' are often heard in design studios, from either tutors or colleagues, and appear to be based on heuristics. There are a number of researchers who directly relate heuristics to intuitive thinking.[2]

Yet, the main principles according to which regulation of flow operates are design intentions and abstractions. Acting at the higher level of interaction, they provide the grounds on which regulation of flow is based. Spatio-imaginal models also play an important role in this. As the primary aim in designing is to embody conceptual manipulations into a spatial configuration, regulation of flow functions as an interface between conceptual and imaginal models and coordinates the processes of the operations.

What is important for our approach is that through regulation of flow, perhaps with the aid of weak search methods, a chart for the continuation of the design task is developed according to which the rest of the cognitive operations are activated. These, in turn, change the current state of the design task, and the consequences of this change give rise to new assertions in the regulation of flow level, resulting in new charts for following operations. In other words, in contrast to the assumptions of most of the approaches to design methodology, regulation of flow indicates that the overall design activity progresses directed by factors internal to design activity itself.

4.2. Cognitive Behaviour and Design Activity

We have seen the characteristics of particular cognitive operations on the basis of which distinct primitive processes in design activity are taken care of and we have

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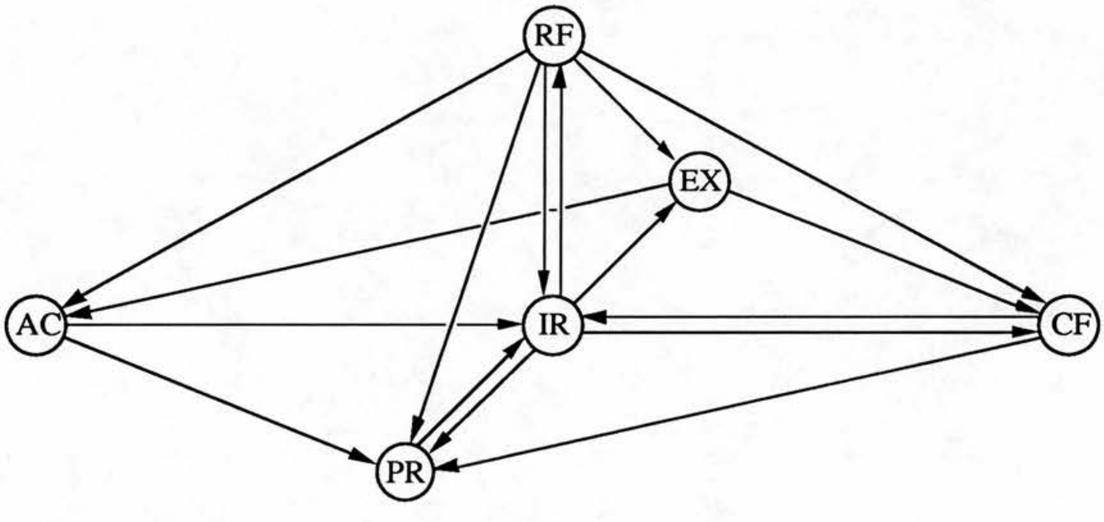
1 Newell suggests generate-and-test and hill-climbing, among others, as methods that can be applied in ill-defined problem contexts, which look relevant to attitudes encountered in some design tasks. Generate-and-test involves a way of generating possible candidates for a solution and a way of testing whether they are indeed solutions. Hill-climbing is similar to the generate-and-test method with the addition that the candidate element is compared against a stored element and replaces it if it is better. In: Newell, Allen, 1969.
Freeman and Newell explore directly the application of heuristic methods in design in: Freeman, P. A. & Newell, A., 1971.

2 See for example: Eastman, Charles, 1970.

tried to illustrate them with evidence from the expressions of designers. However, the accomplishment of a specific design task and the transition from one stage in designing to a subsequent one is achieved by the coordination and cooperation of several of these operations. Let us see how cognitive operations relate to each other and contribute to the overall design activity.

Relations between Cognitive Operations

It should be clear that cognitive operations describe primitive design processes and they co-relate to each other, in the sense that the operation of one allows the operation of another. Accordingly a particular manipulation on a state of design information, and consequently a transition from one state to a next, is accomplished through the activation of a sequence of operations. Not one alone is sufficient and general enough to solely describe a single manipulation, nor is there a secondary one which can be substituted by any others and therefore excluded. However, this does not imply that all of the operations occur in any manipulation. Furthermore, representations in memory seem to hold a central position, to the degree that any manipulation implicitly or explicitly involves some representation.



AC: Acquisition of Information
IR: Representation in Memory
CF: Confirmation of Information
PR: Projection of Information
EX: Externalisation of Information
RF: Regulation of Flow

Figure 4.1

Figure 4.1 is an abstract three dimensional diagram of the sequence that cognitive operations might have in design tasks. The diagram involves only the different operations and not the results of them as states of information. The arrows in the diagram depict the relations that cognitive operations might have to each other in any possible sequence. Thus, for example, projection may follow acquisition, representation in memory, confirmation, or regulation of flow, externalisation may follow representation in memory, and so on.

The position of each operation in the diagram roughly illustrates the level at which it operates. Thus, regulation of flow sits above the rest of the operations, which illustrates the fact that regulation through meta-knowledge and self-knowledge operates at the highest level of interaction with the task. This indicates that regulation may implicitly appear concurrently with another operation. For example, it may be involved during the process of externalising an internal representation.

Regulation of flow is sustained mainly by representations in memory with parallel modifications in knowledge. This is illustrated also by the relation of internal representations to confirmations for the case of meta-knowledge. When regulation of flow occurs after externalisation, it would involve acquisition and representation in memory.

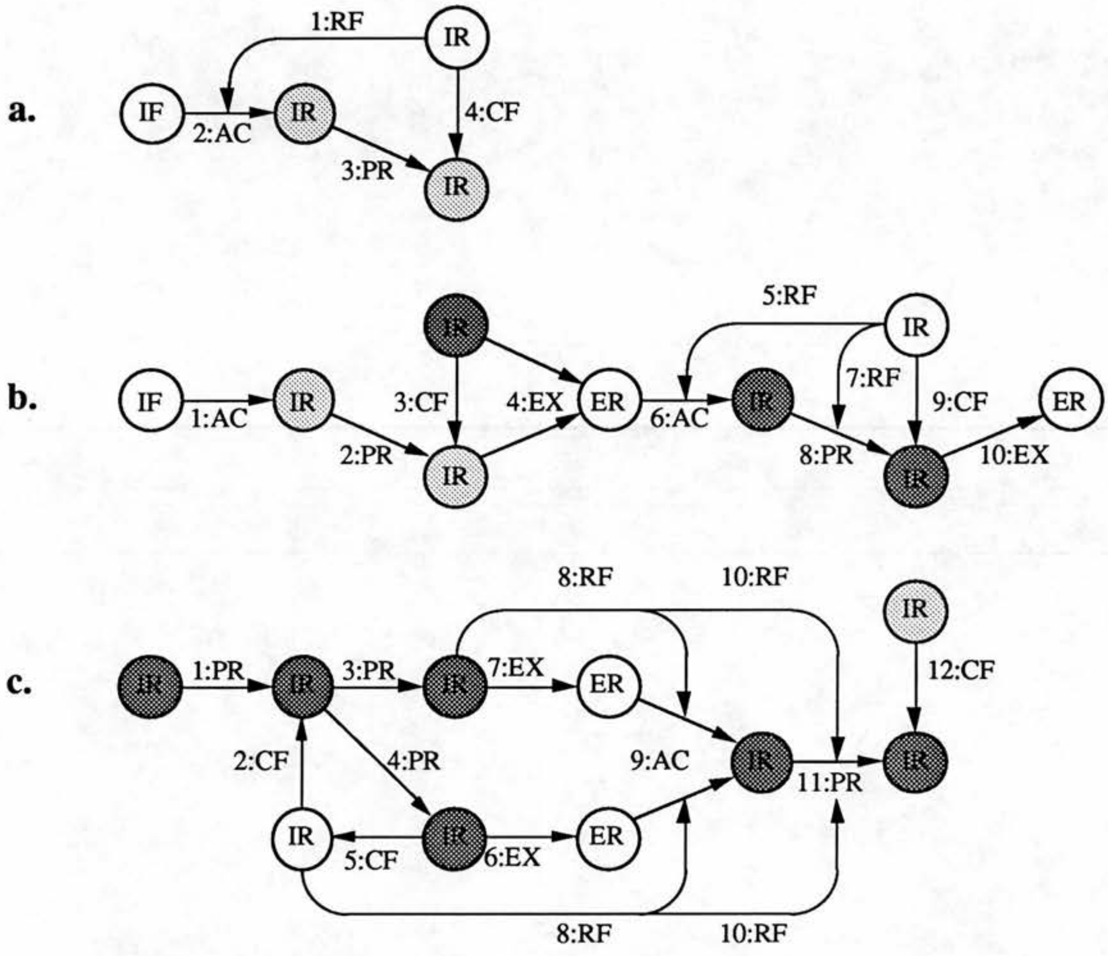
Representation in memory sits in between the rest of the operations illustrating the important role of internal representations and models as the core of the overall design task. These in turn can be directly modified by new acquisitions or projections, or indirectly by meta-knowledge through confirmation or regulation.

New acquisitions are directed by regulation of flow, but they may have as input previous external representations, so they may follow externalisations. Projection may follow a representation in memory, a confirmation, regulation, or immediately after an acquisition. This is the case of search for specific pieces of information which are needed for the accomplishment of a particular problem and they are modified as they are acquired through projections. Yet, even in this case, both of the operations are drawn with respect to some distinctive model that exists beforehand and their activation leads to its re-adjustment.

As the various dependencies of each operation to the others are shown, the diagram can form a basis for the specification of sequences of operations in a transition from one state to another in a design task.

Transitions between States in Designing

States in information, as inputs in the form of presented external information, internal conceptualisations in the form of mental models, or outputs in the form of expressions, are directly related to acquisition, representation in memory, and externalisation respectively. These can be thought of as either starts or ends of a transition. Accordingly, some possible sequences in transitions could have the form shown in *Figure 4.2*.



AC: Acquisition of Information
IR: Representation in Memory
CF: Confirmation of Information
IF: External Information
ER: External Representation

PR: Projection of Information
EX: Externalisation of Information
RF: Regulation of Flow

Figure 4.2

Note that the way in which operations in *Figure 4.1* are related allows some sequences but excludes others. For example, there can be a sequence: acquisition – representation in memory – projection – representation in memory – confirmation – representation in memory (*Figure 4.2, b*), but not: acquisition – projection – regulation, as it implies that the projection does not have a result in the form of an internal representation.

In the diagrams of *Figure 4.2*, internal representations are signified with circles instead of arrows which indicates that they result in a current state of a task, a conceptualisation, an image, or a mental model, in other words, in effects of actions. However, this does not imply that they are in fact static and stable. Their emergence exactly through the rest of the operations suggests that they are in a vigorous condition exposed to continuous changes. Different tones indicate discrete models and progression in their comprehensiveness through transformations.

Let us then have a look at the examples in *Figure 4.2*. The cases illustrated in the diagrams refer to the design activity of student A in our example, and relate to cognitive behaviour that is reflected in the instances of expression that we have already seen and in addition *Instance 014*, *Instance 015*, and *Instance 022*. Even though the design actions that they concern were not explicitly recorded in the map of activities, since most of the cognitive operations are not realised externally, the discussion of the examples could be a possible explanation of quite distinct parts of the design activity in respect to cognitive behaviour.

In the first case, there is a simple task of examining external information in relation to a model which, after its projection, gives rise to a new internal representation that may later contribute to the emergence of a new model. In relation to the early expressions in *Instance 001-002* and *Instance 005*, consider images of Scottish buildings with stone construction and sharp roofs as the existing internal representation. According to the intention of Scottish typology for the designed building and through regulation of flow an inquiry on new information is made, either from experience or from external sources, on the angles that pitches may have. The acquired information is projected through the application of knowledge, and a new piece of information emerges, that of the feasibility of having rooms in the roof. A confirmation may follow, positive in our case, according to the Scottish typology model, e.g. having windows on the facades of the roof. The new information is also important or even contributes to the conceptualisation of other models, that of the distribution of the building, for example.

The second case is a task of accomplishing an output, after an acquisition, a projection, and a confirmation, which in relation to some existing internal model gives rise to a new projection and a new externalisation. Consider, for example, the acquisition of information from the location of the building which is conceptualised as some morphological model of the site, including the slope and the contours, their direction, existing plants or other physical elements, etc. This information is projected according to an intention of a volume against the slope and results in an internal representation of a long building expanding perpendicularly to the direction of the contours. The new representation is evaluated in relation to some existing preliminary model of the distribution of the building, and both are externalised as a rough diagram or plan of a linear building on the site, *Instance 022*. It may have public spaces (reception, exhibition, library, lecture hall, restaurant, etc.) towards the open end of the building and more private ones (laboratories, accommodation, etc.) towards the end facing the contours. According to some other existing energy efficiency model of the building, a new acquisition of the diagram is made, which pays attention to further aspects of it, such as the northerly orientation. Let us assume that the building extends on the east-west axis and the slope increases towards the east. Through projection and regulation of flow, it leads to a modified internal model of distribution, having for example certain spaces along the northern side of the building (laboratories, library, kitchen, toilets) and others looking south (accommodation, exhibition, restaurant), which is externalised in a modification of the diagram of the distribution.

The third case is another account of the sequence of operations in a similar example illustrating how sequences, even for the same tasks, can be differentiated. Differentiation mainly appears because of varied importance that is given to certain models, entailed by design intentions and abstractions. The effects of different sequences are assumed also to be different. However, greater differentiation is expected when further models also participate. In this case, consider as the initial internal representation some model of the distribution of the building. This is projected according to some intention of clear distinction between private and public spaces and results in a modified distribution model, having for example private and public spaces towards the two ends of a linear building. The new model is compared, through confirmation, to some other existing model of energy efficiency, according to which an alternative appears, that of having a central public space (for example, the exhibition hall) acting as solarium and the rest of the spaces distributed around it. Both of the alternatives are externalised in two diagrams, *Instance 014*, *Instance 015*. After acquisition and new projection, in relation to both of the initial models through regulation of flow, a further scheme of distribution emerges. It may be, for example, a linear but curved building around a semi-open space with a glazed roof. The new scheme radically contrasts with some internal image of a building going against the contours.

These cases give an indication of the complexity which characterises the accomplishment of design tasks. They show how transitions from one state to another are determined by the information contents, under the conceptualisation of discrete models, as much as by the transformations applied, in relation to specific intentions and design abstractions. There are dependencies between various states of information which are illustrated in *Figure 4.2* by their connections through operations. In fact, however, the cases above are just simplified examples of cognitive behaviour in designing, within the boundaries of a particular field of attention.

It is anticipated that, in relation to the overall design task, several models occur concurrently which affect transformations, through confirmation and regulation of flow, in various and unpredicted ways. As connections between pieces of information are construed, the patterns that transitions in the conceptual level of the design activity follow can be roughly approximated as having a scheme not of a linear but of a lattice-like structure. (A very small part of this scheme would be similar to those in *Figure 4.2*.) Given that conceptual manipulations are extensively embodied in some spatio-imaginal model, which modulates and conjoins them, the overall activity can be portrayed as having a combination of a lattice-like and a tree-like structure. That is to say, the patterns of the lattice structure can be organised into branch-like paths, each of them corresponding to the context of a particular conceptual model, ending in a peak point that stands for the spatial form of the object which effectively comprises the whole of the transformative activity, taking into account assertions of conceptual models. (Such paths would appear if we connect the states of information that are relevant to specific models indicated by different tones in *Figure 4.2*, even if the portions of the design activity illustrated in the figure are too small to actually have branch-like paths.) This spatial form corresponds to the final and complete description of the designed object and occurs in the set of drawings according to which the designed object is constructed.

This structure is only roughly reflected in the maps of design expression of the students in our case study, since, on the one hand, the majority of the distinct actions which directly result from single cognitive operations cannot be recorded as they occur implicitly, and on the other, the maps describe more abstract activity in which a minor step, such as the development from one drawing to another, is accomplished through the activation of a sequence of operations, as illustrated in the examples just discussed.

Nevertheless, our discussion on cognitive operations indicates a way according to which such steps are made, and more importantly it clarifies the relations between external representations, such as drawings, to design actions as they are described by cognitive behaviour. It demonstrates that drawings can sufficiently capture the effects of the conceptual activity of designers.

4.3. Summary

This chapter has been concerned with the description of designers' attitudes in encountering design tasks. It was suggested that designing occurs as a conceptual activity grounded in specific cognitive operations on the basis of which manipulations involving information and knowledge are construed.

The notion of models, introduced earlier in order to specify the framework within which design activity takes place, are further clarified as multiple views of the design task, which capture the interrelationships within the design episode. Models relate to distinct conceptualisations of such relationships and serve as a medium for their structuring. They refer to different organisational patterns of knowledge.

Models characterise to a great extent the behaviour of designers. By looking at the lower level of the primary processes by which this is manifested, we have been concentrating on the cognitive operations of acquisition of information, projection of information, confirmation of information, representation in memory and externalisation of information, and regulation of flow of these operations.

Acquisition is the selection of external information from the environment or the recall of information from memory. It is the principle operation in which abstractions are involved. This may be followed by a projection or a representation of information. Projection is the application of knowledge to distinctive pieces of information according to design intentions and leads to modified or new pieces of information. Representation is encoding of information in memory. Information is represented by forming associations with existing knowledge structures under different models. Existing knowledge is modified by its adjustment to the new information.

Confirmation is the comparison between distinctive pieces of information. It takes care of the interdependencies between different aspects determined by similar or dissimilar models and on confirmation the structuring of their relationships is based.

Externalisation is the process of accomplishing an external representation as an output of the current manipulations of information by cognitive operations. Externalisation, more explicitly than representation in memory, demonstrates the emphasis on the organisation of information especially when external representations are realised through graphical forms of expression. In order to understand this differentiation we have introduced the distinction between short term memory and long term memory and the distinction between verbal-conceptual and spatio-imaginal models. Internal representations are manipulated in the short term memory which is limited in capacity. During externalisation, however, structures of knowledge in the long term memory can interact more effectively with states of information in external representations which, in this sense, can be thought of as external memory. Additionally, elements of external graphical representations, which constitute reflections of some spatio-imaginal model, are correlated with each other and organised through their dependencies to several conceptual models.

Regulation of flow is a function applied to the rest of the operations coordinating their activation and direction, in relation to estimations of effects from their manipulations. It may be based on weak search methods, such as heuristics, which are related to the specific task through intuition.

An approach to designers' cognitive behaviour explains to a large degree the mode of thinking in designing as it is differentiated from orthodox problem solving activity. Designing is accomplished as a search for a consistent fit between initially unrelated and varied aspects of information with aim to transform this information into a stable spatial form. Acting on distinct states of information, cognitive operations achieve their structuring which is represented externally in graphical forms.

Representations appear to be of great importance in design since they actually constitute the structures on which primary operations of cognitive behaviour are directed. Graphical representations, in particular, manifest the dependencies between spatial forms and conceptualisations of information under models. The following chapter will focus on the attributes of representations and the manner according to which they are structured and interpreted.

5. Representations and their Interpretation

The discussion about cognitive behaviour in the previous chapter indicated a differentiation in the modes according to which representations are stored in memory. This has to do with the distinction between verbal-conceptual and spatio-imaginal models. Verbal-conceptual models are seen as organisational patterns of knowledge that take into account the various distinct views which appear in the conceptualisation of design tasks. Spatio-imaginal models, on the other hand, take into account the spatial and visual counterparts of design artifacts and they are developed on the basis of earlier visual experience and intuitive knowledge about the nature of physical objects. It was suggested that the transformation of conceptualisations of information into a spatial form is achieved through exploration of the dependencies between spatio-imaginal and verbal-conceptual models. This exploration is manifested in graphical representations.

In order to see which are the attributes of graphical representations that make them efficient tools in the accomplishment of this exploration, in this chapter we will briefly discuss some of the theories, mainly from the field of cognitive psychology, that attempt to explain the structure of representations. We want to do so in order to examine whether these theories can qualify for a description of design knowledge. The discussion will look at the manner according to which conceptual knowledge and images are held in memory and it will distinguish kinds of representation. The most important distinction is between *propositional* and *analogical* representations, related to verbal concepts and images respectively. The chapter will offer an account of the connections between verbal-conceptual and spatio-imaginal cognitive models and indicate the manner according to which these are co-related in the process of developing a design object.

The main assumption that underlies the views described in this chapter is that an approach to the structure of representations can show how graphical representations in particular can capture both conceptual knowledge and imaginal spatial forms and, consequently, indicate the manner according to which drawings are used during designing. However, the thesis recognises that, conversely, the ways according to which drawings are used also play a role in the specification of their structure. Occasionally, we will look at aspects of use, like for example how representations are interpreted in connection with cognitive activity and how design intentions and contexts of use specify the character of drawings as representations.

The aim of this chapter is not to explicitly examine the use of drawings during designing, but rather to provide the grounds of an account about the links between drawings and design knowledge that will be developed in subsequent chapters. In close relation to this account, we will strive to obtain a characterisation of systematic representations of drawings in computers which will be examined in the following chapter.

5.1. Knowledge or Representation of Knowledge?

The notion of representation relates to all aspects of thinking and knowledge, since thinking is on the whole about something that is rarely, if ever, immediately present. Objects of thought are represented in mind. A proper account of representation is of central importance in any theory of cognition, language, and logic, and also to theories of art, aesthetics, perception, and other aspects of psychology.

An approach to representation from the field of cognitive psychology is expected to offer an approach to the ways in which concepts and images are stored in memory and to the manner according to which they are manipulated. Consequently, the next section includes a short discussion about accounts of cognition which attempt to clarify the structure of representations of both concepts and images. That can be viewed as background theory, on the basis of which we will develop a view about drawings as representations. However, in examining representations from a psychological point of view, there are certain notions that have to be clarified first. These start from the notion of representation itself.

In general, representation as a term is used to describe a relation between two things. The phrase *x represents y* is taken to mean that *x* stands for *y*. Thus, representation involves a relationship between a *signifier* and a *signified*, as in the relationship between a portrait and the object that it portrays. In this sense, representation has a communicative function telling someone that whenever *x* is used this is meant to stand for what we understand as *y*.

However, when the term is used to describe things that people have in mind about things in the world, representation is used to imply more than a communicative function. What someone has in mind about an object in the world (or a physical portrayal or representation of it) does not simply stand for or communicate about this object, but instead is the knowledge that she or he has about this object. Given that this knowledge is the only information that someone has about the world, it can be said that knowledge stands for the world in a loose and to some degree circular sense. That is to say, in the relation *x* (in mind) *represents y*, each of us knows only about *x* and perhaps about the correspondence between our *x* and other people's *x*s. The use of the term representation in this sense is taken to refer to knowledge itself and to the ways in which knowledge is organised.[1]

Before proceeding further in discussing these theories, it should be made clear that theories of representation, which attempt to describe the ways in which knowledge is kept and organised in memory, are in fact representations of a representation. That is, they are representations of the mental activity which in turn is a representation of the world. "... within the brain there exist brain states that are the representation of the environment. The environment is the represented world, the brain states are the representing world. Our theories of representation are in actuality representations of the brain states, not representations of the world."[2]

Evidently, this distinction goes even further in implying that our access to structures in human memory is only through theories about it, also in a somewhat circular sense. That is to say, study of the representation of the environment in brain states is achieved by means of modelling human mind and memory, or constructing representations of it.

It is worth noting that theories of representation, in trying to explore representations in memory, speak about things that people have in mind, but are actually dealing with representations which are put forward in order to explain thinking and the nature of knowledge that people have about their environment, and the ways in which knowledge is organised. To do so, it seems appropriate to study the

1 See: Mandler, Jean M., 1983, pp.420-422.
2 Rumelhart, David E. & Norman, Donald A., 1985, p.17.

representations that people construct in order to express their thoughts, assuming that there is a close correspondence between these externalised representations and mental representations. We arrive, then, at the assumption that external representations reflect mental representations, and on the basis of this assumption we discuss the ways in which representations might be stored in mind.

This position raises a series of questions which concern the nature of both mental and external representations. If the study of mental representations is based on their modelling in some form of external representation, what does make mental and external representations different? To say that mental representations are in the head, that they are used in thought, does not say a lot about the nature of either and leaves aside the whole assumption. Are external representations actually 'externalisations' that reflect things which exist in mind or, in contrast, are mental representations 'internalisations' of representations that we could otherwise manifest externally? Trying to think in terms of words in order to reason about the objects that words stand for is an example which supports the second view. If this is the case, how can abstract and formal theories of representation contribute to those aspects of knowledge that might exist in mind but cannot explicitly be expressed externally? Is it plausible to assume that the formal rules and theories which govern the accomplishment of external representations apply also to all kinds of human knowledge? Is it not possible that external representations can evoke knowledge *about* the knowledge that they represent?[1]

These questions point to a rather deep philosophical problem beyond the scope of our current discussion. Theories of representation can be justified if we accept the notion of mental representations as a metaphor which allows us to discuss the manner in which people think or, better still, to construct things that work in a manner which might be similar to that of the human mind and observe their performance. In the context of this thesis, we will examine theories of representation with purpose of arriving at conclusions on distinctions relevant to the *use* of representations in cognitive processes, and especially external representations. The use of drawings is what connects them to designing and design artifacts, and this connection is what gives them meaning. Here we are dealing with the question of *what* a representation is, and later we will ask *how* a representation is used. The two questions are interrelated, to the extent that our understanding of what something is regulates what we can do with it.

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1 Some of these issues are discussed in: Lee, John R., 1990.

5.2. Kinds of Representation

With these thoughts in mind, we can now review some of the theories explaining the nature of representation, and examine the features of various representational formats. A representation can be seen as a relation between two worlds, the represented and the representing world. A representation is constituted by the represented objects, the representing objects, and a process which connects them. In order to see what the notion of a representation implies, we could start with a simple example.

Figure 5.1 illustrates three different representational formats. The represented objects consist of two figures, one taller than the other.[1] We recognise in the figures the property of having some height, and as consequence of this property, there could be a relationship between the figures of the form: *tallerthan*.

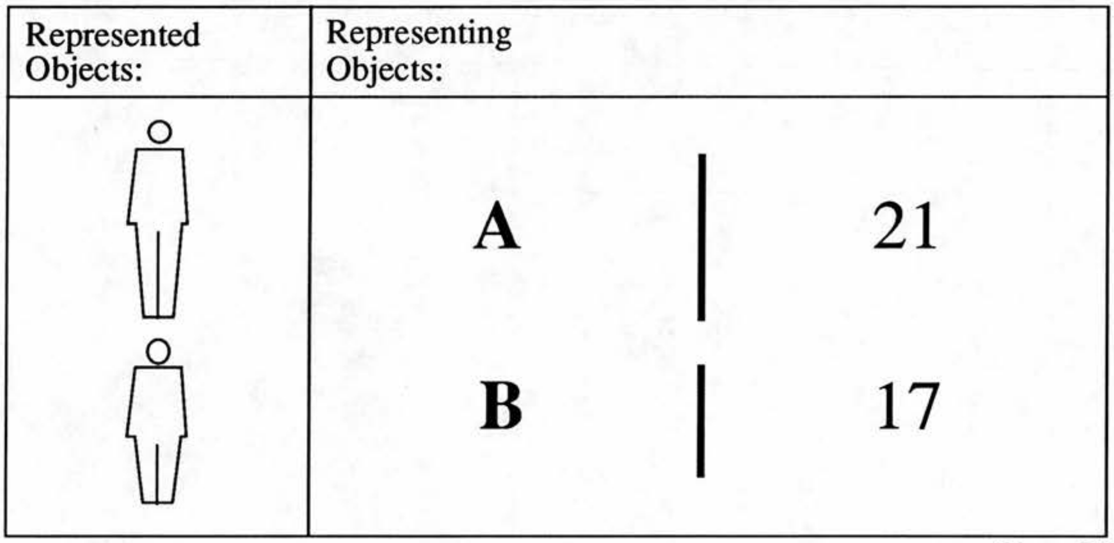

Figure 5.1

In the first case, the symbol *A* stands for the taller figure and *B* for the shorter. The relationship which holds between them can be represented by some formula: *A tallerthan B*, but in this system there is no explicit representation of height. In the second case, the figures are represented by lines. Height is directly represented by line length and the relationship *tallerthan* is implicitly represented by the physical relation *longerthan* between the line segments. In the third case, the figures are represented by

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[1] The represented objects can also be seen as representing objects if we consider another representation in which the pair of represented and representing worlds consists of, say, people and a set of figures. However, let us suppose that here we are not interested in this representation.

numbers and the magnitude of the numbers represents their heights. The relationship *tallerthan* can be represented by the arithmetic relation: *21>17*.[1]

Consider that each of the kinds of representation is accompanied by a process that the representing objects make use of, which assists them to carry their meaning and allows us to interpret the representational structures. If, for example, the purpose is to represent the distinctive concepts that the figures stand for, the process has the form of 'labelling' the concepts using distinct symbols, as in the first case. The same process enables us to compare the symbols (e.g. $A = A, A \neq B$, etc.) and to map to them also the relationship *A tallerthan B*. If, on the other hand, the purpose is to represent the property that is associated with the concepts (e.g. height), the process involves the selection of representing objects in a manner in which they possess a property (e.g. length) to which the represented property can be mapped. The same process allows us to compare properties of the representing objects (e.g. line lengths). If, finally, the purpose is to represent values of the property by numbers, there are processes which can operate upon numbers.

It should be clear that simply the selection of pairs of represented and representing objects is not sufficient to construe a representation. Inherent to any representational system and, consequently, any particular kind of representation, is an account of a process that connects represented and representing objects. The representation is accomplished by virtue exactly of such an account.

In the case of formal representational systems, this process is encountered by *functions*, that connect representing objects with a represented world, which are established before any operation is executed upon the representing objects, and should rely on semantic precision and take into account certain syntactic rules. With 'semantic precision', we should note the fact that certain distinctions within the represented world are recognised as taking part in the representation while others are left outside, as illustrated in our example. With 'syntactic rules', I refer to rules that specify the manner according to which representing objects are related to each other. If, however, we consider people accomplishing a representation, then this process has to be considered in a broader sense, even in the case of people's use of an established formal system. This broader sense has to account for the represented and representing objects being connected in as far as there is an *intention* to connect them. In other words, a representation exists if we want to see it as a representation.

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1 Figure and example from: Rumelhart, David E. & Norman, Donald A., 1985, pp.16-17.

This position might imply the view that there can be a representation that is based on the private and the hidden understanding, being a representation only for the person who makes it.[1] Yet, it seems important to keep in mind this condition especially since we are interested in representations such as design drawings, partly used for self-communication. Here, let us continue with a discussion on different kinds of representation.

Declarative and Procedural Representations

The most widely accepted categorisation of kinds of representation relates to distinctions in the kinds of knowledge being represented. Two kinds of knowledge that are often distinguished refer to knowing about something and knowing about ways of doing something. They are usually called declarative and procedural knowledge respectively. In a declarative representational system, the emphasis is placed on concepts, their relation to other concepts, and the ways in which these are structured into knowledge and stored. Procedural representational systems focus on actions and operations, and the ways of representing knowledge by means of some procedure. Good examples of this kind of representation can be found in computer programs, as they usually employ procedural systems. A program may not know that 2+2=4, in the sense that there is not some table connecting numbers and giving results stored in its database, but it knows how to find the answer rapidly and easily by means of an operation.[2]

A position accepting design expressions as procedural representations should imply that knowledge could be represented by the mechanistic and procedural aspects of the production of drawings. This looks plausible if we take into account the knowledge which underlies the skills of draughtsmanship and the techniques that are developed during the representation of design ideas into design drawings. Normally, such knowledge has to do with using the drawing tools correctly rather than being an essential part of the knowledge incorporated in the design process itself. It can be said that this knowledge neither relates to the cognitive operations by which designing develops nor includes the higher design concepts to which these operations are directed. This knowledge usually is viewed as supplementary to design knowledge and its lack does not seem to affect the competence of a designer. On the other hand, it

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1 See the discussion on the idealistic view of drawings in: Burman, Christian & Säätelä, Simo, 1991.

2 For the distinction between declarative and procedural representations, see: Winograd, Terry, 1975.

also is apparent that the development of drawing tools and techniques is not unrelated to more fundamental design processes. Indeed, there are cases in which specific procedures in the accomplishment of drawings are employed to exemplify spatial relations between parts of a designed object.

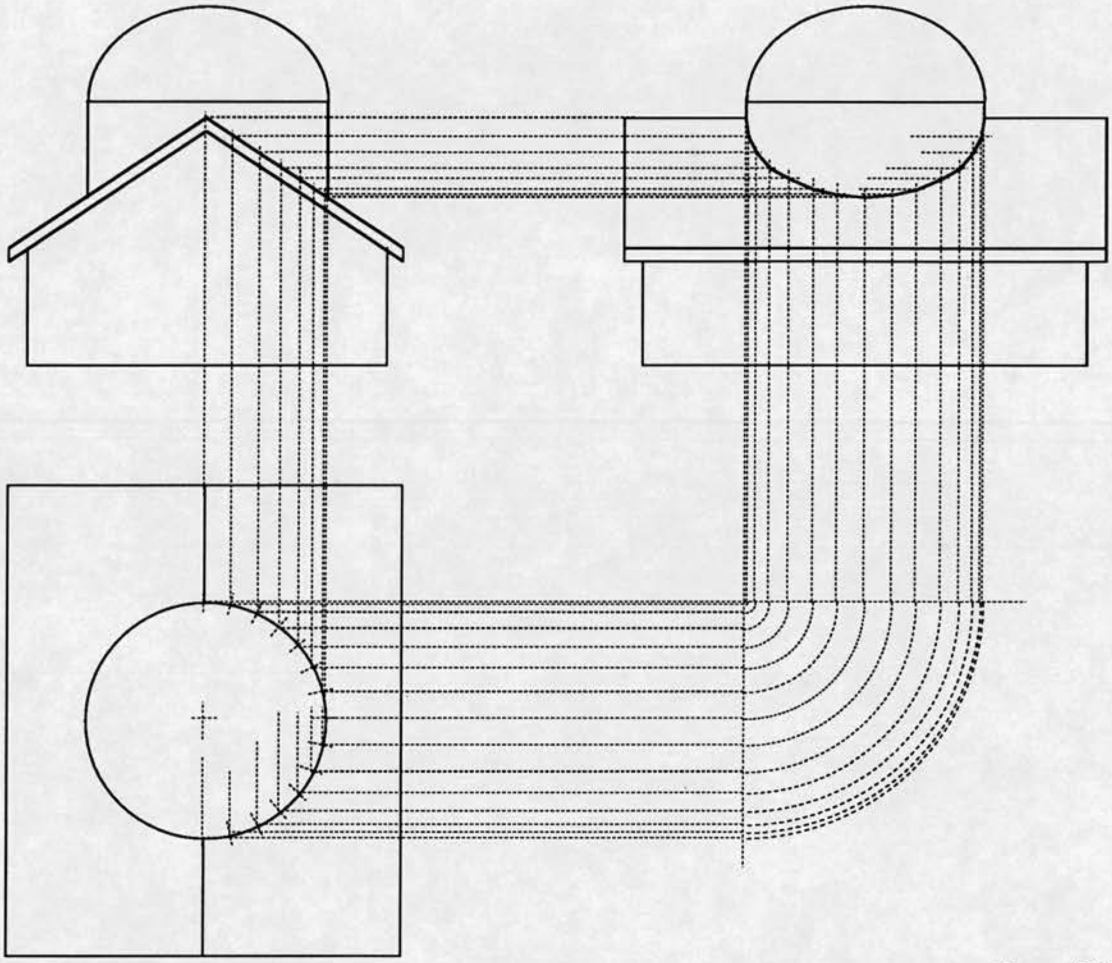

Figure 5.2

Figure 5.2 demonstrates an example in which the employment of a particular drawing procedure is used to obtain the correct position of a spatial element in relation to a base element that supports it. This procedure is a direct implication of descriptive geometry upon which the accomplishment of orthographic drawings is based.[1]

However, the role of drawings in design is better understood if we accept them as declarative representations of design concepts. Even in the example just presented, once the drawing is accomplished it continues to depict the particular spatial relations irrespectively of the procedure that was followed for its construction. This is

[1] It will be argued later that drawing procedures like this are used in order to exemplify the spatial properties of drawings. See: 9.2. Drawings and Spatial Objects.

not a case in which a specific operation is always used to obtain the desired result, but rather a depiction which stores the result, which indicates the capability of drawings to represent spatial concepts. This capability is what concerns us here.

Propositional and Analogical Representations

Distinctions relevant to our topic relate to ways in which concepts and knowledge are stored in human memory and how these affect the ways in which representations are structured. Most theories of representation take the view that knowledge and information are represented as highly structured configurations of discrete symbols associated with certain procedures for interpreting them, so that concepts are represented by formal statements or propositions. Symbols are taken to be arbitrary, that is to have no morphological, structural, or other relation with the realities that they stand for. Systems which are based on this view are often called propositional, symbolic, or digital representational systems. An instance of such a system is illustrated in the first case of our examples of representational systems: A and B in *Figure 5.1*.

It should be noted that although propositional systems quite often make use of examples from language and verbal expression, they are not direct mappings of linguistic representations but instead they refer to abstract structures which underlie expression, the so called 'deep' structures of language. Propositions are what logical constructions say irrespectively of the natural language according to which sentences are uttered. They are factual, i.e. they can be evaluated according to assessments of truth, and they must be 'well formed', i.e. the consistency of their structure is maintained in respect to certain syntactic rules that are independent of the realities that they are expressed.

While propositional systems seem sufficient to model conceptual knowledge, there is a continuing debate over how visual information is represented in human memory. Is visual information stored similarly in a propositional form or, in contrast, in some other distinct form, usually called imaginal or analogical?

Analogical representational systems are often said to be systems in which the correspondence between the represented world and the representing world is as direct as possible. This correspondence is usually accomplished by the employment of variables to represent concepts that are continuous, such as spatial properties, movement, rotation, fluid flow, etc. According to Sloman, an analogical representation is a direct representation in which "properties of and relations between parts of the representing configuration represent properties and relations of parts in a complex represented configuration, so that the structure of the representation gives information about the structure of what is represented".[1] An instance of an analogical system is shown in the second case of our example: the line lengths in *Figure 5.1.*

The Representation of Concepts and Images

The distinction between propositional and analogical forms of representation becomes important if we relate them to the verbal-conceptual and spatio-imaginal models that underlie the development of a designed object, which were discussed in the previous chapter.

If images are held in memory in some representational format radically different from the format according to which concepts are stored, how can mappings between them be accomplished? What is the kind of manipulation that imaginal mental models might have under cognitive operations? If design drawings are just externalisations of images, how can conceptual design knowledge interact with them? In order to obtain an understanding of these issues, it might be helpful to examine some studies on how verbal concepts and images occur in memory, and relate them to our context of design cognitive activity and drawings.

The Representation of Verbal Concepts: Semantic Networks

Theories on the representation of knowledge largely agree on the format of representation in which concepts can be represented as being symbolic or propositional. The main principle behind these views is that concepts are represented as a set of semantic features or attributes. Concepts can be: disjoint, have no attributes in common; overlap, have some but not all attributes in common; be nested, all of the attributes of one concept are included in another; or be identical, have exactly the same set of attributes. This, in some sense, is an application of the set theory to knowledge.[2]

The ideas behind the notion of attributes to specify concepts can be traced back to Aristotle and his categories, species and genera. Yet, only recently has this notion received considerable attention in the development of theories about the organisation of human memory.

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1 Sloman, Aaron, 1971, p.216.
2 See: Rumelhart, David E. & Norman, Donald A., 1985.

Various formalisms have been developed to advance this approach. These include the view of "schemata", as interacting data structures for representing generic concepts stored in memory. The structures exist for objects, situations, events, sequences of events, actions, and sequences of actions, and they include networks of interrelations that are believed to hold generally among the constituents of a concept.[1] Another formalism is based on "frames", which are data structures for representing stereotyped situations, including also networks of nodes and relations. Attached to a frame are "terminals", filled with specific instances of information, which specify the conditions that frame assignments must meet.[2] Also, the view of "scripts" and "plans", according to which the memory system consists of an enormous number of packets of knowledge. Scripts can be thought of as structures for frequently occurring sequences of events, containing a number of "entry conditions", a sequence of "scenes", and a set of "results". Plans are more general and more abstract structures which are formulated in order to satisfy specific motivations and goals, involving future actions to attain these goals.[3]

These approaches include the theory of semantic networks which will be discussed in more detail, not necessarily because it is the most appropriate model to explain the way in which conceptual knowledge is structured, but because it seems applicable to our view on design conceptual models.[4]

A typical example of studies on which the model of semantic networks is initially based is illustrated by the simple semantic verification tasks in which subjects are asked to respond 'true' or 'false' to sentences stating members of one semantic category that could be also members of another. For example, 'A canary is a bird', 'An orange is not a vegetable', etc. The central assumption is that words representing categories could be represented by a set of semantic features which vary in their relationship to a formal definition of the category. These features include necessary attributes of the concept being represented which are sufficient to define it (they must hold for any member of the category, e.g. 'A bird has feathers'), and attributes which

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1 This approach is refined by: Rumelhart, David E. & Ortony, Andrew, 1977. (Schemata originate from the work of Bartlett, F. C., 1932.)

2 Frames were put forward by: Minsky, Marvin, (1975) 1981.

3 This theory was developed by: Schank, R. & Abelson, R., 1977.

4 This theory is based on a series of studies that begin with work on semantic memory (Collins, A. M. & Quillian, M. R., 1969), semantic information (Meyer, D. E., 1970), and continue with the model of semantic features and attributes (Smith, E. E., Shoben, E. J. & Rips, L. J., 1974). The term 'semantic networks' is probably attributable to Quillian, M. R., 1966. For a review of semantic networks, see: Brachman, Ronald J., 1979.

are only characteristic of the concept being represented (they usually apply, but not necessarily for all the members of the category, e.g. 'A bird can fly'). These studies support the associative view of the nature of knowledge, and suggest that there is a detailed structure of knowledge about any single concept.

As an important development in the representation of associations, semantic networks put forward the assumption that knowledge can be represented by a kind of labelled graph structure in which the basic structural element is a set of nodes, representing concepts in memory, which are interconnected by relations, representing the associations between the concepts. Relations are labelled and directed. Concepts might have names corresponding to natural language words (or not) standing for instances of concepts. According to this view the meaning of a concept, which is a node in the relational structure, derives from the pattern of relationships in which it participates.

It can be said that semantic networks departing from the study of linguistic representations, which are expressed in a symbolic and sequential fashion, go deeper into the abstract structures that support this kind of representation. These networks suggest an organisation of associations between concepts that does not have a linear and sequential form, but rather relies on a spatial configuration. Before continuing to discuss what this view suggests for the organisation of design knowledge, let us have a short look at theories about image representation.

The Representation of Images: Analogical Representations

Studies of the representation of images usually refer to processing mechanisms that underlie visual perception, or transformations of images during their mental manipulation. There is also some work on the representation of images for some operative purpose as, for example, the description of pictures in computer programs.

Most of these studies, especially in the first field, take the view that images are represented in memory in some analogical fashion rather than propositionally. Advocates of the employment of analogical forms in the representation of visual information suggest that knowledge underlying images and their transformations is also analogical in contrast to symbolic.

Shepard and Cooper, for example, have studied simple mental manipulations of mental images.[1] They suggest that the process of mentally manipulating an object involves the use of a mental analog of the external manipulation. This process is analogical because it has something common to the internal process that would take place if someone were actually perceiving a physical object undergoing the same manipulation externally. Also, the mental manipulation passes through a series of intermediate states each one of which has a one-to-one correspondence to an intermediate state of an external manipulation of the object. According to them, this last point characterises a process as analogical since in any other type of process, such as symbol manipulation, the intermediate stages of the process have no correspondence to intermediate situations in the represented world.

Kosslyn's theory of image representation while reflecting some of the ideas just presented does not make any strong claim about analogy.[2] According to him, there are two kinds of representation associated with visual information, "surface representation" and "deep representation". Surface representation corresponds to the visual image and occurs in a spatial medium so that parts of it represent corresponding parts of the represented object and distance between parts of the representation correspond to distance between parts of the objects. Surface representations can have a loss in detail if the object is too small and can fade away if the object is exposed for a short time. On the other hand, deep representation is an underlying abstract representation to which the surface representation is related. This representation does not have the same properties as the surface one. Surface representations, once formed, can be compared as a whole to percepts in a template-like manner, while deep representations are better seen as interpretations of surface representations. As such, the assumption involves the existence of an 'interpreter' which acts as an interface between the surface and deep representation. The interpretive process might involve the processing mechanisms that are employed in visual perception, although deep representations cannot be compared to percepts.

There is another view about image representation which discards the analogical form and suggests that images are essentially symbolic.[3] As a representative of this position, Palmer proposes a "feature" representation that looks

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1 Shepard, R. N. & Cooper, L. A., 1982.
2 Kosslyn, Stephen M., 1980.
3 The 'anti-imagist' position is nicely presented in: Pylyshyn, Zenon W., 1973.

similar to the structure of semantic networks.[1] Features are elementary units of which the visual image is composed: lines, curves, angles, etc. The representation of the image is a structure of these features. Features are related to each other with relationships that have to do with spatial location, shape, colour, size, and texture, which are also assigned relational values or dimensions. In this way, features and relationships become structural units that give information about the image. The structural units can be primitive, for example a point, but also complex and highly ordered, like squares and cubes. He suggests that the propositional system is more flexible than the analogical because it can encode diverse types of information in the same format. For example, topological relations and colour. He also suggests that a propositional system can capture the types of image manipulation that are analysed by Shepard and Cooper.

These theories about images indicate that, as in the case of linguistic representations, more abstract structures of knowledge underlie the representation of images. Kosslyn, in particular, makes a clear distinction between a representation that occurs in a spatial medium, and a deeper one, that acts as an interpretation of the spatial representation, which can be directly related to the 'deep' structures of language that propositional formats attempt to model. Palmer goes even further to suggest that all attributes of image representation can be modelled by a propositional system.

Palmer's theory becomes important if we take into account our interest in computerised systems that support image representation. Since representations in computerised systems rely at the lowest level on symbolic structures, this view clearly suggests that all attributes of drawings can be effectively represented in a computer medium. This needs to be the case when, at the level of use, drawings in computers have to maintain their analogical character.[2] However, in contrast to this account, Kosslyn, and Shepard and Cooper recognise the structural differences between analogical and symbolic representations and accept the functional role of mental imagery.[3] These differences are better expressed perhaps by Shepard and Cooper who characterise as analogical the process in which the intermediate states of the manipulation of the representation have one-to-one correspondence to intermediate states in the represented world.

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1 Palmer, Stephen E., 1975.

2 However, as discussed later, this assumption entails certain implications for the use of computerised drawings. See: 7.2. Computers in Use.

3 The role of images in mental activity is clearly expressed by Kosslyn in: Kosslyn, Stephen M. & Pomerantz, James R., 1977.

These differences need to be explored if, indeed, we intend to focus on the functional role of drawings in designing, and the meaning that they obtain during their use. At this stage, we can accept the relationship of mental images to deeper abstract structures of knowledge, and attempt to see what this involves for the modelling of conceptual knowledge in designing.

5.3. Relations between Images and Design Concepts

In our discussion on cognitive operations and the ways in which design knowledge is stored and structured in memory, we have assumed the existence of verbal-conceptual models as the organisational patterns of conceptual knowledge, but also the occurrence of spatial models and mental images by which initial spatial arrangements of the designed object are approached. We have also suggested that the development of mental images and their manipulation under the interrelations and dependencies that emerge within the context of conceptual models facilitates the task, central to design, of organising the spatial form of the designed object in reference to these models.

This assumption certainly implies the view that there is some mapping between mental images and concepts which, however, does not necessarily entail a one-to-one correspondence. Concepts can be thought of, for example, that do not have an imaginal correspondent, as in the case of abstract entities, and concepts may have several imaginal correspondents, like the structural elements of a building. Similarly for imaginal models, some mental image may correspond to not just one but several conceptual entities.

At some organisational level, it seems plausible to assume that conceptual entities in design could be modelled under the formalism of semantic networks. It is evident, for example, that the cost of a structural element in a building is not determined by the price of the materials that compose it but is an aspect which is determined by a series of factors, like the expenses of its construction, its maintenance, the efficiency of its performance, etc. A network of associations, consequently, might be conceived in which relations between distinctive factors are indicated constituting a representation of some conceptual model of cost efficiency of the building. A particular design element could obtain its attributes in relation to this structure. Similar networks could be conceived that might vary from the general principles underlying the definition of a design task, like function, accessibility, circulation, cost efficiency, energy efficiency, etc., to the specific factors encountered under each of these principles.[1] Additionally, these networks could be linked to each other resulting in a lattice-like structure of the overall design task similar to the one suggested earlier in the discussion on cognitive operations in design.[2]

This understanding is based on a rather rough interpretation of the notion of semantic networks, as they were not initially introduced to represent the complexity of context specific problem solving tasks, but to specify the organisation of memory in general. A striking difference is that concepts connected into a network in the case of a design task are far more vulnerable to specifications of attributes which usually cannot be verified by just true or false values. This is entailed by the nature of design concepts but also from the individuality in the way they are interpreted. As we have seen earlier, concepts in design could emerge on the basis of implicit and private abstractions of knowledge and information, closely connected to the context of the particular design episode, which are not always open to rational analytical examination.[3] However, this should not pose us severe restrictions here. As far as the structure of representations concerns, there could be similarities between the associations that semantic networks implement and the associations implied in the conceptualisation of a design task.

If this assumption is valid, it can be suggested that the associations between design concepts, implied by an organisation such as the one under semantic networks, can qualify for the 'deep' structures of design knowledge upon which the interpretation and manipulation of external representations in either linguistic or graphical form is based. This view seems to be consistent with the approaches of the advocates of both propositional and analogical representations.

In order then to see how external representations are connected to structures of design knowledge, we can examine the mechanisms which are employed during the interpretation of representations. The study of the interpretation of representations will help us to identify the manner according to which mappings between images and conceptual entities are attained. Based on the assumption that similar mechanisms are employed during the manipulation of imaginal or verbal information by cognitive

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1 For a series of attempts to represent with the aid of graphs the structure of connections and associations between aspects underlying the design of an object see: Broadbent, Geoffrey, 1988, pp.252-271.

2 See: 4.2. Cognitive Behaviour and Design Activity; Transition between States in Designing.

3 See: 3.1. The Framework of Discourse.

operations, this approach will offer an account of the relations between spatial and verbal conceptual models.

The approach presented below is closely connected to the theories about representation of concepts and images outlined earlier, but it is further developed by relating them to findings of experimental studies in the field, principally to the work of Allan Paivio on verbal and image information processing.[1] There is also a connection with the discussion on cognitive operations outlined in the previous chapter.

The Interpretation of Design Expressions

In our discussion on cognitive operations in designing, we have suggested that external representations serve as a kind of external memory that acts as a repository of elements that are no longer manipulated in the short term memory but can be reached later by recall mechanisms. Recalling, however, involves the further activation of cognitive operations that starts with acquisition of information.[2] To this extent, external representations, in either linguistic or graphical form, are not differentiated from other external information and can be seen as a particular class of stimuli. Consequently, the interpretation of external representations can be viewed as a reaction to these stimuli. That is to say, due to response to stimuli, particular processing mechanisms are activated which cause the emergence of meaning.

The assumption suggests that any stimuli can give rise to meaning with conceptual or imaginal components, in relation to verbal-conceptual or spatio-imaginal models, or both at once. It further implies that, to some extent, the response to other kinds of stimuli is similar; that is not only to information from design expressions but also to the stimuli encountered by all instances of acquisition.

Meaning does not, of course, occur in any measurable form, nor it can be understood except through behavioural manifestation. It can be better thought of as a response "disposition".[3] It can be said that meaning can be variable, that is specific stimuli can invoke varied interpretive mechanisms, in relation to prior events or the situational context.[4] This implies that there is always some ambiguity irrespectively of

1 This work is briefly presented in: Paivio, Allan, 1971, while an extended description of it can be found in: Paivio, Allan, 1979.

2 See: 4.1. Design Actions, Transformations of Information, and Cognitive Operations; External Representations.

3 "Meaning reactions are the *aroused*, covert (inferred) or overt expressions of ... organismic dispositions." Paivio, Allan, 1979, p.51 (original italics).

4 By accepting that meaning is dependent on the context of the interpretation, this position indicates that meaning is also dependent on the specific use of representations each time. However, let us

whether stimuli convey verbal or visual information. However, for particular reasons that we will see later, it is anticipated that ambiguity is higher in the case of visual information. Nevertheless, the variation in reactions is not unlimited, and some reactions might be more consistent than others. Otherwise the relation of meaning to stimuli could not be understood.

The interpretive process can be regarded as a series of elaborations of the incoming stimulus information. It starts with the perception and the encoding of information and then continues with transformations under the cognitive operations of projection, confirmation, and, to some degree, regulation of flow.[1] The way in which these operations collaborate has been extensively discussed in the previous chapter. While meaning is attributed mainly to the encoding process, including acquisition, the activation of these operations might also affect the components of meaning. Apparently, these operations are activated in order to transform the representation, a fact that implies the occurrence of previously accumulated meaning. Yet, since meaning is not stable and since the activation of cognitive operations is interconnected, components of meaning may be affected even during the encoding in respect to some operation, like confirmation or projection, that is to follow.

Accordingly, it can be assumed that the interpretation of external information does not have a definite end, or otherwise that results of interpretations are re-interpreted and re-interpreted through transformations by cognitive operations in respect to specific conceptual models on each occasion. It can even be argued that the conceptualisation and accomplishment of a design task as a whole is an interpretation of external information,[2] in which case each particular cognitive operation can be seen as an interpretive process. Here, however, we concern ourselves with the initial stages of this activity, namely with the encoding of stimuli information.

Levels of Interpretation and Components of Meaning

The encoding of information itself can also be regarded as involving different levels of processing. These are similarly seen as continuous but they could be distinguished for convenience as the *iconic*, referring to the perceptual aspects of

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not concern ourselves with the nature of meaning here, but rather the mechanisms by which it is attained.

1 The involvement of regulation of flow might guide the accomplishment and the interpretation of representations, yet it can be assumed that meta-knowledge is not directly represented in design expressions.

2 This approach to the conceptualisation of design tasks is discussed in: Goldschmidt, Gabriela, 1988.

acquisition, *symbolic*, where stimuli are mapped to symbolic representations in long term memory, *referential*, where verbal concepts and imaginal components of meaning are interconnected, and *associative*, where concepts are related to structures of associations in memory.

The iconic level refers to the fading perceptual 'icon' that is retained for a brief period after stimulus exposure. The icon is the result of an extraction of visual features of the stimuli by some feature-detection process. The features from which icons are composed, either for verbal or imaginal stimuli, include lines, angles, orientations, velocities, and colour. The properties of this trace of the stimuli are attributed mainly to the mechanisms of visual perception. As such, the iconic level can be seen as a starting point in the interpretive process with null or minimal components of meaning. Yet, visual perception is active and 'minimally' implies a differentiation in the way that the feature-detector process is accomplished for the case of imaginal or verbal stimuli. Although icon features are primitive and are not classified under meaning, there is evidence that linguistic information is extracted serially and the features composing each character are combined under labels one-by-one in a left-to-right fashion. In the case of imaginal information, icons are visual in the sense that the perceiver 'looks' at their features and scans them indiscriminately rather than labelling them.[1] At this level, we cannot assume that the perceiver knows what the icon contains. This differentiation might be apparent from involvement of the following level of interpretation.[2]

The symbolic level refers to the hypothetical symbolic representations which are stored in memory. These can be images in the case of imaginal stimuli or auditory-motor representations for the case of verbal stimuli. Images are symbolic representations in memory which could be related to visual patterns that are composed by perceptual features. In this sense, an image is an informational representation of the stimuli rather than just perceptual. It is what the perceiver associates with a particular stimulus configuration.[3] Auditory-motor representation refers to the implicit

1 Visual perception, in the context of this level in the interpretation of stimuli, is discussed in relation to a series of psychological experiments in: Haber, Ralph Norman, 1971.

2 The iconic components of meaning can be compared to the notion of "surface representation" in Kosslyn's theory. However, Palmer's theory of "feature representation" appears to be applicable for its implementation as icons are approached in respect to visual features.

3 This view is consistent with the majority of the studies on visual perception. Arnheim, for example, suggests that "... the optical image projected upon the retina is a mechanically complete recording of [the] physical counterpart [of a shape, while] the corresponding visual percept is not. The perception of a shape is the grasping of the structural features found in, or imposed upon, the stimulus material." Arnheim, Rudolf, 1969, p.27.

or explicit emission of the symbol itself as the initial reaction to the verbal stimuli. For the case of written words the auditory component of the representation is reduced but the interpretive process still involves a grapheme to phoneme transformation. The characteristic representational unit of verbal perceptual forms is assumed to be a word.[1] At this level, the process involves an early matching between stimuli and concepts which is further developed at subsequent levels. Images and auditory-motor representations are put in a correspondence to verbal concepts. This matching can be thought of in the elementary sense of knowing what the stimuli are about rather than obtaining a comprehensive notion of a concept.

At the referential level associative connections between the imaginal and verbal representations are construed, such that a picture can be named, therefore can raise a verbal concept or concepts. A word evokes an image, thus it is related to an imaginal equivalent or equivalents. This referential linkage can be symmetrical or asymmetrical, depending on the conditions of acquisition. Familiar pictures and their labels may be experienced together in such a manner that the word evokes an image as readily as the picture elicits its name, or the associative experiences may be such that the verbal and imaginal referential reactions are differentially available to stimuli. This differentiation depends also on the abstractness or concreteness of the concept. It depends on whether the concept refers to a physical object in the world or a purely abstract entity. However, the distinction between abstract and concrete concepts is better conceived as a relative distinction of degree rather than a sharp one, at least as far as referential linkage is concerned. Paivio shows that abstract concepts can also raise imagery, but do so less readily than concrete ones. Abstract and concrete concepts do not show any difference in familiarity in the case of symbolic representational meaning.[2]

Finally, the associative level has to do with associative reactions that relate to the referent. It involves the development of associative connections, an associative structure of images or conceptual categories. The associative structure is assumed to be notional, that is entirely verbal and propositional, and can be approached by the model of semantic networks presented earlier. Yet, each particular concept in the structure can have imaginal referents, thereby extending the idea of semantic networks to include images as well as verbal concepts.

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1 Paivio, Allan, 1979, p.54, pp.55-56.
2 Paivio, Allan, 1971, pp.12-17.

Significant Schemes

Despite the differentiation in levels of interpretation and the assumption that each of these levels imposes particular components of meaning on the interpretation of a design expression, it should be noted that the interpretation as a whole is obtained through interconnection of the various levels. As such the process of interpreting an expression can be regarded as an attempt to extract information from perceived stimuli in reference to what is currently present in mind in terms of images, concepts, and conceptual models. This process is time and context specific. That is to say, it is dependent on particular stages in the design task in relation to cognitive operations that were active before interaction with the expression, or are about to follow. This view obviously takes into account the purpose for which a particular 'reading' of an expression is made in relation to the design task.[1] As a consequence of this aspect, design expressions become subject to varied and sometimes diverse interpretations, possibly to a greater degree than many other kinds of expressions.

The interactions and interconnections between the different levels in the interpretation can be captured by the notion of *significant schemes*. A significant scheme can be seen as a structure of hierarchical cross-level links in memory.[2] An associative structure, under a conceptual model, can be considered as the base of the hierarchy, which is followed by individual concepts, and then corresponding images. In the interpretation of an expression, significant schemes operate reversely. Thus according to a scheme, a single symbol or a set of symbols in the expression is mapped to a particular image from the series of images that it may correspond to (or directly to a concept in the case of verbal information). The image is similarly mapped to a particular concept from the concepts that may relate to, and this concept is located within a particular network of associations under some conceptual model. It is

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1 Marr supports a similar approach to vision in general. He defines vision as "the process that produces from images of the external world a description that is useful to the viewer and not cluttered with irrelevant information". Marr, David, 1985, p.119.
The role of purpose in interaction with expressions recently gained considerable attention also in linguistic studies. Grosz and Sidner, for example, suggest that discourse structures are composed, in addition to the structure of the sequence of utterances, by the structure of purposes and intentions, and the state of focus of attention. Grosz, Barbara J. & Sidner, Candace L., 1986.

2 Significant schemes are used in reference to the notion of 'chunks' described in: Chase, W. G. & Simon, H. A., 1973. Chunks are defined as organisers of links in memory and can be dependent on particular contexts. Certain features of stimuli can cause the recall of such links so that an instance of external information can be directly related to a specific situation on the basis of earlier experience. Chunks have been studied in the context of chess problem solving activity, and a typical example is the case where a certain pattern of pieces of the board causes the recall of a extensive range of known possible moves to follow.

assumed that conceptual models, placed at the bottom of a scheme, widely condition the relationships within it and, as they are connected to concepts, images, symbols, up to the level of marks on a paper, effectively become discourse models of the interaction with the expression. Consequently, different significant schemes characterise different interpretations of an expression.

Schemes can be thought of as binders of relationships between cross-level components of meaning. As a result, they give immediate access to information relevant to a conceptual model, and they do so from the model's depiction by a drawing, from a single look at the lines that compose the drawing. The way in which they operate can be compared to everyday life examples, such as the recall of a telephone number from the first two or three digits, the recall of a movie from the viewing of a single scene, etc.

Significant schemes are justifiable postulates because of the limitations of the human cognitive system, given the complexity of the interpretation described above. More specifically, a fundamental cause of what limits the quantity of information that can be encoded in memory at a given time, is the span of the short term memory. Short term memory controls the input of information and transmits it to the long term memory. Conceptual models, as we have seen, act as patterns of organisation of knowledge in long term memory. Given the limitations of short term memory, it is expected that a single conceptual model conditions the contents of short term memory at a given time, and this model characterises the selection of information from the external expression. New information, in terms of emerging images and concepts in short term memory, and its external form, in terms of symbols, are related to the particular conceptual model. The transmission function of short term memory is responsible for the binding of information into a significant scheme. The whole process results in the rehearsal and enrichment of the conceptual model which now can be thought of as retaining the cross-relationships that appear within the scheme. An important additional effect is the emergence of familiarity with respect to the groupings of symbols, so that during recall similar arrangements are immediately mapped to the corresponding information. As a consequence, significant schemes have an important role in the decomposition of expressions.[1]

This approach to the interpretation of stimuli indicates the means by which images obtain mappings to conceptual entities. Features of external representations are

[1] The involvement of significant schemes in the use of drawings is examined in more detail later: 9.4. The Connotative Function of Drawings: Significant Schemes.

mapped to either concepts or mental images, in respect to whether they refer to linguistic or visual information. These are related to corresponding equivalents, so that concepts are related to images and images to concepts, and both are connected to notional associative structures of knowledge in memory. The whole process is encountered by different levels in the interpretation but these levels are interrelated so that, on the basis of significant schemes, certain features might appear to be relevant to specific conceptual models that determine the interpretation at a given time.

If the assumption that similar mechanisms occur during the manipulation of information by cognitive operations is valid, this account specifies the manner according to which structures of knowledge under verbal-conceptual models are connected to spatial forms and how conversely spatial forms obtain their correspondence to conceptual models. In a subsequent chapter[1] we will explicitly examine the implications of this view for the practical task of accomplishing a spatial form through its dependencies on verbal-conceptual models, and we will further discuss the involvement of cognitive operations in this task, also taking into account the role that drawings play. Here, however, let us see what it is that makes drawings capable of accommodating this task, by developing our discussion of representations and their interpretation to see what this suggests for the structures upon which drawings are based.

5.4. Drawings as Representations

From the discussion on the interpretation of stimuli there are perhaps two issues which seem to have important implications for a view of drawings as representations of design knowledge. The first has to do with the differentiation in the 'reading' of external stimuli with respect to whether they refer to visual or linguistic information. This is indicated by the indiscriminate scanning of features of icons, in the case of visual representations, in contrast to the sequential extraction of information, in the case of linguistic representations. This characteristic of the interpretation can be related to specific features that can be attributed to the representing objects, which may differentiate them with respect to whether they represent visual or linguistic information. An examination of the features of drawings, accordingly, is expected to give an account of their structure and specify qualities in drawings which are important for designing.

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[1] 8. The Role of Drawings in Design: Spatial Composition.

The second issue is that meaning is in fact obtained from the representation with respect to different levels in the interpretation, up to the level of associations of conceptual knowledge. A central aspect of this view is that the different levels of the interpretation correlate so that existing knowledge structured under conceptual models can have a role in the interpretation. This assumption specifies the manner according to which spatial forms expressed by drawings obtain correspondence to conceptual models. However, as at a particular time distinct conceptual models regulate the manipulation of information by cognitive operations,[1] it indicates that the interpretation of drawings is context and time specific so that different interpretations can be obtained from the same drawing at different stages of manipulation and in different contexts. This aspect of the interpretation of representations is captured by the notion of significant schemes and entails certain implications for the use of drawings during designing.

In this part of the chapter we will try to connect these issues and see what they suggest for both the structure of drawings and their function as representations of design knowledge. Effectively, we will obtain an account of what kind of representations they are, in relation to the distinction between propositional and analogical representations, and examine how this can be applied to specific design expressions. This account will underlie our view on systematic representations of drawings in computers, which will be discussed in the following chapter.

The Features of Drawings and their Structure

If both graphical and linguistic representations are confronted as configurations that are constituted by distinct symbols that stand for represented qualities, then in graphical representations symbols have to be chosen in such a way that they possess spatial properties which take part in the representation to stand for corresponding properties in the represented world. In the case of linguistic representations symbols can be arbitrary in the sense that they have features which differentiate them from each other but none of these features is relevant to the interpretation. If the features of verbal symbols become relevant, verbal symbols can also be viewed as graphical symbols. Such is the case, for example, which appears when young children learn writing by distinguishing characters in respect to their features: 'I' is like a stick, 'O' is like a ball, etc. In the case of drawings, symbols are

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1 See the discussion in: 4.1. Design Actions, Transformations of Information, and Cognitive Operations.

used to stand for a particular concept, so for example a line is used to denote a wall, and features of symbols are used to stand for properties that can be attached to the concept, the length of the line for example to denote the length of the wall. In both cases, the interpretation requires the learning of this difference, that is to say the knowing of the process which connects the represented with the representing objects. These distinctions are well illustrated in the examples of different kinds of representation at the beginning of this chapter, in *Figure 5.1*.

Another distinction might have to do with the character of symbols. Verbal symbols are concrete, in the sense that they have a meaning which is conventionally attached to them, while graphical symbols are abstract, that is to say they obtain their meaning not in respect to some convention that connects symbols to meaning but in respect to relations between each other within the whole configuration. So, for example, it is not the case that all lines in all drawings stand for walls but the relations between graphical symbols within a particular configuration allow us to interpret particular symbols as walls. The depictive value of graphical representations can be attributed to this particular quality.

This assumption does not imply that abstract objects are represented by the use of graphical symbols or, similarly, concrete situations by the use of verbal ones. It suggests, however, that both graphical and verbal symbols can be seen as different classes of stimuli with features specific to their class. In consequence, it can be said that these features of symbols are taken into account during the interpretation of representations. Verbal symbols are interpreted, even from the first iconic level of interpretation, following a serial fashion so that there is *sequential* information processing according to which a word is given meaning that is related to the meaning of the next word, and to the next one, and so on. In the case of graphical representations, there is no starting point from which the interpretation should begin and the interpretation follows *parallel* information processing so that relations between graphical symbols can be recognised, allowing the attachment of meaning to particular symbols, in respect to which further relations are recognised, and so on.

This particular condition is perhaps what causes more ambiguity in the case of graphical representations.[1] If we do not take into account the situational context of the interpretation of a representation, it seems extremely difficult to be sure about the relations between graphical symbols expressed in more that one direction – in contrast

1 See above: The Interpretation of Design Expressions.

to linguistic representations where such relations do occur in one direction – and about the basis of these relations for determining the meaning of specific symbols.

However, some of this ambiguity can be reduced if we consider the context of the interpretation as it is captured by the notion of significant schemes. Significant schemes, acting as binders of cross-level links between the levels of the interpretation, can allow the connection of a particular conceptual model with the features of a graphical representation so that relations between graphical symbols are obtained in respect to it. Yet, it has to be realised that during any subsequent interpretation another conceptual model might be connected to the same graphical representation so that different relations between the graphical symbols can be recognised, and as a whole the graphical representation can cause the emergence of different meaning.

If we consider the kind of information that particular representations are used to represent, we can say that, as relations between the graphical symbols of a graphical representation can occur in various directions, the graphical system can represent units of information which are organised in a spatial medium so that multiple relationships between them are expressed in a coincident manner. Bearing in mind that drawings are used to represent spatial forms, this view brings drawings close to Sloman's definition of analogical representations to the extent that the structure of relations between the graphical symbols that constitute a drawing tells us something about the structure of spatial relations between the different spatial elements that constitute a spatial form.

The same view, however, implies that the relationships between symbols of a graphical representation can also efficiently represent more abstract relations between components of conceptual models. As we have seen, the organisation of concepts according to the formalism of semantic networks follows an essentially spatial rather than sequential pattern. Concepts appear as nodes in a graph structure and can be related to each other through verbal-conceptual associations. A graphical representation, in consequence, can be conceived as depicting the relations under specific conceptual models. Thus, for example, we may have a graphical representation of the topological relations between areas of activity for the model of distribution of activities in a building. This graphical representation might better be understood as having a diagrammatic form, rather than being a drawing.

However, if we take into account the correspondence between elements of spatial forms and components of conceptual models, drawings can also be seen to represent relations under conceptual models. That is to say, drawings can be seen as the representation of the spatial form of the building which in turn can be interpreted in respect to its correspondence to conceptual models with the involvement of significant schemes. This representation would similarly be analogical according to Sloman's definition to the extent that relations in drawings are mapped to relations in conceptual models. This particular aspect of drawings demonstrates a quality in their function as representations which can be directly attributed to their analogical character.

The recognition that the features of graphical symbols play an important role in graphical representations, makes Palmer's theory look applicable for the representation of drawings, since the properties of the graphical symbols that compose them can be mapped to the qualities that they stand for following a propositional format. This view appears to be particularly important for the representation of drawings in a computer medium, as was indicated. Since however the distinction between propositional structures and analogical use has not been clarified yet, at this stage it may be useful to open a discussion about the notion of analogy itself.

Analogies in Drawings

Analogy can be described as a correspondence between two domains which holds in such a way as to allow a mapping of knowledge from the one domain (the base) into the other (the target) in respect to some particular aspect. This entails that the aspect by virtue of which two objects are placed in correspondence can be found in both the base and the target object. In other words, the mappings are judged from within each domain and not by some external arbiter.

It has to be noted that the mapping of knowledge refers to just those aspects that take part in the analogy and not the objects as a whole. Usually, analogy refers to systems of relations that hold among two objects. Consequently, it can be said that the analogy is a way of capturing relational commonalities *independently* of the objects in which those relations are embedded. So, for example, there may be a comparison between the piping system that carries water within a building and an electric circuit. Even if the two systems are quite different in many aspects, there can be an analogy with respect to the flow of water and electricity within the systems. Corresponding attributes of flow can be compared like the leak of either water or electricity, flow in closed loops of the systems, implications of the diameter of the pipes and resistance of wires to speed and intensity of flow, etc. The important point is that once the analogy is established, it follows that the person who recognises the analogy can be confident that implications from the relations applied only to the base object will hold also for the corresponding relations within the target object.[1]

The usefulness of analogical mappings in design should be apparent. They enable the study of spatial relations of the designed object by dealing just with their representation in design drawings. Design drawings demonstrate analogical features possibly to a greater degree than ordinary pictures do. It is evident, for example, that drawings allow us to talk about buildings as if they were already placed within the physical world. Analogy permits direct mapping of properties of drawn objects to corresponding properties of physical objects, which results in the construction of the designed object. In the case of pictures, although there is a more global understanding of the visual features of represented objects, there may be some difficulty in appreciating the spatial relations between the elements that compose the represented objects and their values. This difference follows from the definition of analogy above. We can say that pictures are placed in analogy to an object with respect to visual features, while design drawings are placed in analogy with respect to spatial relations.

However, the application of this notion of analogy to the issue of representation gives rise to some difficulties. Analogy is insufficient by itself to specify the concepts that representations stand for, as it refers only to those aspects which are placed in correspondence. There is nothing analogical about a drawing, for example, which tells us that a line stands for a wall, even if its length is mapped to the length of a wall by virtue of some analogy. In order to access this analogy we have to know that lines stand for walls by virtue of some other process. This might imply that analogy by itself does not establish a representation, but analogy is a particular relation between a representation and the realities that it stands for.

It does not seem plausible to consider design drawings equal to propositional representations. "Features" in drawings are not mapped to spatial concepts in mind irrespectively of some correspondence between relations that hold among them. It could be, for example, that a computer program, e.g. an artificial intelligence system, employs certain processing mechanisms that make it easier to manipulate drawings in the propositional format that Palmer suggests. Indeed, it might use specific interfaces which could allow an observer to recognise in image processing movement, rotation, etc.; aspects that are typically captured by analogical systems. However, to recognise exactly these aspects as analogous to corresponding aspects of the object that the

1 Analogical mappings, understood in this way, are discussed in: Gentner, Dedre, 1988.

drawing stands for implies further processing which is performed by the observer, by reasoning about the drawing, and which is not embedded in any way in the self-corresponding propositional representation in the computer. Similarly, designers confront drawings not simply as symbolic representations of objects but as analogues of the objects they represent. That is to say, drawn objects are manipulated by the application of knowledge that can be mapped to the objects they stand for.

This might seem to imply an objection to the propositional format as the structure according to which mental images are stored in memory. Instead, what it ought to suggest is that if we concern ourselves with the function of representations in the manipulation of information we should consider the operational value of the arguments seen earlier, rather than their plausibility as explanations of actual structures in mind. If there are mental processes which can access data structures and interpret them in a manner that allow us to imagine images and manipulate them as being analogues of external pictures, then it can be said that images are analogical even if the format of the data structures for them within a computer is propositional.

From this point of view, the distinction between propositional and analogical seems to be a question of efficiency, and efficiency depends largely upon the purposes for which a representation is used. Consider, for example, the case of representing information about the distance and location of a number of cities in a country in relation to the capital. There can be two representations: a chart of distances in miles with the coordinates of each city in reference to the capital, which is essentially a propositional representation, and a diagram connecting cities with lines in a two dimensional medium, a representation expressed in an analogical manner. Both of the systems appear to rely on the same information since either one can be generated from the other. Yet, using the chart it is easier to calculate, say, how much fuel someone needs in order to go from the capital to a given city, while using the diagram it is easier to see which other city falls in the same line with the capital. It can be said that the process which is embodied in the construction of the propositional chart has common aspects to the process used to make arithmetic calculations, while the process which the analogical diagram embeds is similar to the process used in order to extract geometric relations.

This brings us to an important implication for computerised systems that support drawing representations. As we have seen in the discussion on representational systems, every representation is specified not only by the represented and representing objects but also by the process which connects them.

Representational formats are essentially just static structures which may differ in the degree of abstraction, and they require active processes in order to make them function in relation to the purposes for which they are used. These processes are partly embedded in the representational format, as we have seen, but if we take into account the people who are going to use a representational system we have to consider people's *intentions*. This has already been indicated in the beginning of this chapter, in the discussion about the definition of a representation.[1]

People's intentions involve the use of knowledge that is not represented explicitly in the representational system, but which can be applied to the products of the system. The application of this knowledge can involve aesthetic considerations, intuitive thinking, and idiosyncratic responses that are not explained in any way in the representational system. This 'human' knowledge can be applied to all kinds of representations irrespectively of the format upon which they are based; in some respect, to all external information. So, for example, the particular visual features that some characters in a string might possess may be considered independently from the meaning that the characters as symbols have, and allow us to say that 'these letters are very serious', or 'these look a bit informal', or 'these letters remind us of Gothic architecture'. As an extension of this example, consider advertising in which what a logo actually says is far less important than what it invokes. Generally, works of art, including designed objects, are directed to this quality of human thinking since, perhaps, all artifacts serve to invoke knowledge as well as explicitly represent.

It might look a little extreme to characterise this kind of thinking as 'analogical' since it also involves metaphors and connotations in which there cannot always be clear demarcations with respect to the aspects which are placed in correspondence. Still, there is always some mapping of knowledge between two domains which is the principle of analogy.

This use of mapping applies in the case of drawings. Drawings are associated with spatial analogies involving the representation of spatial properties of the designed objects in corresponding properties of drawn objects. The representation is required to be accomplished within a spatial medium and allows manipulations of the representing properties with respect to topological, geometric, and other spatial relations of represented objects. However, the mapping between drawings and designed objects is based on the intentions of the designer who makes the analogy, in accordance to what

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[1] 5.2. Kinds of Representation.

she or he knows about designed objects. The knowledge that is applied to these manipulations is analogically mapped to spatial relations that hold among the drawn objects. This knowledge includes manipulations of drawn objects and artifacts that do not refer just to topological and geometric relations but involve metaphorical and connotative meaning based on aesthetic appreciation.

This sort of knowledge cannot occur in a machine that represents drawings. In other words, no matter how rich the representational scheme is that a machine employs, there will be always some knowledge excluded. That knowledge is essentially a human feature.[1]

This condition characterises our view on computerised systems that support drawing representation. We accept that drawings can be represented in a symbolic format in a machine but we take into account that when drawings are used during designing they involve analogical reasoning that departs from the data structures in the machine upon which the representation of drawings is based. However, to return to the point about structure and use at the beginning of this chapter, what something is regulates what can be done with it, and the way something is used tells us what sort of thing it is. In order to have a representation which allows analogical reasoning, the process by virtue of which the representation is accomplished should also allow analogical mappings to be accomplished. The acceptance that a drawing can be represented in some symbolic format does not imply that any kind of symbolic representation can act as an analogue of designed objects.

The processes that underlie the analogical manipulation of representations in respect to spatial qualities entail certain implications for the structure of the representation even for the case of formal representations of drawings by computerised systems. These implications have to do with the aspects of graphical representations that we have seen earlier: the use of abstract symbols where the features of the symbols also take part in the representation, and the accomplishment in a spatial medium where multiple relations between symbols can be construed in varied directions. To this extent, it seems appropriate to maintain the distinction between propositional and analogical representations and refer to drawings as analogical representations.

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1 See the discussion on means by which we develop knowledge in: 3.1. The Framework of Discourse; Abstractions: Self-Knowledge and Knowledge-in-Use.

We can now revise our earlier definition of an analogical representation and say that analogical representations involve at the first level a process through which symbols are mapped to represented objects, that can be seen as a *denotation*, and at a second level a process through which the structure of relations between symbols is mapped to a structure of relations between the represented objects, that can be called a *homomorphism*.[1] It does not seem appropriate to describe this representation as direct, as Sloman does, since, on the one hand, it involves a denotation, and, on the other, any representation implies some directness in as far as it allows us to talk about realities by dealing only with their representations.

The involvement of intentions in mappings of knowledge to drawings recalls the assumption that the interpretation of representations is dependent on what currently exists in mind and is manipulated under cognitive operations. In other words, the meaning of a drawing is context and time specific related to the purposes for which is used. Despite the fact that there is a denotation according to which symbols in drawings are mapped to concepts, graphical symbols can be seen as denoting varied and diverse concepts in relation to the context of their use. Similarly, design intentions determine the analogical mappings of drawings.

This aspect of the use of drawings is directly related to the involvement of significant schemes in the interpretation of drawings. As a result of design intentions, specific significant schemes bring certain conceptual models into the context of the interpretation in respect to which the meaning of drawings is obtained. Significant schemes can be connected to the analogical reading of drawings. Consider, for example, that while lines in drawings are used initially to depict distinctions of spatial qualities such as projection, direction, discontinuity, etc., when lines are composed into shapes or patterns through the involvement of significant schemes, they are seen to depict the spatial distribution of more abstract entities. Thus, depictions in drawings are often used to denote functional units, structural elements, zones of dissimilar energy consumption, access possibilities, etc. We can see the involvement of certain verbal conceptual models in this sort of denotation, and the analogical mapping between relations between shapes and relations between components of conceptual models.

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1 A similar approach to analogical representations is described in: Hayes, Patrick J., 1985.

These differences in the meaning that drawings obtain during designing will be examined in detail later when we will explicitly deal with the use of drawings.[1] Here, however, it might be appropriate to apply the views described above to the examination of certain design expressions in order to obtain an understanding of implications on readings of them by designers.

Evidence in Design Expressions

In design expressions one can observe differences in the purpose for which expressions are accomplished, which are connected to the meaning that is assigned to them. In order to illustrate such differences, let us consider drawings from the case study around which the thesis is developed. *Instance 003*, *Instance 004*, and *Instance 014* of student's A design work, appearing in Appendix B, are three design expressions which demonstrate the emergence of a spatial form of the designed object and it can be assumed that different intentions determine the use of each of them in relation to conceptualisations of the spatial form. The drawings which are missing from the sequence depict information specific to the site.

In *Instance 003*, there is an explicit assignment of words to simple sketches which makes them very relevant to the distinction between conceptual and imaginal models. Yet, concepts and images expressed are relatively abstract, and the correspondence between them looks difficult to capture.

In the part of the drawing which concerns 'expressionist' characteristics of the building, the words and pictures manifested on the paper seem to correspond to the same conceptual entities and look to be used for the purpose of reminding the designer of some ideas that could be embedded in the building. It appears to be a case that a verbal concept is explicitly represented by a word, and it is accompanied by an imaginal equivalent so as to make explicit a particular visual form which is indicated by the concept, with no close dependence on each other. Even if the emphasis is placed on morphology, any image corresponding to a given concept, which could be expressed, for example, with the picture of another different ship, would effectively serve the same purpose.

While both verbal concepts and images are expressed with a single entity, in the form of a word and a picture respectively, the symbols from which these

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[1] 9. Drawings and Design Activity.

representing entities are composed are put together in relation to their distinctive attributes. Consider the case of a possible decomposition of the picture into compositional parts, which allows a specification of the structure of the picture. That would not serve the purpose for which the image is expressed in some greater degree than the picture itself. In other words, the recognition of the features of graphical symbols and the relations between them allow us to map the graphical representation to the visual features of a ship, but this mapping holds only at this level. The analogy between the relations of graphical symbols and the relations between the structural elements of a ship, for example, is not important for this representation.

It can be said that this picture stands for an imaginal template of a concept, but the conceptual model which regulates the use of the picture does not seem to refer to relations in the spatial arrangement of the entity. Rather, it refers to relations between the visual features of this entity and others, like for example a wave, an island, etc. In this case, there is no analogical mapping between relations of graphical symbols and relations within the conceptual model.

In the part of the expression concerning Scottish buildings, however, the role of pictures looks far more important. The emphasis is still on morphology, but in this case a picture, far more exemplifying a particular visual form which corresponds to the written concept, suggests also a specific spatial arrangement that is entailed by the verbal concept. Words and pictures are not used indiscriminately in the sense of conveying the same sort of information. That might be the case if the verbal concept corresponding to the images was simply 'buildings'. Here, the verbal concepts expressed in words like 'farm', 'tower', etc. are kinds of buildings which are differentiated from their general category by virtue of distinctive attributes that are met in each kind. While the words standing for these kinds do not explicitly say anything about these attributes, the pictures indicate something about some of them.

Graphical symbols, in this case, are not related to each other in some different way with respect to the previous pictures. They do not tell us which parts of the drawing depict attributes of buildings. However, knowledge possessed by the reader can be applied to the drawings, as a part of an analogy, and allow the realisation of differences in the features of the graphical representation and the distinction of parts of the drawing that correspond to building attributes. The decomposition of the picture into compositional parts, even though these are not necessarily known as such by the reader, is important to the functional role of the picture.

Such compositional parts can be patterns or sets of lines in the picture which alone can stand for a specific concept. In the picture A4, for example, compositional parts might be the parts of the pictures that depict columns. Compositional parts, in this case, seen independently as pictures, stand for corresponding imaginal templates of columns in a way similar to the previous case. However, their spatial distribution on the paper and their relation to other parts are used not only to manifest corresponding arrangements in the spatial form of the represented image, but also allow us to distinguish them as symbols for imaginal concepts. That is to say, if the four lines which are used to depict a column were alone on the paper there would be a bigger degree of ambiguity in interpreting them as a column and not something else.[1] Consider that, similarly to the previous case, a decomposition of the picture parts into further compositional parts, such as lines, would not serve the purpose of the picture in any additional degree.

Instance 014 is one of the first orthographic drawings made by the student. The fact that there are no notations on the drawing, except for some acronyms, makes its interpretation rather difficult, especially for someone without training in design. However, a designer would be able to say that the drawing is used to manifest the spatial distribution of a building in both the horizontal (plan) and vertical (section) planes, even if the drawing is not accurate and the signification of some of the lines is obscure. This specification of the purpose of the drawing would not change if the drawing were lacking the acronyms.

Despite the fact that the drawing is used for a purpose similar to the pictures in the previous case, it is not a representation of the same kind. If the drawing is seen as a picture, it does not refer to any image that someone might have in mind. It can be said that entities in the drawing do not correspond to imaginal concepts but instead to something like verbal ones. In order to be interpreted, the drawing might require a decomposition into compositional parts down to the level of lines, or even points, which correspond to conceptual entities, even though these entities might have to do with spatial elements.

Obviously, lines are not used like words and the representation is not propositional in the strict sense since it does not constitute any factual assertion or look

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[1] The phenomena and the processes by which shapes and patterns are distinguished as compositional parts of a picture are studied by Gestalt psychology. A study which connects such phenomena to architectural theory and practice can be found in: Hesselgren, Sven, 1969.

to follow rules of consistency. The interpretation of the drawing requires a mapping between lines and concepts, as in the case of verbal symbols, but the lines cannot be replaced by some other arbitrary symbols. That is, the lines are used as symbols but they are chosen because they possess spatial properties, the property of length for example. They could be replaced only by some other devised symbol that could hold similar properties.

There is nothing in the drawing which tells us anything about the concepts that lines stand for. Their mapping to concepts is not determined by a one-to-one correspondence and lines can be used to represent walls, boundaries, directions, etc. It can be said that in the case of pictures, lines are always used to define patterns and shapes. The meaning that lines as graphical symbols attain comes from the analogical reading of the drawing, that is by mapping between the depiction and knowledge which is not explicitly represented about spatial objects. In this case, the role of shapes in drawings becomes important as they allow the grouping of sets of lines and aid the interpretation. The analogical mapping between lines and spatial objects is helped if lines are placed in such a way as to allow their grouping into shapes which can be mapped to known shapes of spatial objects. Four lines, for example, are grouped into a rectangle that can be seen as the plan of a room.

Consider that this interpretation of the drawing would not change at all if the drawing were produced by the aid of a computer. If mechanisms similar to those met during interpretation also occur during the making of the drawing, there would be implications for the use of a computerised system. For example, does the system allow groupings of lines so that a manipulation of a group (for a room, or any other spatial object) does not rely on the manipulation of the individual lines that compose it?

The drawings in *Instance 004* are seen as an intermediary between the two previous cases. They demonstrate the shift from the externalisation of existing images, as in *Instance 003*, to the accomplishment of a new spatial form, as in *Instance 014*. In this case, shapes and lines are used as compositional parts to be mapped to verbal concepts. Distribution of rooms or qualities of access in a building, for example, can be mapped to some of the sketches as a whole. However, parts of the sketches might correspond to existing images, like sequences of steps, holes in a wall, etc., which are placed together in the drawing in relation to conceptual assertions. Even when individual lines cannot be seen to explicitly denote a verbal concept or depict a visual form, their role is important in evoking a response in the reading of the drawings, providing hints of context, clarifying directions, indicating axes, stimulating focus on particular depictions.

This short look at the attributes of drawings illustrates their role in explorations into designing, with respect to correspondence between spatial forms and conceptualisations, and their function as representations of design knowledge. In subsequent chapters, such qualities will be examined in more detail, when we will see the manner according to which drawings are made and used.

Here, before closing this chapter, I would like to quote a phrase by Henry Moore which demonstrates the power of drawings in organising conceptualisations. Drawings, themselves acting as spatial objects due to the particular ways according to which they are structured, evoke intentions through mappings of knowledge to them, even when they may initially be seen as amorphous manifestations with no predominant meaning attached to them. Likewise, so is the response to spatial forms in general, which obtain diverse interpretations in respect to various conceptualisations and individual abstractions.

> ... I sometimes begin a drawing with no preconceived problem to solve, with only the desire to use pencil on paper, and make lines, tones and shapes with no conscious aim; but as my mind takes in what is so produced a point arrives where some idea becomes conscious and crystallizes, and then a control and ordering begin to take place.[1]

5.5. Summary

Having established a characterisation of designing, in the previous chapter, as a conceptual activity aiming at the transformation of information into a spatial form, in this chapter we have concentrated on design representations.

Theories of representation from the field of cognitive psychology provide coherent accounts about the structure of representations of both verbal concepts and images. Verbal concepts can be efficiently treated in the form of propositional representations: this sees knowledge as highly structured configurations of discrete symbols associated with certain procedures for interpreting them. Semantic networks, as a model for the organisation of knowledge based on propositional representations, reflect the associative character of knowledge and indicate ways according to which conceptual models in design might be structured.

1 Moore, Henry, 1954, p.72.

Images are better approached as analogical representations. These can be seen as representations in which properties and relations of the depicted objects are represented by corresponding properties and relations in the representing configuration.

An examination of processing mechanisms during the interpretation of external representations, such as drawings, provided an account of the ways according to which drawings obtain meaning in respect of various levels in the interpretation. Depictions can be mapped to images, conceptual entities, and abstract associative structures of knowledge in memory. Significant schemes, in particular, act as binders of cross-level relationships and indicate the manner through which conceptual models regulate the interpretation of drawings by specifying their context.

The views about the structure of representations and their interpretation were applied to design expressions and resulted in a characterisation of the function of drawings as representations of design knowledge. Drawings can be seen as symbolic representations, so that concepts can be mapped to graphical symbols. However, design intentions which emerge during the use of drawings in designing, allow analogical mapping between depictions and knowledge about designed objects that it is not explicitly represented, but is known by designers. In this respect, drawings can act as analogues of designed objects in respect to spatial and visual qualities. This view on the use of drawings entails certain implications for their structure, which have to do with the use of symbols that possess spatial properties, and with their realisation in a spatial medium so that multiple relations between symbols can be construed.

We have arrived at an approach to the analogical attributes of drawings, which relies on designers' behaviour during their use of drawings. This approach will underlie the examination of computerised systems that support the production of drawn representations, which is the topic of the following chapter. Since this approach entails connections between drawings and design knowledge in general, its implications will also influence subsequent chapters which examine problems in the use of computerised drawing systems, the use of drawings in particular tasks of spatial composition, and operations through which drawings are accomplished.

6. Drawings in Computers

From our discussion on designing and drawing so far we have obtained an account of the connections of drawings to design knowledge, and the manner according to which they are manipulated by cognitive operations. By looking at the processes taking part in the interpretation of drawings, we estimated the character of drawings as representations and concluded that the format of their structure is better conceived as being analogical representations. A central aspect of this discussion was the issue of decomposition according to which drawings, and graphical representations generally, are decomposed into graphical symbols so that their meaning is obtained compositionally with respect to features and relations between symbols that are recognised in configurations.

Yet, we have suggested that the manner according to which drawings are decomposed and interpreted is not independent of the ways in which they are used during designing. This is an attribute that it is connected to the abstractness of the graphical symbols. Graphical symbols do not have any singular predominant meaning attached to them. Meaning results from the analogical use of drawings, by the fact that knowledge not explicitly represented by the configuration but known by the designer is applied to the representation.

This approach outlines our view on the structure of drawings and the qualities that underlie their use and it will continue to characterise the discussions in the following chapters which more explicitly attempt to explore the connections between drawings and design processes. These discussions will start with an examination of the use of computerised systems by the designers of our case study.

In order, however, to apprehend the issues involved in the use of computers, this chapter provides a description of the functionalities of various computerised systems, categorised into bit-map drawing systems, vectorial drawing systems, and solid modelling systems. This categorisation relates to views about the structure in drawings which are incorporated in systems.

Despite the fact that this discussion does not provide a new approach to the systematic representation of drawings, and to this extent could be skipped by someone with knowledge of drawing systems, the description is critical in attempting to connect the functionality of computerised systems with models of designing and drawing behaviour that underlie their development. As such, the functionalities of drawing systems are discussed under the issues of *effectiveness* and *restrictiveness*. These capture the principle of minimising drawing operations, evident in almost all computerised systems, and the effect of this principle in reducing the applicability of systems to situations which are not characterised by well defined and established views of designing. In other words, they refer to the fact that computerised systems become domain specific systems, in contrast to the general purpose handmade drawing environment. These issues will be further discussed in subsequent chapters.

It has to be noted, that the discussion in this chapter refers to drawing systems and not to computer aided design systems that incorporate knowledge representation schemes, inference making, and automated design techniques.

6.1. Structure and Behaviour of Drawing Systems

In computer aided drawing, the methodological tools and operations according to which drawings are made can be as distinctive as the particular system at hand. Systems may be differentiated even in respect to the geometric features that are recognised in graphical symbols. Different systems rely on different approaches to designing and drawing, which entail specific requirements for the accomplishment of drawings, that in turn are manifested in practice by employing specific tools and techniques. This points out one of the most fundamental characteristics of computerised drawing environments which perhaps radically differentiates them from the traditional handmade drawing environment: the imposition of some specific structure, in the case of the computerised drawing systems, in contrast to the lack of any structure for drawings, in the case of the handmade environment.

Specifically, in the traditional drawing environment, despite any approach that can be applied to the interpretation of drawings, there is nothing to tell us how drawings are made. The system is free from any inherent account about how drawn objects or spatial forms are structured. Designers are free to recognise graphical symbols and relate them to each other, in order to compose drawn objects, in the way that they consider most appropriate in relation to their conceptualisations and models.

In the development of computerised drawing systems, on the other hand, the principal objective is to minimise the drawing operations that are needed for the accomplishment of a drawing. This unavoidably has to be based upon considerations about, firstly, the nature of spatial forms in designing, and secondly, the properties of the drawn objects that represent them. In effect, in any computerised drawing system, a model of the structure of drawings is embodied which is presented by the combination of a set of specific tools for the accomplishment of (pre-defined) drawn objects, and a set of tools for their transformation.

It is suggested that computerised drawing systems, in this respect, can be thought of as falling within a dipolic scheme which we can determine by introducing the two factors of *restrictiveness* and *effectiveness*. The more restrictive the view that a system imposes on drawn forms, usually the more effective the system is; and vice versa. In other words, drawings in systems which are open to different varied models of design and drawing practice often require a great number of operations in order to be accomplished, while on the other hand systems that impose restrictions on the composition of spatial forms usually entail minimal operations for their representation. It has to be noticed, however, that effectiveness here is not used to determine whether a system is successful or not. It is solely used in respect to the objective of minimising drawing operations. A system is successful when it combines minimal restrictiveness with maximal effectiveness.

In practice, the issue of restrictiveness is partially resolved by enriching a particular system with additional tools for the accomplishment and transformation of drawn objects. Since, however, restrictiveness is derived from the theoretical model of the system, this enrichment is often accompanied with a corresponding reduction of effectiveness.

For example, most drawing systems follow the assumption that designers most often draw rectangles whose sides are vertical and horizontal. Evidently, systems following assumptions like this are much easier to implement. A system is restrictive when it does not allow the drawing of a rectangle that does not follow this condition. In this case, the rectangle has to be drawn using a tool which is not for rectangles but for primitives of rectangles such as lines, or by the application of a transformation after the construction of a standard rectangle. Some of this restrictiveness can be resolved by providing a new tool for the drawing of non vertical-and-horizontal rectangles but slanted ones. Yet, even in this case, because the initial assumption is taken to be fundamental, the drawing of a slanted rectangle will almost definitely require a greater number of operations than in the case of standard rectangles.

As a result of these conditions on the development of drawing systems, we may have successful systems that rely on a specialised view of drawing composition; systems, for example, developed specifically for architects, or industrial designers, like ArchiCAD®, or MacBravo!™ respectively. Alternatively, we may have general purpose drawing systems that require particular supplementary implementations in order to be used efficiently by specific design disciplines, like AutoCAD® which can be used by architects in combination with the additional AEC Architectural®, or by landscape designers with the LandCADD™.[1] It may seem questionable, therefore, to assume that drawing systems demonstrate more or less the same attributes, and discuss them in general as offering a uniform environment for the accomplishment of drawings that can be compared to handmade drawing.

Nevertheless, there is a categorisation which, even if it is directly manifested in the implementation strategies of systems, seems to be motivated by different views and assumptions about designing and drawing. This has to do with the distinction between *bit-map drawing systems*, *vectorial drawing systems*, and *solid modelling systems*.

Bit-map systems rely on an atomic decomposition of drawn objects into their basic units which are pixels on the screen. Vectorial drawing systems employ databases which store geometric information about the drawings. In this way, they can offer a comprehensive range of graphical symbols and operations but there are some issues about the correspondence between internal representations and their

1 ArchiCAD is a registered trademark of Graphisoft.
MacBravo! is a trademark of Schlumberger Technologies.
AutoCAD and AEC Architectural are registered trademarks of AutoDesk Ltd.
LandCADD is a trademark of LandCADD Inc.

display. Modelling systems are characterised by the manipulation of three dimensional objects. These can either already exist as primitives in the system from which the user can compose spatial forms, or they can be assembled from two dimensional drawings. Despite their differences, systems that fall into one of these categories show similar degrees of restrictiveness and effectiveness, in the sense of allowing comparable depictions to be accomplished by the employment of more or less equivalent operations.

In the discussion that follows, we will follow the categorisation into bit-map, vectorial, and modelling systems, maintaining, however, our original interest in examining the implications that established accounts about the structure of drawings indicate, on the making of drawings. As such, we will focus more on the assumptions about drawing practice that are incorporated in the development of drawing systems and the models of drawing behaviour that each category manifests, even if some of the particular functionalities of systems do not fully comply with them. Yet, we will point out particular differences between systems of one category when these look important from the point of view of drawing composition.[1] In the next chapter of the thesis, we will look at such implications in depth through the detailed examination of one particular system in a worked example.

Despite the fact that most computerised drawing systems are primarily intended to be used as draughting tools, it is anticipated that this discussion will provide an account of the role that they may have in design practice as well as their relation to handmade drawing, where the distinction between design drawing and draughting is less apparent.

6.2. Bit-map Drawing Systems

Bit-map drawing systems are characterised by their emphasis on the visual impact of drawings, and in consequence they are quite often referred to as painting systems. Bit-map systems include MacPaint®, PixelPaint™, for the Macintosh™, or PaintBrush™, for IBM® Compatibles.[2]

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1 The discussion takes into account mostly commercially available systems, mainly for convenience since these can be easily obtained for exploration and evaluation. But, known systems under development or research will occasionally be indicated. Knowledge about drawing operations in computerised systems would be helpful but not necessary.
Most of the systems are discussed with respect to their implementation for the Macintosh™ personal computer. Macintosh is a trademark of Apple Computer Inc.

2 MacPaint is a registered trademark of Claris Corporation.
PixelPaint is a trademark of SuperMac Technology.
PaintBrush is a trademark of Microsoft Corporation.

The Structure of Drawings in Bit-Map Systems

The tools which are used for the accomplishment of drawings confront graphical symbols as complete shapes, such as lines, rectangles, circles, etc., which are defined in the system with respect to their geometric properties. In order to construct each shape, the user has to specify the value of these definitional properties, and its position in the drawing. This is a characteristic of graphical symbols which is met in all cases of computerised drawing systems. However, what radically contrasts bit-map with other systems is the attributes of the internal representation of the drawing.

Bit-map systems store drawings as arrays of pixels.[1] Pixels are the smallest units of screen resolution and can be roughly seen as equivalent to dots on a paper. As such, each drawing in a bit-map system is constituted from the total sum of pixels of a pre-defined area, that usually corresponds to printing paper sizes, each one of which has either negative value, and appears blank on the screen, or positive value, and appears full, that is black or coloured in relation to the particular configuration. It can be said that the primitives of graphical objects are in fact pixels and not compositional parts, such as lines, arcs, etc., since once an object is drawn it effectively becomes a set of full pixels, each one of which has no relation to another, nor any other property apart from being full. In other words, tools in bit-map systems are simply means for turning sets of individual pixels on or off.

This implementation for the representation of drawings in the system can be seen as imposing minimal structure in the representation of drawings, or even no structure at all, since in bit-map systems there is no profound distinction between the depiction on the screen and the internal representation of the drawing in the system.[2] In consequence, the users of the system can manipulate drawings quickly and

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1 This is the way according to which drawings, and generally all sorts of information, are displayed on the screen in all modern computer configurations using raster scan technology. This display, however, is only a low-level surface representation of the data structures that constitute the internal representation of the information in the system. In bit-map systems, surface representation and data structures coincide.
For raster scan display processing units, see: Foley, James D. & Van Dam, Andries, 1982, pp.129-135.

2 This is a condition that holds partially for the old 'storage tube' vectorial systems, too. In these systems vectors were as fundamental as pixels are on bit-map systems. However, there were still distinctions between the surface representation and the database which have to do with the fact that there was no screen representation of the direction of vectors and more importantly of the relations on the basis of which primitives, such as lines, form graphical symbols, such as rectangles. See the discussion on vectorial systems later.

responsively. This aspect is enforced by the fact that bit-map systems, since effectively graphics occur only on the screen, often are supplied with a pointing device through which the editing is done, in contrast to other systems where the requirement of such devices is not essential.

These characteristics of the implementation of bit-map systems allow the accomplishment of depictions that capture expectations of the users in respect to the visual attributes of the drawing, such as shape or texture. A wide variety of tools that rely on the iconic qualities of graphics can be introduced, such as paint brushes in different shapes, air brushes, tools for a wide variety of user-defined but apparently fixed graphical symbols, such as different typefaces for text, different shapes of arrows, patterns, depictions of people, trees, vehicles, etc. These can be used in conjunction with time sensitive pointing devices, that can draw strokes that fade away simulating the effect of dry brushes or charcoal, or even pressure sensitive pointing devices, that can draw strokes whose thickness depends on the pressure that is applied to the pointer. Such tools can be used also in the manipulation of external pictures which are initially created in other media, since when these are translated into computer readable form they can have a bit-map representation. These qualities make them quite efficient in their use as painting systems.

Design Drawings in Bit-Map Systems

Despite the fact that bit-map systems are not really directed at designers, their particular capabilities in drawing manipulation manifest a level of interaction between the user and the drawing environment which cannot be found in all other computerised drawing systems. The system seems to allow various conceptualisations to act upon depictions and direct their manipulation. This makes them worth considering particularly for those stages in designing when artifacts are not yet well structured.

The usefulness of bit-map systems in design drawings can be approached through the factors of restrictiveness and effectiveness. Bit-map systems show the lowest levels of restrictiveness since they employ an 'atomic' decomposition of drawings. Even if depictions are usually initially produced by the use of already defined graphical symbols, their tools can also effectively support freehand editing despite the fact that this is bounded by the technology of the pointing devices. Depictions can be modified down to the smallest units that compose them. Individual pixels can be turned on or off resulting in high levels of control over the drawing.

The atomic decomposition of drawings, in conjunction with the lack of structure, has the virtue of simplicity. What users do is what appears on the screen, without any involvement of internal representations. Modifications are made by erasing earlier depictions and re-drawing, or using simple transformations, such as rotating, duplicating, moving, etc. Knowledge about the system can be minimal, and there are no interrelations between different transformations and different graphical symbols, as is the case with structured environments as we shall see later.

One restriction that occurs is the dependence of bit-map systems on screen resolution. Drawings can only be manipulated in their initial size. When zooming is implemented this is only a magnification of pixels which does not allow editing in more detail. Current technology poses limitations on the density of pixels that can be achieved in screen resolutions. Higher resolutions are time and memory expensive. Another restriction is the difficulty of accommodating a layering facility, normally met in vectorial and modelling systems, so that different views of the drawn object can be explored.

These conditions make bit-map systems very useful at early stages in design when the spatial form of the designed object is not yet established and when drawings are externalisations of images of previous visual experience lacking a well defined structure. During these stages, even ambiguity that arises from the externalisation of images cannot be seen as a limitation as it is an unavoidable condition of the effort of making depictions to obtain the qualities of spatial forms. Even later, when spatial forms accept different conceptualisations in respect to various conceptual models, bit-map systems can have a role. A non-structured drawing environment allows designers to express and explore tentative ideas in spatial composition. Additionally, the capabilities of bit-map systems to import depictions from external sources allows the accommodation and incorporation in the drawing of information that is initially presented in design tasks, such as site maps, contour maps, photographs from the physical environment of the designed object, etc.

However, eventually, spatial forms become more permanent as they begin to obtain correspondence to conceptual models. As a result, the structure of drawings becomes more stable and graphical objects start to maintain their properties. Then, the limitations of bit-map systems begin to be more serious and the reduced effectiveness of their drawing operations makes them impractical. Designers may need an environment in which higher level representations can be accomplished, such as those in vectorial drawing systems.

6.3. Two Dimensional Vectorial Drawing Systems

Most of the commercially available two dimensional drawing systems for designing follow the principles of vectorial drawing. Drawings are represented in terms of vectors which are mathematically defined by their magnitude, their direction, and their sense; the latter is a notion that makes more precise the direction from initial to end points of vectors within compositions. Not all drawing systems make a clear distinction between direction and sense, while, on the other hand, all drawing systems do use a two dimensional coordinate system to position vectors.[1]

Examples of vectorial systems are Claris CAD™, PowerDraw™, for the Macintosh™, and Caddie™, CADVANCE™, for IBM® Compatibles, although there are many systems which are implemented for both operating environments, such as AutoCAD®, and VersaCAD™. Also, most three dimensional modelling systems usually include a two dimensional vectorial drawing component, such as ArchiCAD®, MicroStation™, and Architrion™.[2]

Vectorial systems are far more complicated than bit-map systems and they are primarily used for drawing, in contrast to painting. As such, we will discuss them in more detail and we will distinguish three aspects that characterise the capabilities of a system, which have to do with the structure and the organisation of the drawing, the way according to which graphics are organised and used on the screen, and the particular functionalities that vectorial systems provide.

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1 Vectors are in principle an algebraic rather than a geometric notion which however adds precision in the specification of geometric configurations, especially in cartesian coordinate geometry. For the fundamentals of vector algebra see: Macbeath, A. M., 1964.

2 Claris CAD is a trademark of Claris Corporation.
PowerDraw is a trademark of Engineered Software.
Caddie is a trademark of Computer Business Practice.
CADVANCE is a trademark of Isicad Ltd.
VersaCAD is a trademark of Versacad Corporation.
MicroStation is a trademark of Bentley Systems Inc., an Intergraph affiliate.
Architrion is a trademark of Giméor S.A.
It is difficult to distinguish whether a system is primarily a two dimensional drawing system or a three dimensional modelling system when it includes both capabilities. The distinction here takes into account the ability of starting the modelling of a spatial form directly in a three dimensional environment. As such, some systems which are referred to as drawing systems have also modelling capabilities either integrated, such as with AutoCAD, or as a different system, such as with VersaCAD Design and CADVANCE 3D. In most of these cases, the modelling component of the system uses as input the output of the two dimensional system. However, we will come back to this point in the discussion on modelling systems later.

The Structure and Organisation of Drawings

In all vectorial systems, drawn objects are made by graphical symbols which in turn are decomposed into primitives with coordinates stored in some drawing database. The database stores also the attributes of primitives. As such, in contrast to bit-map systems, drawings are stored as geometric and mathematical information and not in terms of what is depicted on the screen.

Primitives are the simplest elements that compose the graphical symbols, such as lines, arcs, and circles. Text characters are also treated as primitives. Points can be primitives, but they are mostly used for marking rather than as constituents of drawings. In most of the systems arcs and circles are different primitives. Arcs are used as components of non-circular or circular curves. Attributes are usually colour, line style, and thickness. Later, we will look in more detail at issues of the properties of graphical symbols.

An aspect which usually characterises the functionality of a system is the way according to which the database is organised. The most common method of organisation is by *layers*. Each graphical symbol belongs to a layer which is identified by a name or number. The visibility of each layer on the screen can be individually turned off or on. Another method of organising a database is by *sub-models* or *components* of drawings. Sub-models are groups of functionally related graphical symbols which are nested together. They can be also identified by a name or number.

Most of the systems facilitate both methods of organisation but they differ in hierarchical order; in the emphasis that they give to layers or sub-models as the primary means of organisation. In layer oriented systems each individual graphical symbol must belong to a layer. Sub-models and groups of sub-models can be made but they are optional. Usually, objects from different layers can be selected so that transformations to more than one layer can be made simultaneously, but graphical symbols that belong to different layers cannot be grouped together to form a sub-model. On the other hand, in component oriented systems each graphical symbol must belong to a sub-model. Sub-models can belong to different layers, and groups can be made between sub-models that belong to one or more layers. However, individual graphical symbols cannot belong to a layer unless they are used as sub-models. Thus, we have an emphasis on depth organisation, for the case of layer oriented systems, and an emphasis on breadth organisation, for component oriented systems.[1] Let us see the implications of these modes of organisation.

Layers are intended to accommodate different attributes of the elements that compose the designed object, and simulate a layering function met in the traditional drawing environment with different semi-transparent sheets of paper exploring different views of the object. As such, different layers can store information about different sub-systems of a building, such as the structural system, the partitioning system, the electrical fittings, the plumbing pipes, etc., and groups can be made between the components of these sub-systems. A set of layers can be the plan of a floor of the building, another set can be a new plan, an elevation, etc. Layers appear closer to the conceptual organisation of the designed object in terms of conceptual models.

On the other hand, sub-models are intended to accommodate a classification of the compositional parts of a designed object into parts, sub-parts, and so on. As such, the lines depicting a chair can be a sub-model, a desk another one, chairs and desks can be a workstation, workstations can be grouped into a room, several rooms into a floor of a building. The organisation of drawings into components allows the construction of libraries of sub-models from which established drawn objects can be selected and used repeatedly in the same or different drawings. Sub-models appear to correspond to the conceptual associations between the components of conceptual models, and they impose a hierarchical structure.

Despite the fact that both layer and component oriented drawing systems usually employ both modes of organisation, the emphasis on one of them entails certain implications in the implementation of a system. So, for example, even if the layer organisation appears to be more flexible, in layer oriented systems the sub-models of drawn objects within a layer have always to be ungrouped, converted back to unorganised graphical symbols, in order to make a modification to the individual components that compose them. This is not necessary in the case of component oriented systems.

On the other hand, in the latter case, even if sub-models can be copied and used in different parts of the drawing, modifications can be made only to the individual graphical symbols of sub-models. Other restrictions, in relation to particular systems, concern the attributes of the graphical symbols. It could be the case, for instance, that

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1 See: Richens, Paul, 1989, pp.31-32.

all the components of a sub-model or all sub-models in a layer must have the same colour.

It seems that the emphasis on a primary means of organisation for the structure of drawings is necessary. There are examples of systems in which the choice of a primary mode of organisation is left to the user. The user, however, has to follow consistently the chosen organisation at least for a specific drawing. If she or he, for example, is trying to move a sub-model of graphical entities that belong to different layers, into a new layer, thereby attempting to make a layer organisation in a drawing that so far is structured using sub-models as the primary organisation, there could be severe conflicts in the structure of information which may lead to an error state, or a system crash.

Generally speaking, component oriented systems are faster and more efficient in use as draughting systems, when the spatial form of the designed object has been extensively defined. This is because, on one hand, they impose a hierarchical organisation on the designed object, which is not necessarily followed during designing but can be useful for the description of the artifact to builders, and, on the other hand, minor modifications, like those met at late stages in designing, can be made without the danger of disassembling the structure of the drawing.

Layer oriented systems seem to be more effective in accommodating conceptual relations between parts of the designed object. Despite the fact they are less efficient during the detailed editing of drawn objects, they can better support the global modifications in spatial forms that are met in earlier stages of designing.

The Display of Drawings on the Screen

As we have seen, in vectorial drawing systems, drawn objects are stored in a database as geometric information. As such, even if drawings are manipulated on the screen, the screen is just a display of the database of the drawing. In other words, the screen acts as a 'window' through which the user of the system can access, construct and modify, parts of the database.[1] This leads to some interesting effects which have to do with viewing, editing, size, and scale of the drawing.

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1 The calculations which are needed in order to make the display of the drawing correspond to its database are rather complicated and they are achieved through 'clipping' algorithms. (See: Foley, James D. & Van Dam, Andries, 1982, pp.40-42, 143-155.) These are carried out by a sub-part of the system which, for the case of raster scan screens, can be thought of as a bit-map drawing system by itself.

A drawing can be viewed through a single window, so that one part of the drawing can be accessed, or through multiple windows on the same or several screens, so that different parts of the drawing can be accessed simultaneously. Also, different windows can display different drawings and not just parts of the same drawing, or both different drawings and different parts. It could be the case that only one of these windows is 'active', in other words the editing of the drawing can occur only in one window, and the rest are used just for viewing. In other cases there can be several active windows. Additionally, even if a system facilitates several active windows, it might or might not be the case that transfer of information from one window to another is allowed. These options might be sensitive to the kind of machine system used, i.e. power, multi-tasking, etc.

As windows on the screen look at parts of the drawing, there are certain mechanisms for *panning*, moving around the drawing, and *zooming in* and *out*, magnifying or reducing the display of the drawing. Zooming does not affect the actual size and scale of the drawing. It can be also independent of the number of the windows. For example, in one window there could be a display of the whole drawing and in another a magnified part of it.

The actual size of the drawing is set in relation to the object that is represented in the drawing and measured in units that correspond to measurements of the object. We can say that the coordinates of the database of the drawing are world coordinates, describing a notional two dimensional space, potentially infinite, in which both the designed object and the drawing occur. Therefore, the drawing scale is always in a one-to-one relation to the object. The scale of the display, however, may be different when zooming the windows. Similarly, the scale of a hard copy of the drawing can be set independently.

As a result, there must be a way of relating the display coordinates on the screen to the world coordinates of the drawing. This is provided by screen grids which are magnified or reduced in relation to zooming, consistent with the size of the drawing, although they can be differently subdivided or even follow different units of measurement. This can result in some confusion in cases of modification of the units of measurement of the drawing and the display. To avoid this, some systems offer settings for the scale of the drawing in the database.

Grids can be visible or hidden and the construction and modification of the elements of the drawing can be made with respect to them or not. The purpose of grids is to map points in the display to points in the database, in contrast to the traditional drawing practice where grids are used to map points in the drawing to points in space. This possibly explains the fact that many drawing systems do not offer other than regular and orthogonal grid patterns, since grids in computerised drawing are not used for spatial composition. In other words, they are not used in order to obtain a correspondence between drawn objects and spatial objects, but only for the correspondence between display and database.[1] Nevertheless, since the display of the drawing is effectively a rough representation of the information in the database and it is dependent on the screen resolution and the particular zooming setting, the employment of grids seems very important. So is the snapping function that the majority of the vectorial systems offer.

Snapping is a way of precisely positioning or selecting specific parts of the drawing, usually points like ends of lines, middle points of lines, corners of rectangles, etc. and free grid points. There are a lot of cases in which the lack or misuse of the snapping function of the system can lead to problems of correspondence. For example, it could be the case that points that appear to be on the screen at some specific position are not in fact at the intended position in the database. This can be the case since the database uses real coordinates, as opposed to integer pixel coordinates. Problems like this become evident when different zooming settings are used.

Snapping can occur also in conjunction with construction lines. Construction lines can be used in order to obtain a correspondence between unconnected parts of a drawing. In contrast to grids, construction lines in vectorial systems are treated as graphical entities that also occur in the database. These are lines which are defined just by their direction, with two points which do not specify length, and can extend to the limits of the drawing. They can exist in a layer that is hidden or deleted during printing.

It should be clear that in vectorial systems the issue of correspondence between the display of the drawing on the screen and its representational structures in the database is vital. Grids and measurements on the screen and snapping can

1 See the discussion about the use of grids in spatial composition in: 9.2. Drawings and Spatial Objects; Tools for the Description of Space.

contribute, but they cannot cover cases where geometric constraints have to be applied as, for example, in the construction of parallel or perpendicular lines. A lot of systems can facilitate the imposition of such constraints with mechanisms that operate in a fashion similar to snapping. Yet, precise editing of graphical objects usually demands the use of multiple views, or the continuous use of the zooming facilities. In consequence, it seems appropriate for the controlling mechanisms of the display to be independent of the operations of editing of the database. It is very important for the user, for example, to be able to modify the display in the middle of a modification of the drawing. Even though this functionality is more than just an issue of convenience, it does not occur in most systems.

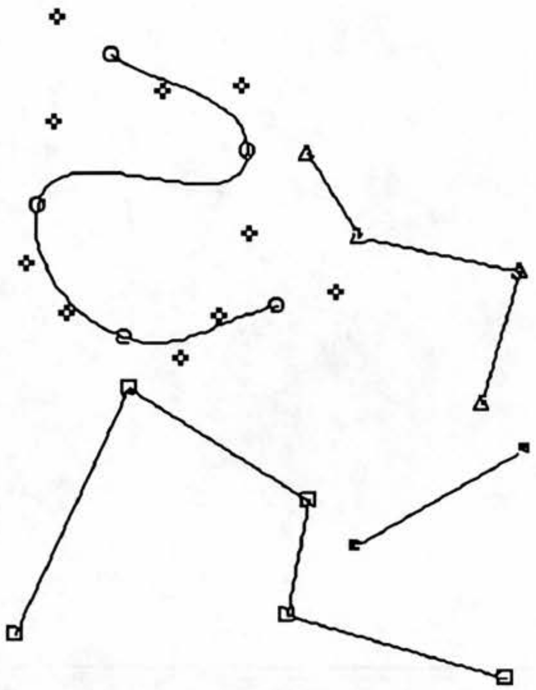
More importantly, there is a certain amount of information about the graphical objects which is not strictly geometric, but relates to their construction or transformation. It seems appropriate that this sort of information can also be exhibited to the user.

The consideration of transparency of the connections between external depictions and internal structures entails certain implications for the interface between display and database. In order to overcome problems of correspondence, some of the systems employ comprehensive and complicated interfaces. These rely on the introduction of handles: symbols that occur only on the screen and not in the database, in order to indicate to the user some state in the editing of a graphical object. They offer position sensitive pointing devices: pointers that display their exact position in measurement units or their relation to an existing object, and the application of a snapping function. They may offer transformation sensitive pointing devices: pointers that change in shape in relation to the various transformations. They might offer guide lines: 'screen' lines that show the geometric and topological constraints that currently apply to the editing of an object. And so on.[1] Examples of such devices are shown in *Figure 6.1*.[2]

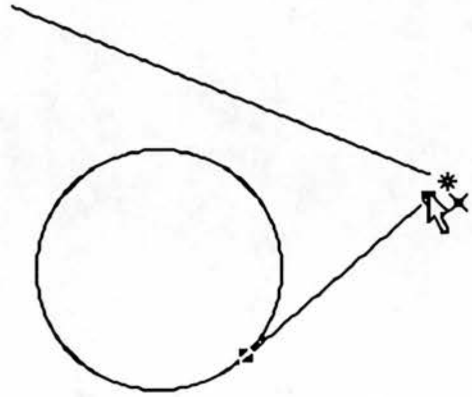
Despite the fact that most issues concerning the relation between the internal representation of the drawing and its display on the screen are not directly connected to

1 Such devices can be most effectively incorporated in the interfaces of drawing systems if they are implemented for raster scan screens.

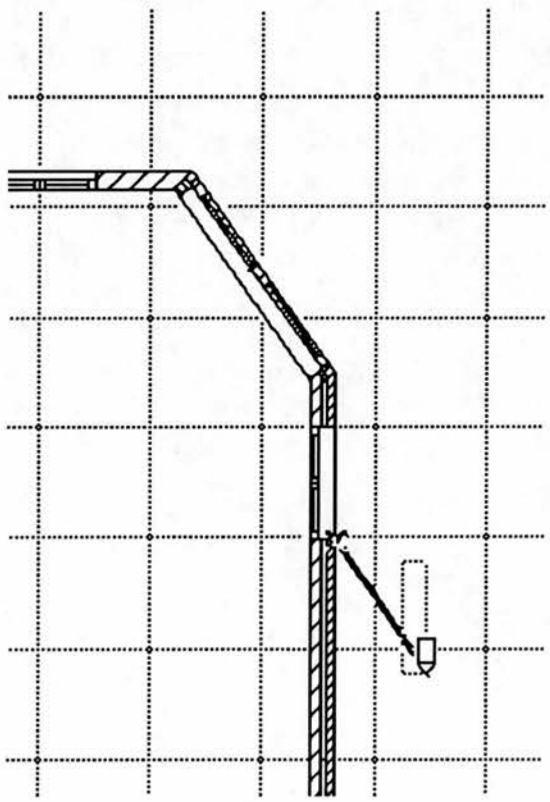
2 The examples in the figure are from the environments of Aldus FreeHand™, Claris CAD™, ArchiCAD®, and Claris CAD™, respectively.
Aldus FreeHand is a trademark of Altsys Corporation.



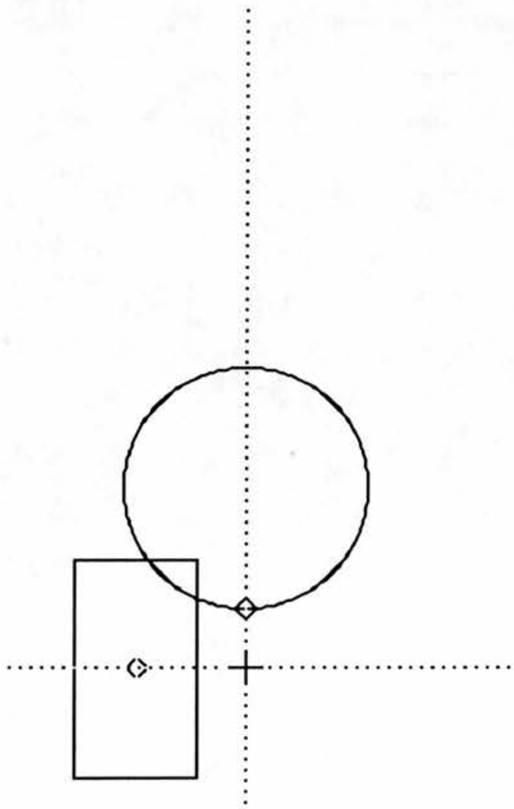
A. Handles



B. Position Sensitive Pointers



C. Transformation Sensitive Pointers



D. Guide Lines

Figure 6.1

the actual functionalities that each drawing system offers, they condition to a great degree what can be done with the system in practice. They condition the manifestation of system-functionalities to the user.

Graphical Symbols and Transformations

The functionalities that the various systems offer relate to the range of the graphical symbols provided, issues on their decomposition into primitives, and the transformations that can be applied to them.

Graphical symbols in vectorial and generally in computerised drawing systems are always accomplished through their selection from a palette that is available to the user, either directly from a menu in the form of a toolbox, or (in the earlier days of computers) by their name. The geometric properties and other features of symbols and their compositional parts are already defined, and the user has to specify the value of these properties when she or he is positioning the symbol in the drawing.

Decisions about the range of graphical symbols that should be embodied in a system are made on the basis of assumptions about drawing and designing practice. They are a manifestation of the theoretical models on which the development of computerised systems is based, and they are directly connected to implications about the restrictiveness and effectiveness of systems. Despite the fact that most drawing systems allow the production of different kinds of drawings, specific systems may be addressed to specialised design disciplines by easing the accomplishment of certain drawings through the provision of a particular range of graphical symbols.

Another issue which is connected to the functionality of a system and relates also to its restrictiveness and effectiveness is the decomposition of the graphical symbols into primitives. In other words, whether the decomposition of symbols is transparent to the user, and relevant to her or his intentions and the purposes of the drawing. As in the case of bit-map drawing, vectorial systems which employ a primary decomposition into lines so that sides of rectangles or polygons can be individually modified show reduced levels of restrictiveness. Yet, it seems useful to also allow global modifications of complete shapes. Most of the current systems offer this functionality.

The *transformations* that vectorial systems offer are related to this aspect. These can also be *global*, operating at the level of graphical symbols or sub-models, or *local*, operating at the level of primitives. Global transformations, such as moving, rotating, stretching, mirroring, scaling, etc., include deleting, duplicating, copying and pasting. Such transformations are directly connected to the effectiveness of the system. Local transformations can include smoothing, trimming, reshaping, etc. Drawing systems that allow these kinds of transformations are associated with low levels of restrictiveness.[1]

A few systems may offer combinations of a global and another global or a global and a local transformation so that, for example, a movement, duplication or rotation may also involve a stretching, reshaping or trimming. Such is the case in which a side of a rectangle is moved to a new specified position without its disconnection from the rest of the sides but involving their reshaping, shown in *Figure 6.2*, case *A*. Another example is the elongation of a rectangle in order to meet another one with parallel trimming of the parts of the sides that coincide, same figure, case *B*.[2] Such transformations could appear to be important to the interests of particular design disciplines.

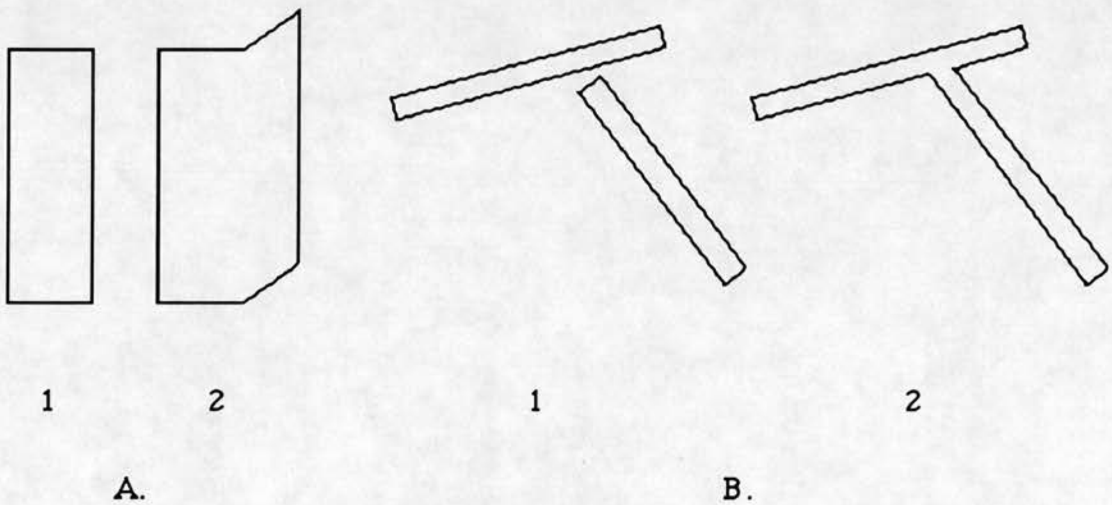


Figure 6.2

It should be noted that transformations that affect the primitives of graphical symbols are not in fact alterations in the decomposition of symbols even if they may look like this to a user. Strictly speaking, the decomposition of symbols generally cannot be altered from the system's point of view. Alterations in the decomposition,

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1 These terms do not necessarily correspond to the terminology found in computer aided design literature. They rather try to capture the user's perception of transformations. As such, global transformations may refer to 'linear' transformations, in which all straight lines of the initial shape are also straight in the final shape and unchanged in number, and local may refer to 'non-linear' or 'curvilinear'. For a description incorporating the geometric constraints in each of the transformations, see: Steadman, P., 1987, pp.61-67.

2 Case A in the figure is made in the environment of ArchiDraw™, the two dimensional component of Architrion™. Case B in Claris CAD™.

from the user's point of view, are in fact connected to extensions in the definitional and constructional properties of symbols. This is the case for the combined transformations that we have just seen.

Consider, as another example, the case *A* in *Figure 6.3* in which a chain of three lines is made using a tool for straight lines in a particular drawing environment.[1] The line in the middle of the chain can be altered into a curved line using a tool that divides and transforms a straight line into two curved segments, forming an S shape curve, case *B*. Similarly a tool that forms a C shape curve can be used, case *C*. Cut points of the initial straight line specify also the points of change in the curvature, and the position of the handles by which the shape of each curved segment can be altered. However, the initial lines have to be drawn by a tool that defines straight lines that may change into a different shape later. Not all straight lines, made using other tools, are susceptible to this modification.[2]

These particular transformations appear to be functionalities of highly flexible systems which are oriented to the drawing of freehand shapes. A more common operation, that occurs in many different drawing systems, is the division of a single straight line into two or more straight segments, shown in case *D*, which may occur without any discrimination in the initial tools.

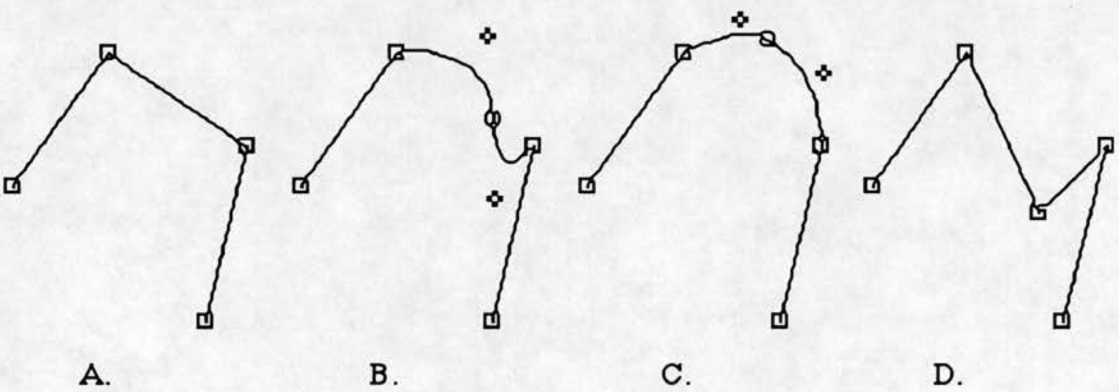

Figure 6.3

These complicated transformations are also related to the issues of transparency between the connections of internal structures and external depictions, and the accounts of interfaces. The occurrence of transformations that affect particular

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1 The drawing system used is Aldus FreeHand™.

2 Curved lines which are susceptible to editing in respect to their curvature, in other words which are not parts of regular geometric shapes such as circles or ellipses, may be referred to as 'Bezier curves'.

graphical objects is a direct manifestation of the theoretical models on which the accomplishment of drawings is based in computerised systems. It should be clear, from the discussion of the examples, that drawn objects are not treated indiscriminately in order to have an increase in the effectiveness of operations or to reduce restrictiveness. The emphasis on particular graphical symbols or transformations is based on assumptions about the functionality these may have in the accomplishment of depictions.

An effect of this emphasis is that objects which appear to be similar on the screen may not actually be represented by the same representational structures internally. When the complexity of these structures cannot be effectively exhibited by sophisticated interfaces, the user has to rely on her or his knowledge and understanding of the system. She or he has to be sure about the choice of proper graphical symbols as well as about the interrelations between these symbols and the transformations that apply to them, and has to memorise their past use in previous operations on a drawing. This is a crucial point that drastically affects the usage of a system.

Another facility in most of the computerised drawing systems is the *dimensioning* of the drawn objects. Exact dimensioning is usually regarded by design practitioners as one of the most tedious exercises in draughtmanship. In computerised systems, since any drawn object is placed in the drawing precisely by virtue of its coordinates, dimensioning is a straightforward calculation. The dimension lines and their values in vectorial systems are usually regarded as ordinary graphical symbols. Once the dimensioning is accomplished they can be edited like the other lines or text. Few systems incorporate some sort of 'active' dimensioning so that dimension lines can correspond to the editing of the drawn objects. This might be very useful in late changes.

Yet, the impact that dimensioning as a whole may have in drawing composition is not very important. During the making of drawings designers mostly rely on grids, construction lines, and measurements that are not required to be stored in the database of the drawing but just displayed on the screen, since drawings are susceptible to radical changes later.

Finally, a functionality that is related to active dimensioning even if it is more closely connected to issues about the definitional properties of graphical symbols, is *parameterisation*. This can be seen as some sort of geometric or topological constraint maintenance. In parameterised drawing, the values of the geometric properties of graphical symbols that compose a particular drawn object are defined as variables of some constant specified by the user or even as variables with respect to each other, so that a change in one of these properties affects the whole drawn object. This functionality is particularly useful in cases where the topological relations between the graphical symbols or the shape that they compose are well defined. As such it is not met in the majority of general purpose drawing systems, but it is usually a feature of systems which are particularly developed according to the domain-interests of specific companies or institutions.[1] Typical applications of this concept are in the representation of sections of steelwork or precast concrete where the same shape of beam or other unit is produced in a wide range of different sizes. Similarly, it may apply to the representation of a whole beam structure where a change in the dimensions of a particular beam has to be followed by corresponding changes in the rest of the beams, and consequently in the dimensions of the whole structure; or vice versa.

Design Drawings in Vectorial Drawing Systems

The issues which appear to be important for the use of vectorial drawing systems in designing, have to do with graphical symbols and transformations as well as with the organisation of the drawing in the database, since accounts of the display of the drawings on the screen are not directly connected with the purposes for which systems are used. Also, it does not look worthwhile examining the usefulness of vectorial systems as draughting systems used only for the presentation of drawings. We want to explore the assumption that computerised drawing systems can be fully employed in designing when they can accommodate perceptions about drawing that are met during different stages in design practice.

We have seen that the objective of increasing the effectiveness of drawing operations in computerised systems implies the use of vectors as the primary vehicle for the representation of drawings, in contrast to pixels, so that relations between graphical objects can be accomplished that can be affected by comprehensive transformations.

Strictly speaking, the use of vectors by itself does not drastically improve either the effectiveness or the restrictiveness of a system. Design drawings are

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1 A system which incorporates this facility is CADRAW™, developed during the seventies by and for Ove Arup Partnership. CADRAW was later made commercially available by Oasys, Ltd.

constituted from lines, and not points as in bit-map systems, and vectors look to be a straightforward approach for their representation. A system in which drawings are just lines without any structuring of these lines into more complete drawn objects, and without the application of transformations that can affect drawn objects and not only individual lines, would not be radically different to the handmade drawing environment. However, the motivation for using such a system in designing would be minimal, since its usefulness would be reduced to issues of storage, maintenance of quality after multiple reproductions, etc., which are related to the management of production, but not to the act of designing itself. The increase of effectiveness, in consequence, is based on the structuring of drawing, and vectors as primitives of drawings are used because they can facilitate this structuring.

The primary structuring occurs through the implementation of graphical symbols. Graphical symbols can be considered as sets of vectors and to this extent are not different to sub-models as a means for organising the drawing. What differs is that graphical symbols are given and imposed in the composition of the drawing in contrast to sub-models which are accomplished by the user. They are offered in order to minimise the drawing operations, as in the case in which already composed sub-models occur as libraries in the system.

However, this difference becomes very important in relation to the effectiveness and restrictiveness of the system. The drawing of objects that do not coincide with the graphical symbols provided by the system requires a large number of operations. Such is the case of the rectangle that we have seen in the first part of our discussion on computerised drawing systems. Many drawing systems attempt to reduce this restrictiveness by allowing their disassembling into primitives and/or by providing wider ranges of graphical symbols. This may result in systems that offer a series of graphical symbols ranging from less comprehensive with few properties incorporated, such as lines, to more complete with a lot of pre-established properties, such as symbols for walls with different layers of construction with different hatching styles.

It is important to realise that these decisions about the effectiveness of drawing systems directly derive from assumptions about the way drawings are used, that are incorporated in the development of systems. Such assumptions take into account the conceptualisations that drawings depict during designing. Thus, for example, models of drawing behaviour anticipate depictions as corresponding to domain-specific elements and they provide graphical symbols that can be used to represent behavioural properties of domain-elements. Despite the fact that models of drawing behaviour are not directly represented in the system – there is no mapping of graphical configurations to other symbolic structures that can be used as representations of concepts – these models regulate the structure of graphical representations. In other words, they recognise that certain features of graphical symbols and certain relations between them take part in the representation, and these are the features and relations which determine their definition in the system.

We have seen that the definitions of geometric properties of graphical symbols, as well as of the relations by which primitives are composed into graphical symbols, are pre-specified (before the use of the configuration as a representation in some particular context and alterable by the user). At this stage we may assume that models of drawing behaviour capture the expectations of designers, at least in the case of those drawing systems that have been particularly developed for designing. Furthermore, we may expect to see that systems developed for particular design disciplines, such as architectural design, can be successfully used.

After all, the values of all of the properties of graphical symbols in computers can change during their accomplishment, and there are relations which can be specified solely by the user with respect to what she or he wants to express. Such is the case of relations that appear at the level of the organisation of the drawing in terms of layers or sub-models. Layers and sub-models attempt to accommodate, in the drawing environment of the system, the conceptual associations between components of spatial forms, and in consequence graphical symbols, that occur in design activity. As such, they do not rely on considerations about the nature of spatial forms but they recognise that spatial forms are conditioned by varied conceptualisations by individual designers, and allow their expression. Yet, given all this, we have to recognise that systems impose a hierarchical structure with respect to whether layers or sub-models are used as the primary means of organisation.

We will come back to issues of the initial specification of graphical symbols after looking at three dimensional modelling systems, especially in the discussion about the use of computers by the designers in our case study. In the case of modelling systems, the imposition of pre-established views about drawings is perhaps more strict since additional aspects of the structure of spatial forms have to be taken into account beforehand, so that a system can be used 'effectively'.

6.4. Three Dimensional Modelling Systems

Three dimensional systems, while they are not strictly speaking drawing systems, are intended to be used as modelling environments within which the representation and manipulation of spatial forms can be made. As such, they can be seen as playing the same role as drawing in designing, and to this extent they can be discussed along with computerised drawing systems.

Modelling systems can be regarded as an extension to two dimensional vectorial systems. They rely on the same principles that apply to vectorial systems but they extend their capabilities to three dimensional geometries. In other words, there is also a distinction between database and display, and they follow the same modes of organisation of the database. The difference is that here we are dealing with representation of solids in a three dimensional coordinate system. Also, modelling systems offer some additional transformations which are used in the construction of three dimensional objects.

Examples of modelling systems include ModelShop™, ArchiCAD®, Architrion™, for the environment of Macintosh™; Archway™, Mega Model™, for IBM® Compatibles; and MicroStation™, AutoCAD®, VersaCAD Design™ for both.[1]

Despite the fact that most of the modelling systems allow the disassembly of solids into vectors, which can be edited independently as two dimensional representations for reasons of presentation, there are differences in respect to the representation of solids in the three dimensional environment. These differences have to do with the employment of sets of *cells*, *lines*, *planes*, or *blocks* in the description of spatial objects. These differences might be further extended in the implementation of specific systems, so we have combinations of different kinds of representation in a system, such as with the description in terms of sets of *objects*. There are also differences in the ways descriptions are accomplished. We can have constructions in terms of three dimensional transformations, assemblage of primitives, or by the explicit definition of coordinates as vertices.

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1 ModelShop is a trademark of Paracomp, Inc.
Archway is a trademark of Design Computing, Ltd.
Mega Model is a trademark of Mega CADD, Inc.

We will not re-examine those principles of modelling systems which are the same as vectorial systems. However, it should be noted that the distinction between internal representation and external presentation, either on the screen or in a hard copy, is far more apparent in the case of modelling systems. In all modelling systems, irrespective of the mode of description they use, the three dimensional model of the designed object is only in the database of the system. The user can edit it by viewing just two dimensional projections of this model on the screen. These can be single or multiple, with respect to the implementation of windows, so that they can be plans, sections, axonometrics, perspectives, or combinations of these; and some may be editable and others not.

Descriptions of Three Dimensional Objects

The different ways of describing a three dimensional object in a computer implementation refer to the kinds of representation in the database of the system. Usually, the attributes of this representation condition the usage of the system and the ways according to which a model can be constructed.

Descriptions in terms of Cells

The simplest approach to representing solid objects is by employing cubic cells which occur in a three dimensional matrix. The sets of cells that correspond to a solid are considered as occupied by matter.[1] Cells can be seen as being similar to pixels in the case of two dimensional bit-map systems. They are, however, a database representation without any restrictions from a depiction on a screen. The representation of space in terms of cells looks to be the closest equivalent to physical solid objects in computer descriptions. However, the size of computer memory that is required for the storage of such descriptions makes this implementation useless for spatial objects that normally occur in design, or for detailed manipulation.

A recent development of this scheme resolves some of the problems by applying a cell decomposition. According to this, big cells are divided into sub-cells at different levels. Higher hierarchical cells occupied by the solid at one level are stored, and sub-division occurs only for the partially occupied cells, reducing substantially the amount of memory for the model. A similar approach is to sub-divide the solid into

1 Cells might be referred to also as 'voxels', and this sort of description is sometimes called 'spatial occupancy representation'. See: Radford, Antony & Stevens, Garry, 1987, p.139.

non-cubic and non-identical cells.[1] Still, in cell representations the amount of detail incorporated in the model is dependent on the particular way of division. Complex spatial objects require quite complicated descriptions, and the algorithms that handle the representation are very slow. Systems that follow this sort of representation are not convenient for practical applications, especially for designing.

Descriptions in terms of Lines

Another simple way of describing a solid object is in terms of lines depicting surface discontinuities. In this case the endpoints of lines that define two dimensional polygons become coordinates in a three dimensional coordinate system. The system requires information about the position of the points in the space, and about their topological relations to other points so as to define lines.

This kind of representation allows easy construction of models directly from existing two dimensional drawings. However in this case, the user of the system is responsible for the consistency of the object. Two dimensional shapes have to be precisely positioned in the model so that the same lines in different projections coincide in the three dimensional space. Furthermore, as the system does not 'know' about planes and solids, there cannot be a distinction between polygons representing enclosed surfaces and polygons representing open space. The system can only produce wire-frame views, showing all the lines in the space. For the same reason, the representation of curved surfaces is particularly difficult if not impossible. The user has to combine lines in space by herself or himself in a way that conveys the impression of a curved surface. Individual lines, however, can have curvature so that curved surfaces are not necessarily represented in terms of curved lines broken into segments, as usually is the case for plane descriptions.[2]

This sort of description is associated with lack of validity, and ambiguity. Lack of validity appears because models can be produced of objects that cannot actually exist in reality. Ambiguity, on the other hand, appears because a certain model can be interpreted to stand for more than one physical object.[3] In result, the user has to take care for the resolution of these conditions externally as in the case with

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1 The first approach is known as 'octree decomposition'. The latter as 'cellular decomposition'. See: Jared, G. E. M. & Dodsworth, J. R., 1987, pp.155-161.

2 In this case, the implementation of curved surfaces is more easily done by segmentation for reasons of topology. See below the discussion on plane descriptions.

3 See the discussion on wire frame modelling and its disadvantages in: Rooney, J., Bloor, M. S. & Saia, A., 1987.

handmade drawings. She or he may have to use, for example, only those lines which are appropriate to a particular view, in other words to construct a partial model of the object, if the aim is a realistic projection. The accomplishment of a three dimensional view might look similar to the case of handmade drawing in which information, for example, from two elevations is used in the production of a perspective. Because of these attributes, this sort of modelling can be seen as the positioning of two dimensional line drawings in a three dimensional space rather than actually solid modelling, and it is no longer used widely in design systems except with the combination of richer descriptions.

Descriptions in terms of Planes

Most of the current modelling systems base the description of solid objects on opaque flat surfaces or planes. Planes can also be extracted from two dimensional drawings and positioned in a three dimensional space. Planes may have polygonal boundaries of arbitrary complexity, and may also be a combination of opaque and transparent surfaces for the representation of holes and openings. They can also be associated with non-geometrical properties, such as colour.[1]

Solid modelling based on plane descriptions relies on structures of geometric and topological information. Geometric information concerns the coordinates for the vertices of planes, the curve geometry for their edges, and the surface geometry for the faces. Topological information is the network of relations which interconnect the vertices, edges, and faces into a solid. Because the main principle is the binding of primitive geometric information, through topological relations, into a complete description of a solid, plane description might be more correctly called description in terms of *boundaries*. For the same reason, normally, the representation of curved surfaces is not allowed but most of the systems provide means of breaking up curved surfaces into flat facets, and curved lines into straight segments. However, there are some plane description systems which take into account only geometric information.

With this sort of representation considerable detail can be achieved in the description of the spatial object. Yet, the process of modelling is usually based on a series of complicated transformations according to which complex three dimensional objects can be obtained from simple two dimensional ones.

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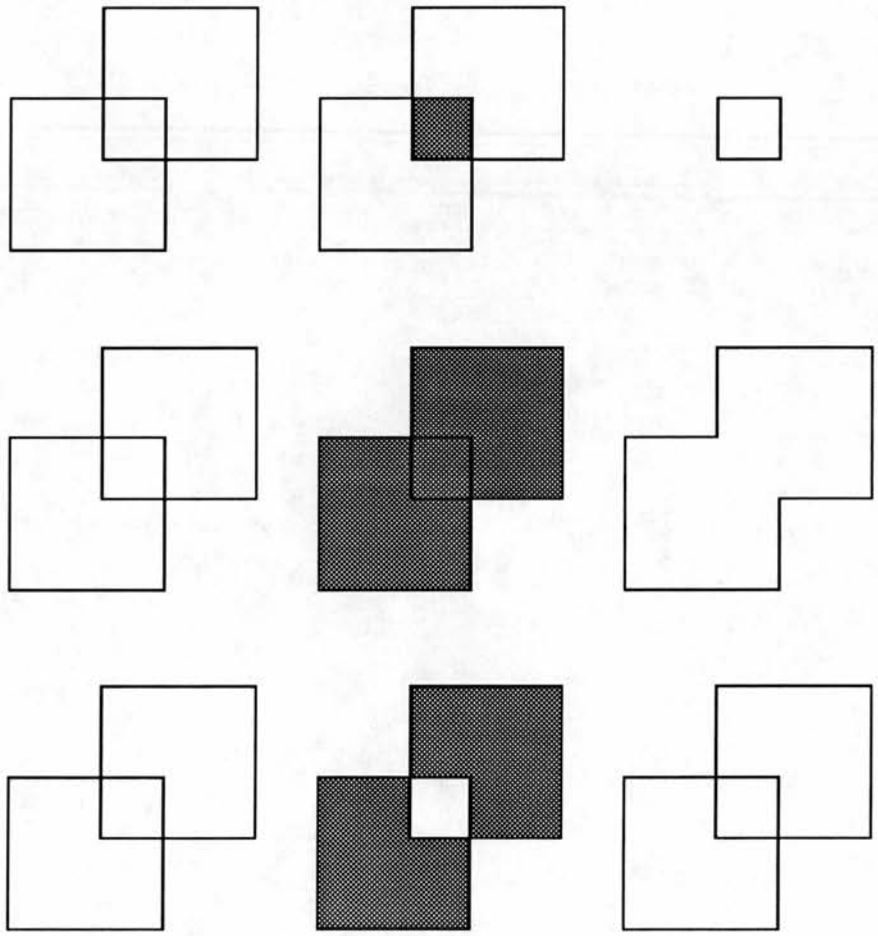
1 Richens, Paul, 1989, p.41.

Descriptions in terms of Half-Spaces

Similar to plane descriptions, there are descriptions in terms of blocks in which the model is constructed out of combinations of simple solid objects. The system provides a range of primitive solid objects and often these are themselves combinations of even simpler entities. Primitive solids are defined in terms of 'half-spaces' which roughly correspond to a region of space that is solid and another that is void. Several half-spaces can be combined to produce complicated solid and void divisions of space, so that solid volumes of space enclosed by void represent the required spatial object.[1]



Intersection

Union

Subtraction

Figure 6.4

As such, the system can be thought of as 'knowing' about space, in contrast to plane descriptions, and any point in the space is either inside or outside a solid, or on the boundary surface of it. Intrinsic to solid descriptions is the incorporation of a

[1] This kind of description is known as 'constructive solid geometry'. See: Jared, G. E. M. & Dodsworth, J. R., 1987, pp.162-164.

set of algorithms, relying on Boolean operations, which take care of the intersection, the union, and the subtraction between solids, upon which the construction of the model is based. Examples of intersection, union, and subtraction are shown in two dimensions in *Figure 6.4*. Particular implementations also allow the incorporation of Boolean operations in systems that employ plane descriptions. Modelling in terms of solids is similar to the assembly of two dimensional drawings in vectorial systems.

Solids as Objects

There is a kind of systems that employ a rich description of solids which we might call modelling in terms of objects. This is not a particular way of implementing solid modelling but a way of combining the attributes of the kinds of description that we have seen in the representation of a spatial object. Objects can be combinations of solids, planes, lines, or other objects, and can be associated with 'real' element properties, such as cost and constructional attributes, and also physical characteristics, like texture, density, U-value, light and sound transmission, etc. The information that such systems incorporate can be used by other applications to calculate the conditions which are associated with the designed object as a whole.

The main difference from the other systems is that assumptions about the role of a particular component in the whole spatial configuration of the designed object suggest the manner of its description, so that, for example, walls may be represented as solids, doors as planes, windows as lines, and so on. In this respect, description in terms of objects is not just the modelling of the spatial form of the object, incorporating conceptual interpretations, and it does not have an equivalent in the traditional modelling environments. Obviously, systems that rely on this sort of description are mostly specialised and intended to be used by specific design disciplines. For architectural design, systems that rely on object descriptions may be referred to as 'integrated building description systems'.[1]

Generally, most of the currently available modelling systems can only handle the representation of homogeneous, rigid, and non-manifold solids. Manifold solids are the class of objects which are joined to one another or to themselves at an edge or a vertex. Yet, the majority of objects that are the subject of architectural design tend to be modelled in terms of combinations of parts, each one of which may not fit within these categories.

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[1] Radford, Antony & Stevens, Garry, 1987, p.141.

The internal representation of the object determines to a great extent the attributes of the system. Plane, solid, and object description systems can produce realistic depictions of spatial objects, including shadows and shading, relying on the principles of descriptive geometry and calculations of density of light rays. This task is often called 'visualisation' even though, at least for small micro computer systems, the results cannot be really compared to actual visual perception.[1]

Yet, as already indicated, the construction of the model in all solid modelling systems, with the exception perhaps of the line description systems, relies on complicated three dimensional transformations. The functionality of each system is actually entailed by the combination of the attributes of the internal representation and the manner according to which the construction and the editing of the object is done.

The Construction of Three Dimensional Models

Despite the fact that the kind of description followed in the representation of solids in computerised systems indicates an approach to the modelling of spatial objects, particular implementations allow different manners of construction and combinations of operations. There can be systems that primarily follow a plane description but offer simple solids as primitives so that the manner of construction is similar to the case of solid descriptions. Conversely, a system based on solid descriptions can allow transformations of primitive solids similar to those that occur in plane description systems.

To this extent, it seems appropriate to categorise three dimensional operations under two different manners of accomplishment. One is the composition of three

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1 An interesting point that becomes apparent after the evolution of computer imagery, but relates back to accounts of human perception (see the discussion on active perception in: 5.3. Relations between Images and Design Concepts; Levels of Interpretation and Components of Meaning) has to do with the calculation of perspectives in computers. As computers can handle big calculations, the construction of spherical perspectives, which closely approximate visual perception, is easy. Yet, such perspectives do not look right to the human eye because we have learnt to perceive straight lines in the visual world as straight even if they are actually projected in our eyes as curves. Our mind interprets percepts and categorises them into concepts by taking into account known properties of the perceived objects such as their geometry. In computer images, because projections lack depth, the corrections which normally occur during the visual perception of real world scenes cannot be applied and instead there is an application of conditions that occur during the perception of surface depictions. As a result, spherical perspectives look wrong since they do not coincide with known perspectives. The same may not occur in the perception of photographs since these can also represent the depth of the scene by corrective mechanisms of lenses, such as the focusing on objects at specific distances from the camera, as well as by capturing atmospheric density. We may foresee, however, that this can occur also for computer scenes, due to future developments of rendering algorithms.

dimensional elements by the transformation of two dimensional ones, and the other the construction of the model by assembling primitives, simple three dimensional objects. There are cases of modelling systems which allow combinations of these two manners of accomplishment in a single model. Generally speaking, plane description systems may follow both manners of accomplishment, while solid description and object description systems rely on accomplishment in terms of primitives. Nevertheless, this categorisation attempts to clarify different attitudes towards the construction of the model, rather than attributes of particular kinds of description. The operations that we shall see do not apply to systems that rely on descriptions in terms of sets of cells or lines.

There is an additional factor that is associated with this categorisation. Usually, systems that follow the former manner of accomplishment, being primarily plane description systems, allow the incorporation and transformation of previously produced two dimensional drawings. In systems that follow the latter one, especially when they are solid description systems, previously produced drawings can be incorporated, but these are usually not integrated into a single model and, instead, they are used as if they were transparencies, for tracing geometric information into a new model. It seems that the integration between two and three dimensional representations into a single model is not a difficult problem in the implementation of plane description systems since the description of a complete two dimensional drawing can be similar to that of a plane of a three dimensional model. The same condition does not hold for solid description systems.

Modelling based on Two Dimensional Shapes

In systems that rely on the transformation of two dimensional entities for the construction of three dimensional objects, the most elementary operation is *extrusion* according to which a planar cross section is given depth to form a prismatic surface. In principle, the application of the operation to closed two dimensional graphical objects, such as circles, rectangles, closed polygons, etc., adds capping planes at the ends of the three dimensional object, so that the appearance of it is of a solid cylinder, a block, etc., while its application to open shapes results in forms like folded sheets and tubes. Ideally, some control by the user is allowed so that the result is what the user requires. A restriction in some systems is that the initial two dimensional objects should be made directly through the palette of the system; else a shape produced by a set of lines, even closed, cannot be extruded.

Another elementary technique is the formation of a surface by the *revolution* of a profile. This produces a solid that could be a cone, a dome, or a sphere.

More complicated operations include *sweeping* and *swinging*. Sweeping is like an extrusion including additionally a centreline, which could be polygonal, that specifies the direction and the length of the extrusion. It produces duct-like surfaces. Swinging is a rotational sweeping, to produce elements like pipes in complex shapes, handrails for staircases, etc. Also, *skinning* is the development of a surface from several dissimilar cross sections. Finally, *tweaking* provides the capability to make localised changes to the form of an already constructed element, like the enlargement or reduction of one face of it, the change of the shape of an opening, and so on.

These complicated operations, with the exception of tweaking, are not provided by the majority of small computer systems. Instead, the accomplishment of a complete model is achieved by additional transformations, similar to those met in vectorial systems, like movement and rotation in space, duplication, etc., by virtue of which different elements can be combined together. Still, there are shapes which cannot be modelled at all by such transformations, like bodies with indentations.

Additionally, as solids are produced on the basis of two dimensional shapes, transformations like *trimming* and *chamfering* of solids, which involve a change in the topological information that defines the solid, are very complicated to perform or not provided at all. The user has to rely on tweaking to simulate the intended shape. For the same reason, there are cases of systems in which there is no verification of the consistency of the spatial form and as a result tweaking may produce unrealisable solids, or otherwise incomplete modelling. Systems like this are usually plane description systems (systems that rely only on geometric information), in contrast to boundary description ones, and an example of such a case is shown in *Figure 6.5*.

Another limitation that a great number of systems have is the inability to make holes in surfaces that are produced by some transformation. So, for example, if the initial two dimensional plane includes a hole, the hole can be extruded in three dimensions along a specified direction, but new holes cannot be made in the planes that are parallel to this direction. This would similarly entail a major change in the topological relations that define the solid. The problem is not severe, as the resulting solid can be rotated or another initial plane can be used in order to achieve the required result. However, it is a major restriction for architectural design because initial two dimensional shapes usually belong to plans. As such, the punching of holes for openings in walls that are extruded from rectangles in a plan is particularly difficult. Some systems may partially resolve the problem by attaching line descriptions of openings on walls.

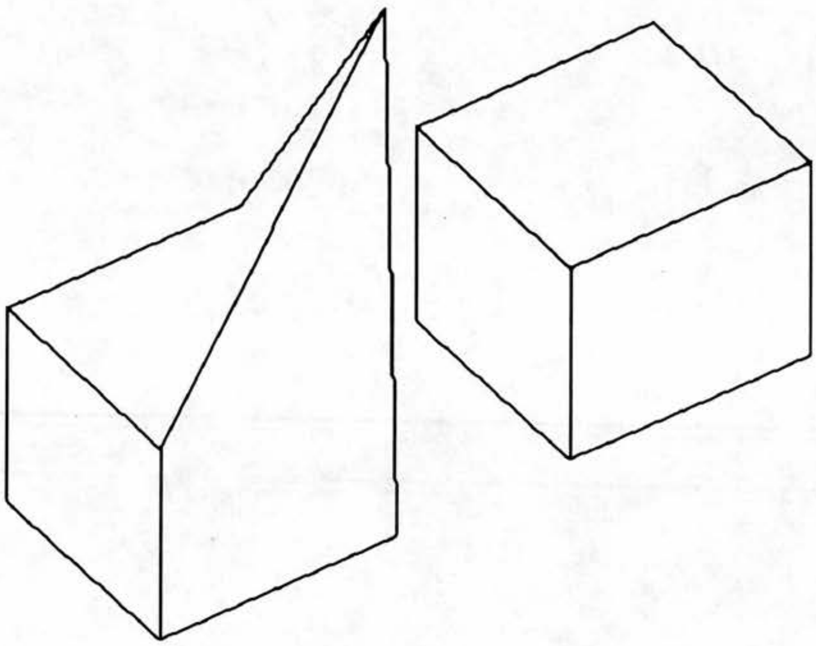

Figure 6.5

Most of these limitations can be handled by Boolean operations. However, the incorporation of Boolean operations in plane description systems tends to be expensive and impractical because they require scanning of the whole data structure of the object involved in the operation, even if the end result of the transformation is only a minor change in the object.[1] As such, they are only met in large systems.

Modelling based on Primitive Solids

In the case of systems that rely on accomplishment of models by the assemblage of primitives, operations are less complicated. These are mainly the operations met in vectorial systems, but in three dimensions. Usually, such systems include operations for the elongation and trimming of solids, and for tweaking. Also, they may provide combined operations such as linked duplication and movement or rotation so that the solids in the resulting chain of primitives are attached to each other.

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1 Jared, G. E. M. & Dodsworth, J. R., 1987, p.173.

In most of these systems, pre-defined void spaces, for the representation of holes and openings, can be provided as primitives. This is a straightforward implementation for systems that rely on solid descriptions, but it seems that this also is not difficult for plane description systems that use primitives.[1]

Solid description systems may also provide Boolean operations for the combination of primitives into complicated solids. When this is not the case, there could be problems with solids that nest into one another. If we exclude this condition, there rarely occur cases of unrealisable spatial objects because of the particular manner of accomplishment. This is because models are made through the assemblage of well defined solids and not through the binding of two dimensional surfaces.

In comparison to modelling in terms of initial two dimensional shapes, modelling in terms of primitives may result in less detailed and accurate descriptions, as complex shapes have to be made by assembling a number of primitives in various relationships. The decomposition of the intended spatial object into primitives then determines the quality of its model.

Another restriction, in a number of systems, is that primitives retain their initial descriptions and in consequence all of their edges are shown in projections from the model, even if they are used in conjunction with others to represent a particular spatial element. This problem cannot be handled by Boolean operations as in this case primitive solids are attached one to another, but they do not fall into one another. An example of the difference between modelling in terms of two dimensional shapes and primitives, in relation to this aspect, is shown in *Figure 6.6.* Many systems employ particular algorithms for the elimination of such edges in the two dimensional drawings that result from the projections, with some problems, however, when primitives are partially attached. In such cases, there is a need for additional trimming operations which usually are left to be accomplished manually by the user. Obviously, the major limitation is the inability for active incorporation of two dimensional drawings in the final model. Models have to be composed only from three dimensional entities.

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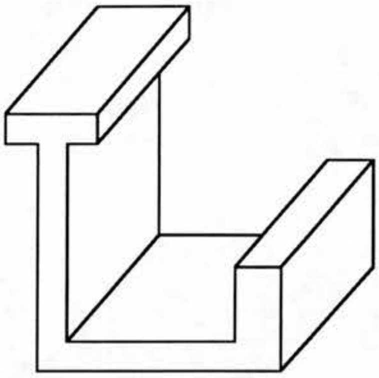
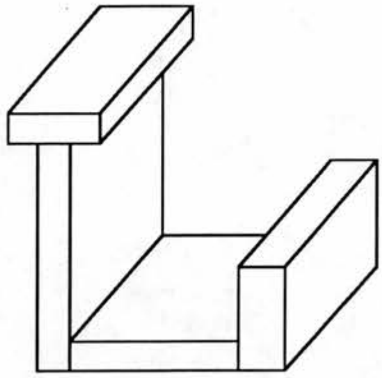
1 Possibly, because it does not involve a change in the topological information of a solid but a definition as if it were an extrusion.



Modelling on the basis of initial
Two Dimensional Shapes



Modelling in terms of
Primitives

Figure 6.6

There is another operation that can be used for editing solid elements that is very comprehensive and can be seen as a method for accomplishing three dimensional models, by itself. According to this method a solid is presented to the user as a combination of three dimensional 'splines'. Splines are sets of segments in space, connected to each other, which can be thought of as wrapping the solid. They are controlled by nodes, which can be individually moved in space to form the intended shape of elements, and can include excrescences and sinkings.[1] There are some limitations on the representation of holes with the use of splines. Splines can be used for the creation of sculptural forms and occur in boundary description systems. They can be used in addition to the standard operations of such systems, but they are usually offered by large systems or systems that are developed for the interests of specific design disciplines.

Three Dimensional Modelling and Designing

In general, it can be said that, similarly to the case of two dimensional vectorial drawing systems, the functionality of modelling systems is also conditioned by the issues of effectiveness and restrictiveness. Systems that operate in closed domains, relying on strictly disciplined views, appear to be more effective within the context of these domains, like object description systems. Systems that are intended to be used for general purposes and changing views lose in effectiveness. However, the characterisation of the issues of effectiveness and restrictiveness in the functionality of

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1 The use of splines is similar to the case of bezier curves in two dimensions as in the example of *Figure 6.3*.

modelling systems can be better approached if we consider their use as designing tools in contrast to aids for the presentation of a design project.

Generally speaking, the operations used for the accomplishment of a three dimensional model in computerised systems are quite distinct from the processes that underlie designing. They are ways of producing a three dimensional model of, to a great extent, established spatial forms, rather than a manner of exploring the qualities of speculative spatial forms. Yet, there are distinctions between the different manners of accomplishment, as we have just seen.

For the case of modelling on the basis of initial two dimensional shapes, transformations involve the detection of cross sections that can be used to generate the solid. There are elements with defined spatial forms, such as prefabricated concrete blocks, beam sections, pipes, etc., which can be easily described in terms of cross sections. However, explorations in the spatial distribution of the designed object may result in plastic forms which either use small construction units that do not seem to offer a basis for modelling in computerised systems, such as with brick construction, or plastic materials, such as mass concrete. The specification of cross sections of such forms is a tedious task, and to a great extent irrelevant to designing itself.

It is also worth noting, that cross sections may not be obtained directly from standard projections used in designing such as plans, sections, and elevations. The modelling of a simple pitched roof with a window, for example, may involve the extrusion of a shape that does not correspond to either the plan or a section of the roof. For more complicated spatial forms, the active involvement of existing two dimensional drawings in the modelling could be worthless.

We might assume that the majority of designed forms follow regular shapes, with appropriate cross sections which can be easily obtained. Yet, modelling on the basis of initial two dimensional shapes is not the kind of modelling that is required during designing. It assumes that the spatial form of the designed object is established and has been achieved with the aid of two dimensional drawings, entailing the use of tools for the conversion of information from such drawings into solids.

In consequence, the purpose of such modelling systems for designing is mainly for the presentation and the visualisation of the artifact. It might also help the realisation of minor or even major problems that could otherwise become apparent later during the construction of the artifact. Boundary description systems in particular, which generally are not characterised by cases of inconsistency in spatial forms, can offer a critical evaluation of the form in respect to this aspect. They may also help evaluations in respect to lighting and other physical conditions that seem very difficult to model through the traditional modelling environments.

These considerations are connected to designing and justify the use of computerised modelling systems, but the complexity of the operations used imposes limits on their involvement in the process of exploring and defining a newly proposed spatial form. Namely, we come back to the issue of economy of operations. Modelling systems that rely on accomplishment on the basis of two dimensional shapes show reduced effectiveness, as they firstly assume existing drawings and established spatial forms, and secondly they involve the additional task of the specification of cross sections.

The employment of systems that rely on modelling in terms of primitives in spatial composition seems to be less flexible, since changing a design in such systems involves, effectively, the rejection of early drawings and the accomplishment of a new model almost completely from scratch. However, we may assume that the problem disappears if we consider such systems as replacing the role that two dimensional drawing plays in spatial composition. That is to say, modelling systems like these might be used earlier in designing, before the specification of the form in precise and detailed drawings. Systems which support global changes and multiple editing of primitives, with combined operations, and local transformations, with operations like trimming, might suit this approach.

This assumption suggests the replacement of the modelling environment that two dimensional drawings normally offer by introducing as a substitute the process of three dimensional modelling. In other words, it implies that assertions from conceptual models are directly connected to three dimensional entities which are positioned in space to form the spatial object.[1]

The approach is supported by some systems which usually rely on object descriptions of spatial forms. Thus, they take into account particular interests in spatial composition and concern a specific domain of designed objects. However, the employment of such systems in designing is also associated with problems which in fact are the problems met in vectorial drawing systems extended to three dimensions.

1 An example of a system that follows this approach and its consequences for designing are discussed in: Aish, Robert, 1986.

As such, there is an initial specification of properties of spatial objects and an imposition of pre-established views to designing. Difficulties may also occur in respect to the organisation of the information in the database.

The problem of correspondence between database and display is far more apparent as models are constructed in three dimensions while their editing can only occur on the two dimensional display. The system may allow editing only in plans and sections, reducing the advantages that could be gained for designing by the involvement of three dimensional manipulation of spatial forms. There are systems that allow editing in three dimensional projections, such as perspectives or axonometrics, by the use of complicated interfaces, like pointing devices that can be moved in three dimensional space. In this case, there are problems of ambiguity: instances of inconsistency between the perceived position of the pointer on the screen and its actual position in terms of the coordinates of the database.

Despite the limitations, it is anticipated here that modelling in terms of primitives can provide an alternative to the traditional mediums of modelling, as the shortcomings of its operation can be balanced by the advantages of spatial composition in three dimensions. The system that we will examine in detail in the next chapter of the thesis, follows this manner of accomplishment. Implications in actual design situations will be further explored.

6.5. Summary

In this chapter, a view on computerised drawing and modelling systems has been developed, focusing on the functionality that these systems may have in explorations during designing, in contrast to presentation and visualisation of the designed artifact. This functionality was considered in terms of effectiveness and restrictiveness that systems demonstrate.

Effectiveness refers to the objective of minimising the drawing operations needed for the accomplishment of certain depictions, by the provision of specific graphical symbols and comprehensive transformations for their manipulation and editing. However, increased effectiveness is usually associated with an increase in restrictiveness. Restrictiveness refers to limitations on the applicability of symbols and transformations to depictions which do not fall within the range of drawn objects anticipated by the system developer. It was suggested that a specific system is successful when it combines maximum effectiveness with minimum restrictiveness.

These issues are seen as a direct implication from models of drawing behaviour that underlie the development of computerised systems. These models determine the specification of the structure of drawings as produced by systems. Bit-map systems, which are directed at expressive drawing and painting, show reduced effectiveness and restrictiveness. They rely on a decomposition of drawings in terms of pixels that refer to basic units in screen resolution.

Vectorial drawing systems, such as those directed at designers, show closer dependencies between models of drawing behaviour and system-functionalities. These systems rely on the structuring of drawings in terms of vectors which convey geometric information about drawn objects; extensive graphical symbols and transformations are introduced. Since relations between symbols and transformations can be defined with respect to the purposes for which a drawing is used, vectorial systems seem to operate well within the context of specific domains.

The case of modelling systems is similar. Modelling systems generally follow the principles of vectorial drawing systems, but their functionality is extended into three dimensional space. Thus, there is also a distinction between the database and the display; the database holds geometric information, though the description of three dimensional information may follow different principles of solid modelling. However, the issues of effectiveness and restrictiveness here are more closely connected to complicated transformations that are used in the accomplishment of models. Modelling can be made based on initial two dimensional shapes or on primitive solids. Modelling based on two dimensional shapes can make use of existing drawings, but this usually involves conceptualisations and processes specific to a model that go beyond the explorations normally met during the accomplishment of spatial forms in designing. In contrast, modelling in terms of primitive solids might be used effectively when it occurs prior to two dimensional drawing.

Consistent with this discussion, we decided that a system developed specifically for architectural design, following the principles of modelling based on primitive solids, should be used by the designers in our case study. The implications of the use of such a system will be discussed in the following chapter.

7. Example of the Use of Computers in Design

After the theoretical discussions in earlier chapters, on the cognitive operations by which representations are manipulated during designing, and on the approaches to structure of representations and drawn representations in particular, this chapter begins to discuss and examine the implications of these accounts in the use and accomplishment of drawings. Following the description in the previous chapter of the various computerised drawing systems that can be involved in design activity, we will now examine how a particular system was used by the designers in our case study. The discussion will indicate problems and limitations in the employment of computers, that emerge when they are used during the accomplishment of design tasks.

Specifically, a central aspect of the discussion on the interpretation of drawings was the issue of decomposition according to which graphical representations are decomposed into graphical symbols so that their meaning is obtained with respect to relations between symbols in the configuration. In this chapter we will examine what happens when established views about the decomposition of drawings determine their accomplishment beforehand, that is irrespectively of qualifications that drawings obtain during their use. This is the case with computerised drawing, as we have seen in the previous chapter.

It will be argued that problems in the employment of computers on design tasks are connected to this issue. The initial specification of features and relations of graphical symbols in drawings determines their use, and in consequence the use of the systems. Aspects of complexity of transformations, apprehension of functionality of systems, or directness in the manipulation of drawings are also related to this issue.

This chapter will show the role that drawings can have in the accommodation of design explorations. It will pose questions on the connections between the operations by which drawings are accomplished and the design processes by which drawings and spatial forms are manipulated. These questions will direct the discussions in the following chapters.

7.1. A Specific Modelling and Drawing System in the Context of the Case Study

The second chapter, dealing with the example of architectural design which is analysed in the thesis,[1] explicitly describes the objectives and the expectations of the case study as well as the conditions that underlie it. Here, we can recall some of these aspects in order to see how the use of computerised systems is related to them.

The design project undertaken by the students was about a small conference and exhibition centre for Greenpeace on Cramond Island near Edinburgh. The brief presented to the students and the map of the island are shown in *Figure 2.1* and *Figure 2.2* of the second chapter, respectively. The objective of the case study is to examine the relations between drawings and the design activity. Thus, drawings from each of the students are categorised in respect of the drawing environment used, and related to each other with respect to processes by which each drawing is developed from a previous one. This results in maps of design expressions shown in Appendix A. As the main focus is on the role of drawings in designing, the context within which each drawing is developed is obtained by recording the range of activities undertaken on the basis of discussions with the students. Let us see, however, which assumptions underlie the use of computers.

A main objective underlying the choice of a system to be used by the students, as well as its involvement in the case study, results from the approach to designing that the thesis takes so far. As we have seen earlier in the discussion about conceptual models and cognitive operations,[2] the thesis takes the view that the spatial form of the designed object may be initially obtained on the basis of existing spatio-imaginal models by virtue of experience of the designer, but it is developed through its dependencies on conceptual models. This view rests on the assumption that, in explorations about the attributes of spatial forms there is a progression from abstract

1 See: 2. An Example from Architectural Design.
2 See: 4. Objects in Mind.

forms which only loosely relate to the circumstances of the particular design project, to more concrete and stable forms which begin to show correspondence to the conditions of the project as these are conceptualised under conceptual models. In other words, there is a top-down approach to designing. The objective then was that, in order to use a computerised system in the early stages in designing, the chosen system should reflect this quality.

Other objectives affecting the choice of the system have to do with the factors extensively described in the previous chapter. The system should have been developed particularly for architects, and if offered the possibility of three dimensional modelling this should be in terms of solid primitives. It was anticipated that involvement of three dimensional modelling in the early stages of designing would enhance spatial composition.

The principle system chosen was Architrion II™ (Version 5.0), running in four workstations of the Macintosh™ laboratory of the Department of Architecture, of Edinburgh University. The students could also have the choice to use occasionally SuperPaint™ (Version 1.0),[1] which combines bit-map and vectorial representations of graphics in a painting/drawing environment. Before examining how the systems were used by the students, we may have a short look at the specific characteristics of Architrion II™ which differentiate it from other modelling systems.

Architrion II™ is a quite large system which consists of separate programs, the main ones being: ArchiDesign™, for three dimensional modelling; ArchiDraw™, a vectorial drawing environment; and ArchiList™, a program for quantitative analysis and calculations of the design elements. ArchiList™ was not used by the students, basically because it is directed at the analysis of finished buildings, it is not involved in designing at all.[2] Architrion is a layer oriented system which also allows sub-models to be accomplished and nested in each other. The system makes extensive use of libraries which are accessible from most of its sub-programs.[3] Libraries may cover pre-defined three or two dimensional sub-models, frames for windows and doors, structural components, different typefaces for text, hatching patterns, etc. However,

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1 SuperPaint is a trademark of Silicon Beach Software, Inc.

2 In the following by referring to 'Architrion' I refer to attributes met in either ArchiDesign™ or ArchiDraw™, as indicated, of the above mentioned version of Architrion II™, excluding ArchiList™, unless otherwise stated. Similarly, 'SuperPaint' refers to above mentioned version of SuperPaint™.

3 Characteristics of computerised drawing and modelling systems are discussed in: 6. Drawings in Computers. See, in particular: 6.3. Two Dimensional Vectorial Drawing Systems.

the best way to apprehend the functionality of the system is to consider the philosophy which underlies it.

The developers of the system claim that "Architrion was designed to operate as closely as possible with the way architects *think*. ... Any Architrion project ... may be laid out starting in a volumetric manner. ... A designer can be as rough or as precise as the situation demands ..."[1]

This conception seems to recognise the top-down progression in spatial composition. To implement it, Architrion uses ArchiDesign as the core of the system which gives output to all other programs including ArchiDraw. ArchiDesign is the modelling environment where the design process starts and finishes and ArchiDraw is used mainly for the documentation of the process in two dimensional drawings. Outputs of ArchiDesign for use in ArchiDraw are made by projecting the model on various planes.[2]

In ArchiDesign the primitives which can be used are just 'blocks', 'openings', and 'frames'. Blocks are three dimensional solid elements which can be defined either just in dimensions or up to the level of layers of construction (concrete, brick, insulation, etc.) in terms of hatching styles and colour. Openings are negative solids, serving as holes which can be placed in blocks, defined only in dimensions. Frames are two dimensional drawings that act as projections for windows, doors, or other elements and can be attached to openings. Thus, in order to place an opening there must be a host block, and in order to place a frame there must be a host opening. These elements are interrelated so that the openings always follow the thickness of the host block, and the frames always fit the host opening. Global transformations of blocks, movement, rotation, etc., affect also the openings and frames that are attached to them. As such, Architrion can be seen as an object description system, since on one hand it 'understands' about different building elements, and on the other it combines different representation techniques for particular elements. "Architrion is truly *object oriented.* It views elements of a design as true objects, rather than a collection of lines and surfaces ..."[3]

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1 Gimeor, Inc., 1989, Introduction/p.4 (existing emphasis).

2 'Projections' are seen as a category of the processes by which instances of design expression are related to each other and they are indicated as such in the maps of design expression discussed later. For the description of these processes see also: 2.2. The Case Study; Method of Investigation.

3 Gimeor, Inc., 1989, Introduction/p.19 (existing emphasis).

Elements can be selected from libraries but, with the exception of frames, the name and the individual attributes of each element can be specified at the time of their placement in the model. The introduction of a new element in the model is through its specification in the library. Yet, extensive changes in the geometric properties of individual elements can be made interactively on the screen without the use of libraries. In order for the system to accommodate changes, there is active use of the two dimensional libraries involved in the modelling environment. So, for example, if a type of frame is redefined in the library, all existing instances of this type in the model change accordingly unless they are 'smashed', that is converted to lines and disconnected from the library. Similarly for the hatching styles of construction layers of blocks. However, the flexibility that can be gained in the use of the system centres on the transformations that affect blocks which conceptually can be regarded as the principle spatial elements for the accomplishment of spatial forms. All other primitives are attached to blocks.

A block is a prismatic element which is initially defined in the library in terms of dimensions, but it can be modified later on the screen in terms of geometry, orientation, and location in a variety of ways. However, there are two conditions that blocks must always satisfy. First, each block must have six faces, though the dimensions of a face can be as small as the smallest unit of measurement in the system. Secondly, the four faces of a block must be vertical. The top and bottom face may be angled. A great range of shapes can be achieved by the use of local or global transformations that affect the position and geometry of blocks.[1]

Global transformations, used for the positioning of blocks, often combine local transformations that modify their geometric properties which in most of the cases are relevant to modifications in the spatial form of the object. Thus, a block can be inclined to become a roof; a block standing for a wall can be elongated in length or height to meet another wall or a roof; one face of a block can be extended in order to be connected with the face of another block; a block can be duplicated and rotated to become a circular wall; a block can be duplicated and moved in one direction and height to become a staircase; a block can be cut along different directions into several smaller blocks; and so on. Most of these transformations can be made on the screen in either plan or section view, but the system allows only one model to be viewed and edited at a given time and only one window per model. Undesired effects that result

[1] For the distinction between local and global transformations see the discussion in: 6.3. Two Dimensional Vectorial Drawing Systems; Graphical Symbols and Transformations.

from the combination of blocks, such as the ones shown in *Figure 6.6* of the previous chapter, can be eliminated semi-automatically during the conversion of models into line drawings in ArchiDraw. Examples of the various shapes that can be achieved are shown in *Figure 7.1*.

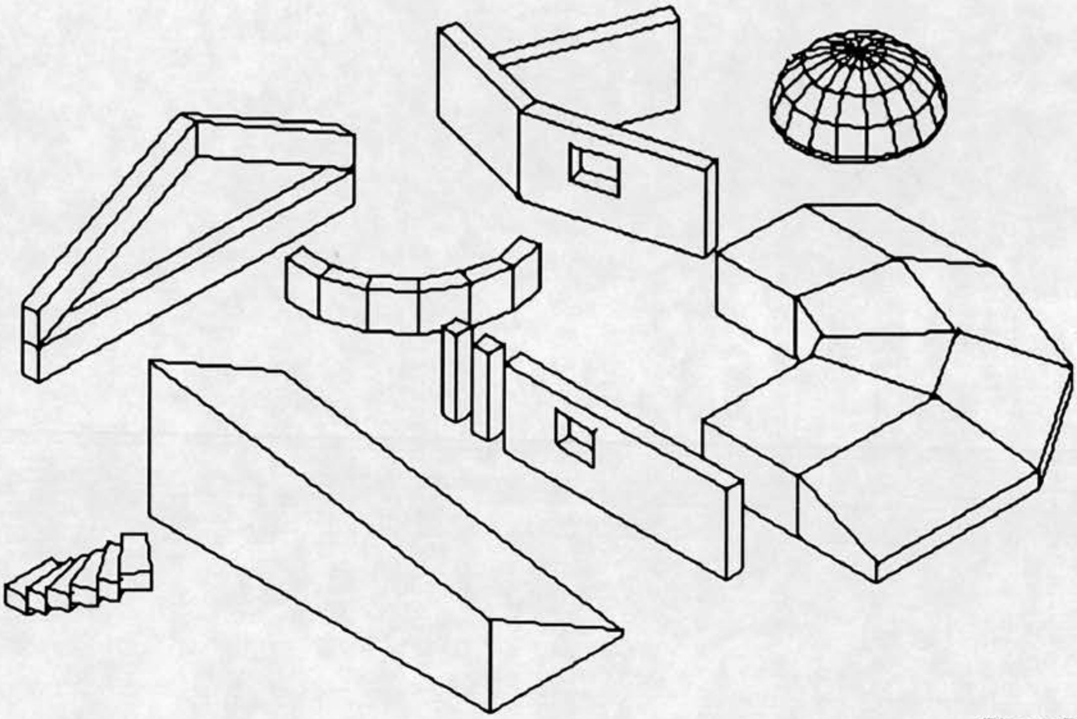

Figure 7.1

The employment of a single primitive element for the construction of models results in simplicity in the use of the system. The designer knows that all transformations for blocks are applicable to any block irrespective of whether it is used as a wall, a roof, or a beam in a steel frame. Yet, the conditions that we have seen earlier impose restrictions on the construction of certain solid forms. The developers claim that forms which can be handled by the system are met in "nearly all of today's buildings ... since they are flat-surfaced and rectilinear".[1] A limitation in the construction of models is that, despite the fact that transformations to single blocks recognise the existence of other blocks, there is no notion in the system of topological relations between blocks. Thus, there could be an undesired effect of blocks intruding into one another.

Other peculiarities of the system include the way according to which transformations are made which follow the tool-object principle, in contrast to most Macintosh™ applications which follow the object-tool principle. In other words, the

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1 Gimeor, Inc., 1989, Introduction/p.4.

user has firstly to select a tool and use it in order to construct, edit, modify, etc. an object, instead of selecting an object and then transforming it. This might seem contrary to the way that designers work, to the extent that the normal focus of attention during spatial composition is mainly on design elements, which in respect to conceptualisations that they obtain may be appear susceptible to transformations, rather than on transformations that apply to design elements. However, there is consistency between the tools for the insertion of elements, which obviously have to be selected before the elements, and the tools for transformations. As such, there might be a gain in simplicity.

Also, Architrion allows the 'merging' of models. Merging is a way of grouping a number of existing models into a single final one. The proper use of this particular feature can result in a further means of organising design information, in addition to the standard layer and component means of organisation. So, for example, organisation in terms of components may be used for the grouping of elements into sub-models, layers for separating information in terms of vertical distribution where each layer can hold the elements that belong to a particular floor, and separate models for keeping information relevant to different sub-systems of the designed object (a model for the piping system, a model for the furniture fittings, and so on).

This feature was found important in the case study, since the students could use it at different stages in designing. They could, for example, merge several early models exploring alternative directions in the spatial distribution of the building, define a new model, and so on. Yet, there is a limitation in relation to the accomplishment of this operation. The system does not take care of the consequences of merging. Layers from early models merge into corresponding layers in the new model. As a result, blocks may intrude into one another. The designer has to anticipate in the early stages how the merging will be done later.

Nevertheless, it is conceivable that a designer may start using the system at early stages in designing. In addition to the feature just presented, the comprehensive transformations that we have seen above could be used for modifying or replacing initial large blocks standing roughly for spatial volumes, obtaining eventually a fairly precise spatial composition. Similarly, the fact that the system has been developed particularly for architects was indicative that the system could accommodate the conceptualisations that characterise architectural design. Also, layers as the primary means of organisation support the use of the system in early stages.[1]

Architrion was found appropriate for the case study. The students were asked to use the system from the initial stages in the development of the project, mainly in three dimensions but also for two dimensional drawings. They might go back to the drawing board and handmade drawing when they anticipate that the computerised environment could not support specific design tasks. As was indicated in the second chapter, such action was expected to indicate complications in the use of the system for particular design situations. In that chapter, there is also an extensive description of the conventions used in the presentation of the development of the project.

7.2. Computers in Use

After the short discussion above on the assumptions and the objectives that underlie the use of computers by the students, as well as about the particular system used, we can now review some of their efforts and attempt to examine the implications of the employment of computers in design tasks. The following part of the chapter gives firstly a general description of the development of the project. Later it focuses on particular examples and aspects of the case study by trying to indicate problems and limitations in the involvement of computers. The chapter closes by estimating issues on the basis of which such problems emerge. The discussion will follow the objectives above, without going into deep detail concerning technicalities in the use of computers.

Overview of All Projects

Generally speaking, at the beginning the students were quite enthusiastic about the project and the computerised system. After the introduction of the brief, they tried to find appropriate information about buildings of similar type as well as about the site. There were some studies in the library of the department and a number of visits to the island.[2]

For most of the students, the first attempts in the studio have to do with the specification of the location of the building on the island as well as work on the particular site map. Their work is indicated on the maps of design expressions for

1 See the discussion on the use of layers in: 6.3. Two Dimensional Vectorial Drawing Systems; The Structure and Organisation of Drawings.

2 Some of the first activities of the students are discussed in: 3. The Design Episode.

each one of the students, three of which are shown in *Table A2*, *Table A3*, and *Table A4* of Appendix A. Consider also the actual drawings shown in Appendix B, when this is appropriate.

The general overview of the developments is examined by describing the work as it is recorded in the maps of design expressions. As such, references to particular instances of design expression, in most of the cases, relate to their position in the maps of design expressions including their relations to other expressions. However, a look at the actual drawings will contribute to a better understanding of the developments. In the following part, which examines the developments in more detail, aspects that appear on specific instances of expression, drawings, models, or sketches are discussed.[1]

Thus, for student A (*Table A2*), *Instance 001* through *Instance 006* refer to conceptual work that was discussed earlier.[2] *Instance 007* is the map given to the students in computer readable form (SuperPaint). *Instances 008-011* refer to an attempt to construct a three dimensional model of the site in Architrion, including the projections *Instance 012* and *Instance 013*, in which later the proposed building was expected to be incorporated. This attempt was completely abandoned mainly because of the inflexibility of Architrion in coping with irregularly shaped forms. The student proceeded to work on the site in two dimensional drawings (*Instances 017-019*), after some continuation of the earlier conceptual work in *Instances 014-016*. The second attempt to work on the site was made in the vectorial drawing environment of Architrion, and the student developed some ideas from the earlier handmade drawings in respect to the distribution of the building and its positioning in the site.

The case of student B (*Table A3*) is similar. This student, however, worked on the site only in two dimensions (*Instance 006*, *Instances 009-010*). Instead,

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1 The captions of the design expressions in Appendix B refer to their sequence in the progression of the projects by each of the students and not to their sequence in the presentation. The students who have produced them are also indicated. In this way, the context of each instance can be obtained by relating it to the maps of design expressions in the tables of Appendix A. For the same reason, instances that appear in Appendix B are shown in the tables in bold-italic.
In most of the cases of snapshots from models, each instance is presented with two views, usually a plan and an axonometric. If more than two views of one instance occur, these correspond either to a different layer set up of the same model or drawing, or to a detail. These appear as a separate figure with the same instance number and an alphanumeric index. However, in some snapshots of particular models certain layers are omitted, or views with more than one layer settings appear overlapping in the same snapshot, so that specific aspects of the developments are highlighted. This should not be taken to indicate that blocks of a model that do not appear in a subsequent development of the same model are actually deleted.

2 See the discussions in: 3. The Design Episode; and: 4. Objects in Mind.

student C (*Table A4*) worked on the site by elaborating the map with handmade sketching (*Instance 004*, *Instances 005-007*).

The first major development occurs for student A (*Table A2*) with the drawings and models from *Instance 020* through *Instance 068*. This starts with reference to the earlier attempts but there is a great deal of new elements introduced. Consider that most of the basic work occurs in handmade drawings, sketches and orthographic plans and sections, where in fact all of the new elements are introduced. The work continues in the three dimensional environment of Architrion but most of this task is by developing a model incorporating the distinctions that appear in the handmade drawings. This goes until the completion of the model (*Instance 046*) and finishes with a series of two and three dimensional projections which are presented for a crit after elaborations with pencil. *Instance 017* is the map of the site, the information of which is also incorporated in handmade drawings in the presentation.

Instead, student B and C attempt to involve three dimensional models very early in designing (*Instances 003-004* and *Instances 011-012* in *Table A3*, *Instances 002-003* and *Instances 008-011* in *Table A4*). For both cases all of the models have to do with basic volumetric design with reference to the area requirements of the brief. Both of the developments are abandoned but it can be said that they have made some contribution in realising the magnitude of spaces.

It is interesting to observe, however, how the first major development unfolds for the case of student B (*Table A3*). Some of the most fundamental ideas, in respect to the distribution of the building, are introduced in the sketch of *Instance 008*. Then, there is some work on the map (*Instances 009-010*) and volumetric arrangements (*Instances 011-012*), and some developments of the ideas of *Instance 008* in the sketches of *Instance 013* and *Instance 014*. From this point onwards, until the drawing presented in the crit (*Instance 126*), the work continues by relating three dimensional models and handmade drawings. In other words, ideas from sketches are introduced to models, two dimensional outputs of models are elaborated in new sketches, and on the basis of these sketches there are either developments of the previous models or constructions of new ones. The most interesting example of this kind of work occurs in *Instance 036* through *Instance 065*. *Instances 036-043* refer to the development of a three dimensional model which, after a great deal of work in two dimensional outputs and sketches (*Instances 044-064*), gives rise to an alternative direction for the spatial distribution of the building which it is attempted to represent in three dimensional form in *Instance 065* and onwards.

It is worthwhile mentioning that most of the models involved in the development are characterised by arrangements of spatial volumes, for example blocks standing for rooms, rather than the precise definition of structural elements, such as walls, roofs, etc. When such elements occur, like for example with the staircase in *Instance 087*, it is because they cannot be enclosed in basic spatial volumes but they have a role in the distribution and the visual impression of the building.

Student C (*Table A4*), instead, works in a similar manner to the case of student A. Some initial attempts to express his ideas about the building in three dimensional form (*Instances 008-025*) is abandoned, but these ideas are developed extensively in the drawing of *Instance 026* which is then used as a basis for the construction of a new model that effectively goes on to the presentation in the crit (*Instances 063-064*). The drawing of *Instance 026* is a plan and a section incorporating a great deal of information about the building.

After the first crit, design work for all of the students continues in a more or less similar manner, even though it might be said that the progression is somehow 'smoother', as indicated in the tables, perhaps because by that time the students knew what the system can offer.

Student A (*Table A2*) proceeds to a new alternative (*Instances 069-112*) starting again with handmade sketches (*Instances 069-087*) and continuing by developing the new three dimensional model (*Instances 088-101*, *Instance 108*) and by presenting it for the second crit (*Instances 102-107*, *Instances 109-112*). The fact that work with the system largely depends on initial handmade drawings is perhaps better shown in the third major development where sketches direct the construction of the model even at final stages in designing. Consider, for example, the relations that appear in *Table A2* between the drawing in *Instance 121* and the development of the model up until *Instance 138*. Similarly, for *Instance 118*. *Instance 121* is the final plan of the development in handmade drawings on which the construction of the final model is based. *Instance 118* is the plan of an alternative distribution which is firstly explored in three dimensional form. The case of *Instance 132* is also interesting as this is a two dimensional computerised drawing, basically tracing grids made on the basis of the drawing in *Instance 121*, used as a background drawing for the direct transference of information in the model. The completed designed object is finally presented in three two dimensional drawings (*Instances 178-179*, *Instance 189*) which are made combining and merging several orthographic and three dimensional projections of the model. The drawing in *Instance 113*, development of *Instance 017*, is the map of the site which is also incorporated in the final presentation.

The case of student C (*Table A4*) is similar. The second and final major development involves the construction of only one model and includes the second crit (*Instances 107-110*). The design work starts, as for the first development, with handmade sketches (*Instances 068-075*) and continues with the construction of a three dimensional model (*Instances 076-106, Instances 113-126*) and the presentation (*Instances 127-186*). There are, however, some sketches involved during the construction of the model (*Instances 111-112*) which are connected to the second crit. These are elaborations of spatial arrangements in the model but there is also an introduction of some new elements.

The situation changes, however, for student B (*Table A3*) after the first crit. Instead of developing ideas in three dimensional models, which is the case before the first crit, he works firstly in handmade sketches and drawings, similarly to the rest of the students, (*Instances 127-129, Instances 169-170*), and then proceeds to the construction of models. However, he explores a number of different alternatives which are indicated in the table with the models of *Instance 130, Instances 131-136, Instances 140-155*, and after the second crit with the model of *Instances 167-168*. Also, with the developments in two dimensional drawings of *Instances 171-181* and *Instances 182-189*, and the final model of *Instances 190-218*. There is a case of involvement of sketches that elaborate information of computerised drawings with *Instances 175-176* and *Instances 178-179*, but within the whole development this seems to play minor role. The presentation finally occurs by developing and merging orthographic and three dimensional outputs of the last model (*Instances 220-241*) in three final drawings (*Instances 242-244*). *Instance 010* is the map of the site in vectorial form, developed from the presented bit-map drawing.

An interesting aspect of this progression is the developments of the two dimensional computerised drawings, *Instances 171-181* and *Instances 182-189*. In both of these cases these drawings are plans made in ArchiDraw and seem to be made with the intention of working later in the environment of ArchiDesign. Even though they incorporate information about the distribution of the building in the horizontal plane, they are in fact tracing patterns and grids made intentionally to be used as underlays in the construction of a three dimensional model, taking into account the conventions for using the system. This aspect becomes apparent later when two separate models (one in *Instances 190-203*, *Instance 206*, *Instance 213* and another in *Instances 204-205*, *Instances 207-212*, *Instances 214-219*) are developed in parallel following the assertions in the drawings to be merged later. These models have to do with two distinct parts of the building.

As a whole, as we can see in the review of the developments, the employment of the computerised environment occurs from early stages in designing for all of the cases. The students make use of the three dimensional capabilities of the system in order to model the spatial form of the building. The results, in respect to the buildings produced, were satisfactory in demonstrating ideas about a variety of issues related to the requirements of the project and its context.

However, by looking at the stages that the design activity has passed through, we can observe that there are a great number of handmade drawings involved particularly in stages prior to the use of the computerised system and the construction of the models. This may indicate that most of the design activity aimed at composition of the spatial form does not really occur in the computerised modelling environment but it is realised in the traditional manner. To see whether this is the case, a closer look at particular aspects of the developments and specific instances of design expression is needed. This will contribute to an understanding of the implications of employing computers in design tasks.

Focus on One Project

Perhaps, the most interesting case to study in detail is student B who manifests design and modelling behaviour that relates to both of the main manners of working with computers that were met throughout the case study. That is, either to attempt to obtain a spatial composition in three dimensions that is elaborated later in handmade drawings, or to develop the composition in sketches or drawings which are used as a basis for the construction of a three dimensional model later. We will therefore make a closer examination of this particular case.

However, since the main objective of the case study is to observe the manner according to which conceptualisations under cognitive models are externalised and related to spatial objects, there will be an emphasis on examples that relate to this issue, and to this extent we will also discuss particular aspects of the work of the other students. The sketches, drawings, and models discussed appear in Appendix B, labelled according to which student who has produced them.[1]

It is expected that particular observations and insights about the use of computerised systems will be revealed by relating depictions to information conveyed by a *sequence* of drawings developed within a particular context. So, for example, if there is a sequence of drawings clearly demonstrating an emphasis on a particular aspect of designing, it is assumed that similar conceptualisations underlie the development of all of the drawings in the sequence even if there may be a drawing within the sequence where the conceptualisation is not very explicit. This strategy might look a little arbitrary, but it indicates shortcomings when computerised drawings are involved and specifies the context of the drawings better than relying solely on discussions with the students. As will become clear later, only discussions about quite profound situations make use of this strategy.

To start with the examination of the development, the first model produced by student B (*Instance 004*) is a massing study that directly relates to the area requirements of the brief as they are interpreted by the student. The model is a rough representation of spatial volumes that looks out of context, possibly without even serving the purpose of showing the magnitude of spaces as there is no sense of the scale of the volumes. We may assume that the student knows how big the spaces are, but perhaps the inability to see in the model relations in respect to the magnitude of the volumes directs him to produce by projection the orthographic plan of *Instance 005*, where he assigns dimensions.

The first attempt in spatial composition occurs with the sketch of *Instance 008* which is used as a basis for another model (*Instance 012*). Despite the fact that the sketch attempts to convey a visual impression rather than to articulate spaces, consider how context and scale are introduced particularly in the figure at the top of the sketch. This is made by depicting information from the physical environment, differentiating between big volumes and small elements such as windows, etc. This sketch can be compared to the sketches of student A in *Instances 003-004* that have been extensively discussed earlier.[2]

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[1] For the conventions used in the presentation of the design expressions see the footnote under: Overview of All Projects.

[2] See the discussion about the qualities that we recognise in sketches and drawings in: 5.4. Drawings as Representations; Evidence in Design Expressions.

Student B's drawing of *Instance 014* is made with reference to a previous bubble diagram, and shows a link, with respect to the distribution of the building, to the sketch of *Instance 008*. Here, there is a more explicit attempt to articulate spaces and areas of activity. This is used as a basis for the construction of a new model (*Instance 015*) and, after some handmade elaborations of outputs to the slope of the roofs (*Instance 019*, *Instance 023*), leads on to the model's further development (*Instance 026*).

The handmade elaborations indicate exploratory activity. However, we can assume that the elaborations in respect of the roof are mainly directed from considerations about the visual impression of the building.

The first actual impact of the work on the model so far, in relation to the spatial distribution of the building, occurs when an attempt is made to place the building in the context of the site as shown in *Instance 033*. Here, we can see how information about the surrounding natural environment, which is indicated in the original plan of the site, direct the designer to change radically the orientation of a part of the building. This change is explored later in the drawings of *Instances 034-035*. We can assume that the need to change the orientation of the building could not be realised earlier as there was no information in the model about the context of the building.

Consider the emphasis manifested in both of the drawings of *Instances 034-035* on dimensioning and specification of angles and slopes of roofs. Work on the specification of angles goes on to the point of solving trigonometric equations. This emphasis can probably be attributed to an intention to be precise in the construction of a subsequent three dimensional model in the computerised environment, since it is rather odd to have such precision in basic volumetric design in normal circumstances.

The model that follows complies with the assertions that were made in the above drawings (*Instances 034-035*), as we can see in *Instance 043*, but it includes a number of new elements. We can assume that the designer had thought about the new elements before, but introduced them only when the building is realised in three dimensional form. This is assumed on the basis of hints that appear in the previous drawings, like for example, the arrows indicating the direction of ramps.

Two dimensional outputs of this model are elaborated in sketches (*Instance 047*, *Instance 051*, *Instance 058*). As we can see in the sketch of

Instance 047, initially these elaborations have to do with elements that refer to elevation design, such as windows and openings, but we can assume that elevation design is connected with the functions that are enclosed by the spatial volumes. However, the emphasis on such elements can be attributed also to an intention by the designer to apprehend the scale of the building which is still missing from the model. It is quite common in designing to depict in drawings forms that can be directly related to human dimensions in order to conceptualise the scale of the designed object. Human figures, trees, windows, etc. can serve this purpose. Note that despite the fact that openings are a class of primitives in Architrion, they cannot be introduced in the current stage since blocks in the particular model stand for spatial volumes and not structural elements. As such, we may not have different openings along two faces of a single block, as is required in our example.[1]

Thoughts about another major change in the orientation of the building are indicated in *Instance 051*, where the model is placed again in the context of the site. Later (*Instance 081*), this is elaborated into a change in the direction just of the pier that connects the building with the sea.

Other elaborations have to do with particular parts of the building as shown in *Instance 058*. Similarly to the case met earlier, great emphasis is given to the specification of the values of geometric properties of elements. Another aspect in this particular drawing is the indication of focus on the spatial organisation of specific functional components such as units of accommodation and staircases. However, the effects of this task are not introduced in the following model, as we can see in *Instance 065*, *Instance 087*. We can assume that the designer wants to examine whether such components will fit within the spatial volumes that he explores in the computerised environment. The change in respect to the pier is finally introduced in the model in the last stage of the current development (*Instance 109*), just before the first crit.

The drawing presented in the crit is shown in *Instance 126*. Plans and sections appearing in the drawing were developed on the basis of outputs of the model in the two dimensional vectorial environment of ArchiDraw, where three dimensional projections were also elaborated.

As a whole, we can recognise in this particular development that the modelling environment is used for explorations connected with the spatial form of the building.

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1 See the discussion on the characteristics of Architrion above.

However, these explorations have to do mainly with the visual and sculptural qualities of the spatial form. Thus, for example, considerations about the spatial organisation of functional units are not introduced in the model since they are enclosed by the volumes.

The emphasis on visualisation is well illustrated by the examples of unequal treatment of spatial elements. Thus, for example, when a staircase has a role in the visual impression of the building it is introduced in the model, and it is ignored when it does not have such a role. A better example occurs with the latest instance of the development (*Instance 109*), where an element that may be visually interesting but is relatively unimportant in respect to the whole synthesis so far, like the lighthouse, is introduced into the model. This emphasis on visualisation explains perhaps the fact that modelling with the system is still at the level of spatial volumes, even though the current state of the development is at a quite advanced stage in relation to the whole project.

Emphasis on visualisation and modelling in terms of spatial volumes characterises also the development following the first crit. However, there are a number of alternatives explored which are based on ideas about the distribution of the building, that appear in initial sketches (*Instance 127*, *Instance 129*). As we can see in the sketches, the new distribution recognises the principles that underlie the previous models as these were first introduced in the project. What radically changes is the shape of the building, which now follows a circular form. Similarly to previous drawings, much consideration is given to dimensioning (*Instance 129*).

In the following models (*Instance 135*, and *Instance 143*, *Instance 155*) there is an attempt to make explicit the ideas involved in the new distribution. An interesting aspect of both these models is that Architrion blocks no longer stand for corresponding areas of activity in the building, for example rooms, as in the previous developments. They are instead just abstract solids used in order to model the circular shape of the building. This is well illustrated in the plans generated on the basis of the models. The spatial distribution shown in both *Instance 138*, a plan from the first model, and *Instance 159*, a plan from the second model, is different from the analysis of the building into blocks followed in the construction of the models.

The following and last development shows similar general principles in respect to the distribution. We have the same activities in the same parts of the building as in the previous cases. However, a new shape is developed which has effects on particular aspects of spatial organisation, like for example the connections between the various areas. This is developed in two different directions, one with the drawings of *Instances 171-181*, and the second with the drawings of *Instances 181-189* (*Table A3*). These drawings seem to indicate a change in focus, exploring aspects of geometry and how it may dominate detail later.

The two alternatives are firstly developed in two dimensional drawings in ArchiDraw. In both of the cases, these drawings are tracing patterns and grids to be used for the construction of the model later. It is interesting to observe that grids are also firstly developed in handmade orthographic drawings and then introduced to the vectorial environment of ArchiDraw. This is illustrated by the drawing of *Instance 170*. As we can observe in the drawing of *Instance 181*, there is a clear categorisation of the information in layers, which has to do with distinctions in respect to different parts of the building as well as structural systems. In the second development, the specification of the layout of the building in grids goes on to a very detailed level incorporating also information of the site (*Instance 187, Instance 189*). The drawing of *Instance 188*, which is a section depicting the sight lines in the conference hall, indicates that the development takes also into account aspects of distribution of the building in the vertical direction.

The final three dimensional model (*Instance 190, Instance 195, Instance 205, Instance 214, Instance 219*) is constructed step-by-step, constantly following the tracing patterns. As was indicated earlier, the construction of the final model of the building is made by the parallel development of two separate models of distinctive parts of the building which are merged later for its completion. On the basis of this merged model, plans, sections, perspectives, etc. are generated which are elaborated and combined together in ArchiDraw for the final presentation (*Instance 242*).

What perhaps distinguishes the last developments from the previous ones is the different emphasis that is given to the modelling of the building which is directed by different intentions for the use of the computerised environment. The earlier developments seem to involve assembly of separate volumes and visualisation of the results. The latter developments involve a dominant overall geometry and then decomposition into parts. We have seen, for example, that there is a curvilinear form which is analysed into blocks to be modelled. Blocks no longer correspond to conceptually distinctive parts of the building.

In the final development, the global description of the building is achieved firstly in handmade drawings. When the designer is satisfied with the spatial form of the building, he proceeds to its analysis and the construction of the model. Blocks in this case may be used to stand for structural elements.

This differentiation is attributed to the intentions underlying design activity. In early stages, designers want to comprehend the various conditions and the information that the design task involves so as to formulate conceptual models. Distinctive aspects of the task, such as requirements in particular areas of activity, are explored and the modelling environment of Architrion can be partially used to accommodate these explorations. When, however, conceptual models have been formulated, the spatial form of the building has to be confronted in its totality so as to evaluate its correspondence to models. This process is followed by the decomposition of the spatial form into distinctive parts. The transition from conceptual models to spatial forms and subsequently to compositional parts exemplifies the top-down progression in spatial composition. In contrast to our expectations, Architrion seems to impose limitations in accommodating the top-down progression of the final development. It is rather used when the spatial form of the building has been already established in handmade drawings.

Particular Aspects of Other Projects

The other projects of the case study demonstrate similar intentions. The difference is that the first stages of formulating conceptual models are less evident. Instead, the other students attempt to achieve a global description, even from their early developments, working mostly in handmade drawings. In almost all of the cases these handmade drawings are in fact complete plans, sections, etc., in contrast to the more abstract sketches produced by student B.

Thus, for example, student A starts the construction of the first main model after achieving a global description in handmade drawings as indicated in *Instance 022*, *Instance 026*, as well as *Instance 032*. An interesting aspect appears in *Instance 021*, actually before these drawings. Here, the designer attempts to formulate a description starting with three dimensional modelling that demonstrates emphasis on detailed structural aspects of the building. The attempt is abandoned, or rather, it is continued in handmade drawings.

This particular attempt is influenced by the following conditions. The designer wants initially to model a curved form, but he wants eventually to achieve a detailed description of the building in contrast to a model of spatial volumes. As he has to analyse the building in minor units, since this is the only way to model curved forms in Architrion, he prefers to do this in some detail so that he will not have to go back later and re-define the minor units, on the basis of which the circular form is generated through the various transformations that the system offers. Architrion allows the modification of rough spatial volumes into precise structural elements when these follow a rectilinear geometry, but there are no such operations for curved geometry because curved forms are made by putting together prismatic rectilinear elements.[1] Thus, the student starts by modelling the beams that support the roof of the building. Effectively, he realises that this effort disengages him from the task of achieving the general spatial distribution of the building, which is presumably what has to be done first, and he goes back to the drawing board to do so.

After formulating the description of the building in handmade drawings, the construction of the model is made step-by-step, following the assertions in these drawings, similarly to the case of the last model of student B (*Instance 030*, *Instance 038*, *Instance 041*, *Instance 044*). Once the modelling is completed, even in respect to detailed structural elements, the whole model is cut into pieces which are individually rotated (*Instance 046*) in order to achieve the desired curved form. This manner of accomplishment indicates perhaps the impact on the designer of the effort in *Instance 021*, in starting with the modelling of the curved form. It illustrates a severe restriction of the system in coping with irregular geometries, even when the form of the building is already established.

Another interesting aspect in the construction of the model occurs with *Instance 038*, and *Instance 044*. As the designer has not produced two dimensional computerised drawings which can be incorporated in the model and used for the tracing of information from drawings, he has to conceive a way of obtaining a correspondence between his handmade drawings and the model. To do so he uses three dimensional blocks as 'construction lines'.[2] Such is the case with the blocks that appear at the far end of the building in *Instance 038*, as well as with those that appear along one side of the building in *Instance 044*.

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1 See the description of Architrion above.

2 For a discussion on construction lines see: 9.2. Drawings and Spatial Objects; Tools for the Description of Space.

The progression of the project for student A continues in a similar manner in the following developments. Consider the correspondence between the snapshots from the construction of the model in the second development (*Instance 088*, *Instance 094*, *Instance 098*, *Instance 108*) and the initial handmade drawing in *Instance 081*. *Instance 087* is a section illustrating that the building is firstly explored in handmade drawings in detail, while *Instance 075* refers to another alternative that is initially developed also in considerable detail. The correspondence between the first model of the last development (*Instance 124*, *Instance 131*) and the drawings of *Instance 118*, *Instance 119* is similar. Also, between the second model of the development (*Instance 133*, *Instance 136*, *Instance 148*, *Instance 152*, *Instance 156*) and the drawings of *Instance 118*, *Instance 119*, and *Instance 121*. In this case, however, tracing grids are firstly produced (*Instance 132*), to be used for the transference of information.

Despite the fact that the two models of the last development are to a great extent similar, the designer prefers to construct the second model from the beginning, rather than copying and pasting parts of the building which remain identical. This is because the construction of both of the models is made in the manner that the construction of the actual building would follow, like for example starting from the form of the ground (*Instance 133*) and having walls that sit on the ground and extend to the roof. In other words, the model does not follow a decomposition into functional units, but into structural elements, so that copying and pasting of rooms, for example, which have not been changed, would entail the complete disassembly of the model. Even then, certain rooms may not be extracted as one of their walls might extend along a whole facade of the building.

Modelling in terms of structural elements is followed also by student C throughout the project, except for some initial models such as the one shown in *Instance 008*. This particular model indicates that when the building has a compact form, like the one chosen by the student, modelling in terms of spatial volumes does not contribute much to spatial composition. Blocks standing for a number of functional units are difficult to manipulate.

An interesting aspect in the developments of student C occurs with *Instance 058* as well as later with *Instance 080*, where the designer attempts to achieve a quite detailed description of a particular part of the building, such as the pier. A similar case occurs later with *Instance 091*, and *Instance 098*, *Instance 104* where he does the same for the paving of the ground and the wood covering of the floor, respectively. The plan of the wood covering is shown in *Instance 125.b*. A corresponding example appears in student's D work with *Instance 010* relating also to the modelling of the pier.

In all of these cases, the designers make extensive use of the duplicating transformations offered by the system, so that by the definition of only a few blocks and the application of these transformations they can achieve a full description. These examples demonstrate the ease of coping with repetitive elements in designing by using the system. It might be said that the modelling of some of these elements is not absolutely necessary as with the case of the paving. However, the use of such transformations cannot be attributed merely to a fascination with the particular transformations, but rather to an intention of being precise. To some extent, this intention is imposed by the system. Thus, for example, in the case of the wood covering of the floor (*Student C; Instance 125.b*), the designer has to analyse the plan of the floor into smaller units anyway, since he cannot use a single block in order to model it. Instead then of having a rough model of the floor with a decomposition into blocks, which is inhibited by considerations of model construction, he is induced to start with a very detailed analysis.

Another interesting aspect in the projects of both student C and student D occurs with the modelling of the site. Student D attempts to model the contours of the site by placing blocks one on the top of another (*Student D; Instance 055, Instance 076*). Student C instead prefers to incorporate the site in the model by 'drawing' the contours using blocks (*Student C; Instance 080*). Even though these are only rough approximations, they result in the context of the building being included in the model.

Role of the System

The discussion of the stages through which the progression of the project has passed, particularly for student B but also for the rest of the students, illustrates the design intentions which characterise the use of the computerised environment. In contrast to what was expected, the developments do not seem to integrate modelling with designing. In most of the cases, models are used in order to specify a spatial description or to visualise the form of the building in three dimensions, and to this extent some design activity can be assumed relating to these aspects. However, the externalisation of conceptualisations happens firstly in two dimensions, mostly in sketches and not computerised drawings.

Use of the system seems to be guided by an intention to represent *effects* of the design tasks, even though they might be susceptible to modifications later. The system does not seem to be used to apprehend assertions from conceptualisations with respect to spatial properties and relations, and not used for modelling the activity of composing and articulating spatial form. This is particularly true for the developments in which the computer is used to model the structural system of the building. In these cases, after the composition of the spatial form there is a detailed analysis of the building into structural elements which are subsequently introduced to the models. However, this is also true for the instances of the work of student B, in which there is a use of the system to realise the visual form of the building. Although elements of the models which seem relevant to visual qualities are elaborated in sketches and modified later in the following models, most of the decisions, even with respect to these elements, are taken beforehand in initial drawings.

As a whole, we can recognise that, either for detailed modelling or for visualisation, the system is used in order to convey a *finished* and *complete* view of the designed object, rather than in order to externalise tentative representations of design concepts to be used for further exploration. In other words, the system is used in order to formulate the model of the building but the spatial information upon which this model is based is firstly manipulated and established in sketches and then is transferred in the computerised environment.

As we have seen, the specific system is not particularly difficult to use, and this is evident in the comprehensiveness of the descriptions that were achieved. Indeed the students seemed to apprehend the functionality of the system and there was no misuse of the system resulting from incorrect anticipations of the operations that it offered. There were not a lot of cases in which the application of some transformation led to undesired effects. Instead, the construction of the models within each development progressed smoothly, without deletion of considerable parts of the building as a result of the mishandling of the system. There was extensive use even of the most complicated transformations in the system by all of the students.

The use of the system, then, for the description of an established form of the designed artifact, rather than the externalisation of conceptualisations, is perhaps attributed to the way in which it is able to decompose spatial forms. In other words, to the use of blocks as the primary means for the construction of representations, and the implications that this entails for the properties and the structure of representations that can be supported by the system. The following and closing part of this chapter attempts to explore this particular issue.

7.3. Drawing, Modelling in Computers, and Designing

As we have seen in the previous chapter, each computerised system can be characterised by the issues of effectiveness and restrictiveness of operations.[1] Effectiveness has to do with the objective in the development of a system, to minimise the operations needed for the construction of a drawing or a model. Restrictiveness refers to limitations in the applicability of these operations in the accomplishment of representations of objects that do not coincide with those that the system is built to handle.

Architrion, and in particular ArchiDesign, is a system which can be characterised by high levels of effectiveness of modelling operations. Thus, for example, the fact that there are no complicated relations between specific transformations and primitives, the particular way in which libraries are implemented so that global modifications can be made and elements can be also directly edited on the screen, the different manners according to which spatial information can be categorised and organised with respect to qualifications of the designed object, are all aspects which contribute to effectiveness. We see, however, that these aspects and the functionality of the system as a whole are based on the employment of a single unit, a prismatic block, which can be transformed and modified in order to become a primitive 'symbol' for the accomplishment of the representation of all spatial forms. In other words, there is a particular view on the decomposition of representations of spatial forms.

In order to arrive at the specification of blocks as the primitive of Architrion, the developers of the system foresee that there is usually an analysis of buildings that architects design into elements each one of which can correspond to a prismatic block. This applies to analysis of aspects such as spatial volumes or structural elements, which occur often within design tasks. In consequence, there is firstly a recognition of distinctive elements in built forms, which can be assembled into whole buildings, and then a recognition of distinctive properties in each of these elements and relations between them, by virtue of which the assemblage is actually obtained. This is applied

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1 See in particular: 6.1. Structure and Behaviour of Drawing Systems.

to the specification of the representational scheme of the system. In other words, the properties of elements specify properties of primitive symbols, and the relations between them determine the transformations by which these symbols are put together.

This account is directly relevant to the approach to representation of drawings in computers discussed earlier in the thesis. We saw for example that, according to Palmer's theory, in systematic representations of graphics, features of represented objects are mapped to corresponding features of representing symbols, and relations between the represented objects are mapped to relations within the representing symbolic configuration.[1] Thus, there is a specification of attributes of designed objects which directs the manner according to which configurations which represent them are decomposed. This is the approach which is followed by both vectorial and modelling systems, as we have seen in the previous chapter, and Architrion is not different, in this respect, from other systems. It can be said that in Architrion this approach is far more apparent since the view of design behaviour incorporated in the system is strictly defined, leading to a limited number of primitives in the system. Now let us see how a defined and limited view of the decomposition of representations affects the effectiveness as well as the restrictiveness of the system.

To increase the effectiveness of the system, the features which are recognised in represented objects have to be qualified in respect of their importance, so they are categorised into conceptualisations more or less commonly met in design, and they have to be limited in number. In this way, the values of the properties of primitives in the system will be more easily defined and their number will also be limited. The same applies to relations. Thus, for example, while there can be a recognition of the feature of roundness in some built forms, if most built forms are rectilinear then the most commonly used symbol in the system has primarily to recognise the feature of rectilinearity. To further increase effectiveness, there can be just a single primitive in the system by which all rectilinear elements and relations between them can be directly represented through simple transformations. In order to keep the restrictiveness of the system low, the same symbol, with the aid of additional and usually more complicated transformations, might be used for the representation of other forms, such as round. We can see, consequently, that the effort aimed at effectiveness is based on a provision for the most common design *intentions* with respect to designed objects.

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1 See: 5.2. Kinds of Representation; The Representation of Images: Analogical Representations; and: 5.4. Drawings as Representations; The Features of Drawings and their Structure.

This, however, seems to contradict the notion of analogy also discussed earlier. We have indicated, for example, that mappings between design objects and their representations are determined by intentions which are developed by the people who employ the representational scheme during their use of it. In other words, people's intentions involve the use of knowledge that is applied to the products of the representational system, which departs from the knowledge explicitly represented by the system. This kind of use of representations was referred to as analogical, and the ability of drawings to evoke such knowledge specifies their analogical character.[1]

We may say then that by following the approach above, the system recognises that knowledge is applied to representing configurations. However, by rigidly specifying the properties and the relations between the symbols that compose the configurations, the system allows some knowledge to be more readily evoked during use, while other knowledge is evoked in complicated ways. Thus, for example, while knowledge about rectilinear forms can be directly applied to prismatic elements and the relations between them, in the case of curvilinear forms there has to be intervention of conceptualisations which do not otherwise relate to knowledge about such forms. In other words, when designers model curvilinear forms in the system, they necessarily have to think about them in terms of prismatic elements. Restrictiveness of the system, consequently, is closely connected to complications in the analogical use of its products. Conceptualisations about designed objects, which determine the properties and the relations between designed objects, as well as their decomposition, are based on intentions which evolve within the context of design tasks and cannot all be specified beforehand.

The discussion of the examples from the case study indicates that the conflict between intentions and established ways of looking at spatial forms is perhaps the key cause of difficulty in involving a system in design activity, in contrast to its use in modelling completed designs for buildings.

If we look again at the examples of the case study, we see that when student B firstly attempts to interpret requirements into spatial volumes he does not have any alternative other than using blocks. When later he explores the visual form of his building in terms of spatial volumes, he ends up specifying angles and dimensions. The emphasis on dimensioning indicates an imposition by the system on the designer, to concentrate on attributes of the building that do not really coincide with

1 5.4. Drawings as Representations; Analogies in Drawings.

his intentions in respect of the spatial form, which at that time had to do mainly with abstract visual qualities.

The particular way according to which spatial forms are analysed prevent the designer from incorporating in the model important information, with undesired consequences. Such is the case with information about the context of the building, the site and its physical environment. We see, also, how students C and D proceed to model the contours of the site in ways completely irrelevant to intentions built into the system.

The inability to apply a different function for representing objects, other than explicitly representing spatial volumes, directs student A to use blocks in order to represent construction lines. Similarly, in the case of the grids in the last developments of both student A and B, they have to go back to the drawing board in order to define the tracing patterns upon which the distribution of spatial elements is based.

If there are difficulties in the application of analogical knowledge to representations, it does not really make much difference if the transformations by which non rectilinear forms are modelled in the system are simple or complicated. In the example of the curvilinear form of the first development of student A, this can be modelled quite effectively, but when he attempts to use the operations of the system during spatial composition he finds himself disengaged from the task of spatial composition itself. This is because the knowledge that is involved in the designing of curvilinear forms cannot be applied to sets of prismatic elements.

There could be an intended decomposition of whole spatial forms into prismatic elements during designing, such as with the structural analysis of the building. To this extent, the system could be used, if not from the beginning of designing at least at those stages where there are explorations about the structural system of the building, aiding the comprehension of the constructional attributes of the building. We have seen, however, that this can occur only for a limited number of cases. Even buildings that are based on simple rectilinear geometry but have a compact form, like the building of the last development of student C, require a decomposition that is different from their structural analysis in order to be modelled.

Even when buildings are analysed into structural elements in the way that the developers of the system anticipate, such as with the building of the last development of student A, the slightest deviation in respect to the initial intentions for this analysis entails the re-construction of the model from the beginning. Perceptions about design objects change constantly during designing, in efforts to make spatial forms corresponding to different conceptual models, and we cannot assume that intentions remain constant throughout designing.

As a whole, what occurs in our examples is the decomposition of buildings into Architrion blocks, rather than any analysis into spatial volumes, structural elements, or other things. The system imposes a particular view on the conceptualisation of designed objects which is differentiated from designers' intentions. The emphasis on extraneous precision, manifested by all the designers in our case study, illustrates the consequences of following this view and eventually leads to use of the system mainly for modelling completed and established spatial forms.

Although the view that computerised systems incorporate in their implementation might be global and general, there will be always be some design intentions which cannot be anticipated beforehand, because such intentions evolve during the course of designing. These intentions demarcate what is needed from representations each time, and how representations are used within design tasks. These intentions specify the knowledge that has to be applied to representations, and this knowledge needs to determine the structure of the representations.

In the following chapters of the thesis we will approach representations and drawings from this particular point of view. We will examine how design intentions emerge within the context of conceptual models, how they are involved in the task of spatial composition, and finally whether intentions can tell us something about the way in which analogical representations are structured. In those discussions we will continue looking at the expressions of the designers in our case study, as well as other examples, but we will concentrate on handmade drawings.

7.4. Summary

Following a discussion in the previous chapter on the representation schemes that are used by various computerised drawing system and the functionality that they offer, in this chapter we saw how a particular system was used by the designers in our case study. The particular system used is an integrated three dimensional modelling and drawing system developed particularly for architects. As such, the system was expected to follow an approach that relates to the perceptions which are applied to buildings during designing.

However, the discussion of the stages through which the progression of the projects passed, as well as the examination of particular aspects of the developments, have shown that during the accomplishment of design tasks design intentions divert from established accounts about designing, even if such accounts are general and comprehensive. Thus, most of the exploratory tasks which characterise spatial composition were performed in the traditional drawing environment rather than in the computerised one. The system was used mainly for modelling and drawing completed views of the buildings. In other words, the system was used to visualise effects of spatial composition, rather than to externalise conceptualisations so as to obtain a correspondence between conceptual models and spatial forms.

This usage is attributed to the particular approach to representation of designed objects which is followed by the system. The system applies a decomposition of models and in consequence of spatial forms into prismatic blocks which are related to each other through a series of transformations. Although the variety of shapes that can be modelled is extensive, and the system shows high levels of effectiveness of operations, this results in restrictiveness.

Restrictiveness is closely related to analogical use of representations, leading to complications in the application of knowledge to representations, other than knowledge developers of the system anticipate. Thus, even if it might not be difficult to conceive spatial forms in terms of prismatic blocks, this is not the way designers conceptualise designed objects during designing. Instead designed objects obtain conceptualisations on the basis of intentions which emerge in the context of designing.

The discussion of the projects in the case study is suggesting that established views about the decomposition and the structure of representations of designed objects cannot support the analogical use of such representations. The specific system used in the case study is perhaps a particular case, as it was used mainly for three dimensional modelling, but we have seen that its view on representations of designed objects is not differentiated from the approach upon which representations of drawings in computers is based in general.

This chapter has opened a discussion on the use of drawings in designing. However, after the examination of the implications in designing of established views about the structure of representations, we will continue by looking more closely at the role that representations have in the accomplishment of design tasks, their connections to design conceptualisations, and whether the way according to which they are used specifies the way according to which they are structured.

8. The Role of Drawings in Design: Spatial Composition

The discussion about drawings in the previous chapters, and in particular in the chapter examining the use of a computerised system by the designers in our case study, indicated that accounts of the structure of graphical representations in design cannot be specified independently of the manner according to which drawings are used during the accomplishment of design tasks. This chapter starts a discussion about the ways through which the use of drawings affects their structure.

It has already been indicated that the primary objective in designing is the externalisation of abstract concepts into spatial forms which additionally have to be described in such a way that they can be constructed and materialised. The role of drawings in designing is not to realistically or impressively depict the forms of existing physical objects but in fact to aid the generation of new ones. That is, to contribute to the composition of spatial forms, so that conceptual manipulations can act upon them and establish their correspondence to conceptual models. This objective differentiates design drawings from pictures and confronts drawings as an environment in which assertions in respect to the spatial form of designed objects are modelled, explored, and justified.

Here, we will briefly examine the task of spatial composition itself. We will discuss the objectives underlying the accomplishment of spatial forms, the involvement of conceptual models and cognitive operations, and finally, on the basis of an example from the case study, the manner according to which drawings facilitate this particular task.

The chapter will clarify the ways through which abstract design knowledge, in the context of conceptual models, is applied to concrete objects such as spatial forms. Drawings can be seen as an intermediate state in this process acting as analogues of spatial objects upon which conceptualisations are applied. To this extent the chapter will identify the analogical character of drawings. This will be discussed extensively in the following chapter, where we will examine the structural properties that drawings acquire as a consequence of their use.

8.1. The Accomplishment of Spatial Forms

In earlier discussions on design tasks, we have described designing as a conceptual activity which aims to transform an initial, partial, and incomplete description of an object, into an accurate and complete one, through the application of knowledge and information.[1] This definition, however, applies in general to any thinking or problem solving activity without taking into consideration the particular features of designing. The central aspect of design activity is that an eventual description has to be a spatial object in a materialised built form.

The task of spatial composition, in other words the task through which spatial forms are accomplished, is often taken to be synonymous to designing itself. It involves objectives, principles, and processes which are specific to design activity and radically different from other conceptual activities.[2] In this part of the chapter, we will discuss the characteristics of spatial composition. In the following part, we will attempt to clarify them by examining two particular examples. Let us start by looking at how spatial composition is connected to conceptual activity in designing and drawings.

Conceptual Models, Spatial Forms, and Drawings

Designers, like other problem solvers, employ conceptual models which take into account the effects of cognitive operations upon information.[3] In addition, however, in order to meet the purpose of a design task, they also employ a spatial model under which spatial relationships and spatial forms are considered.[4] The

1 See: 2.1. Towards an Account of Designing; Information Processing.
2 See for example the discussion in: Cross, Nigel, 1982.
3 See the discussion on conceptual models and cognitive operations in: 4. Objects in Mind.
4 Nevertheless, spatial models are not unique to designers. Problem solving activity is well enhanced by models of space in fields like physics, chemistry, mechanical engineering, too. The emphasis on space is entailed because of the specific interest about it. Accordingly, distinctive

fundamental objective in designing is to obtain a single spatial form for the designed object. This has to correspond to all possibly conceived conceptual models and has to take into account the dependencies that emerge from the connection to each other. This objective is achieved by clarifying and developing an initial spatial model, under the tendencies and stabilities that are imposed on spatial relations by processes within the context of a single conceptual model, and then evaluate it against corresponding processes under another conceptual model, until a consistent fit is obtained. This task is continuous and integrated. Implications from the application of conceptual models to the spatial one may also lead to the re-specification of the conceptual models.

The spatial form of the designed object is expressed in drawings which can be seen as means of organisation of relationships between different conceptual models since the spatial form maintains its connections to them. In other words, drawings by representing the spatial form of the designed object allow knowledge in the context of conceptual models to act upon them. To this extent, it can be said that the role of drawings in designing is to serve as an intermediate state between conceptual models and spatial forms. This role is attributed to three functions that they obtain during their use which flow from their analogical character: a *denotative* one, according to which they explicitly express abstract verbal concepts in the context of conceptual models; a *referential* one, according to which they primarily convey information about the spatial form; and a *connotative* one, according to which on the basis of the two previous functions they evoke knowledge which could also be relevant to conceptual models but is not directly expressed.[1] Even though we will examine in detail these three functions of drawings in the following chapter, it is worthwhile looking at how they are developed.

Initially, designers interpret and conceptualise the perceived information, and express such conceptualisations in verbal expressions. As cognitive operations begin to act upon information, there can be expressions describing transformations of it, such as specifications of utilities, declarations of properties, such as quantities or

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aspects of objects can be expressed diagrammatically and aid thinking activity in almost any kind of problem. See: Albarn, Keith & Miall Smith, Jenny, 1977.

1 Yet, these are not the only functions that drawings have in general but the ones which are of interest for spatial composition. Drawings may also have: *emotive* function, by trying to raise emotional response for the designed object – particularly in areas of furniture and fashion design; *conative* function, by persuading a preference for the designed object on behalf of others – competition drawings or drawings presented to developers; *poetic* function, by evoking metaphorical interpretations and commenting on social status, philosophical issues, or even art and designing itself – mostly self-expressive drawings not intended for building; and others. See: Ashwin, Clive, 1989.

magnitudes, etc. Successively, the results of such operations are organised into conceptual models. Diagrammatic drawings are essentially expressions of the associations within distinctive conceptual models. Gradually, imaginal attributes are attached to concepts and mappings between them are employed, so that concepts are expressed in shapes and properties of concepts – spatial and visual properties in particular – in features of shapes. This leads to the formulation of a spatial form which organises spatial information. Further concepts are considered, related to other aspects of the building, and further analogical mappings allow the activation of cognitive operations under different conceptual models. Through confirmation of information, in particular, a consistent fit between the spatial form and a number of conceptual models is obtained. Depictive drawings represent the spatial form of the designed object, but, since this is determined by its correspondence to conceptual models, drawings continue to constitute a medium for the expression of relationships within the context of conceptual models.

There could be conceptual models, relevant to aspects of the realisation of the designed object as a physical object, whose expressions never turn out to be drawn representations or, generally, involve spatial analogies. Conceptualisations, for example, relating to economic aspects of the building, or to wind pressure of the structural elements of it, are often expressed in propositional forms like mathematical notations, tables, lists etc., or sometimes diagrams whose depicted relationships do not refer to the spatial arrangement of the designed object; like, for example, pie charts. Even so, drawings may still evoke conceptualisations relating to these aspects, in reference to the spatial form and on the basis of their connotative function, as for example when the magnitude of spatial volumes indicates an expensive building.

The limitations of drawn descriptions in capturing analogies related to other than spatial or perceptual aspects of the object indicate a lack of a universal representational scheme for the description of the design task as a whole. Consequently, tables, lists, and charts may accompany drawings until the completion of the task. Yet, since most of the conceptualisations about the designed object apply to the spatial distribution of it, drawings remain the central means of expression in design. They offer the medium for the exploration towards the fit between conceptual models and spatial forms. Let us see, however, how this exploratory process is exemplified.

Spatial Composition

We have already said that designers from early stages in designing formulate spatial models under which spatial relationships are organised. Initially, spatial models are formulated by virtue of existing images and previous experience in spatial manipulation of individual designers, abstracted and generalised, in the form of design preferences and styles. Generally speaking, the particular spatial form of the designed object can be seen as the specification of an initial spatial model through elaborations that aim to make it correspond to assertions occurring in the context of verbal-conceptual models. However, in examining particularly how this task is performed further considerations have to be taken into account.

Firstly, even if initial spatial models constitute an elementary comprehension of spatial attributes and relations, and put forth a direction towards the final spatial form, they are loosely related to the conditions implied by the design object in hand and, consequently, they are susceptible to substantial modifications when they are brought into context and these conditions are considered. Thus, for example, a spatial model may indicate a particular spatial distribution of the object, say an 'organic' attitude to a building,[1] which may have to be restricted or even rejected because of limitations in the site or the physical setting. Even though such directions are in general terms maintained, they are widely conditioned by decisions concerning the structure, the construction, the materials, etc. of the artifact which cannot be foreseen.

Secondly, distinctive propositions resulting from manipulations in conceptual models may entail particular physical attributes of design elements or indicate specific spatial arrangements. Such distinctions cannot be anticipated by initial spatial models concerning the overall spatial form. Yet, the accomplishment of such arrangements may imply considerations about the overall spatial distribution. In the domain of a model of the structure of a building, for example, the loads that a load bearing element supports imply certain physical and spatial attributes for the element. Modifications of this particular spatial element may cause changes to other elements whose attributes are not necessarily determined by a model of structure.

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1 'Organic' approaches appear mainly in the context of architecture, and refer to the view that treats the building as a living organism. They are characterised by distinctive attitudes to particular parts of the building, in relation to their role in the 'organism', in contrast to a uniform approach to the whole of it. They are quite often manifested by a free and uncompact spatial distribution, resulting in a fluid space, where specific volumes and elements appear to be extruded from the mass of the building, retaining individual perceptual and spatial characteristics.
For a description of the spatial qualities of organic architecture see: Blundell Jones, Peter, 1988.

It should be clear that considerations in relation to models concerning structure or construction are more apparent and vital than in the case of other conceptual models, as far as the spatial formulation is concerned, since the physical manifestation of the designed object is almost always an objective. To this extent, conceptual models related to constructional attributes of the designed object are distinguished and play a central role in spatial composition. Suggestions about the width of a door, for example, in relation to some model of circulation, have to be re-considered if there are structural limitations. In effect, a lot of decisions about the spatial form are manifested during late stages in designing, when principles of construction are considered, and they are exemplified through the use of detailed and precise drawings.

Thirdly, despite any precision in the verbal-conceptual specification of such attributes or insight in the apprehension of spatial models, the spatial forms of the elements that constitute the designed object have to satisfy certain geometric conditions, in order to allow construction, which usually cannot be explored unless these elements are geometrically represented.

However, the objective which perhaps is the most important in spatial composition is aesthetics. Aesthetic principles may rely on various philosophical theories and design styles, idiosyncratic preferences, individual approaches. All these point to what might be called functionalities within persons that are not explained.[1]

We can say that, in the context of spatial composition, this objective is manifested as a designers' concern about the response that the designed object evokes in people to whom it is directed, not necessarily in respect to exemplified requirements but primarily in respect to abstract conceptualisations which are not explicitly addressed by the object. This can be seen as an intention towards an 'analogical' interpretation of the designed object itself by the people who interact with it. While, for example, a building may efficiently meet aspects of structure following certain rules and principles, the particular ways according to which these are realised by the built form can propagate abstractions that go beyond aspects of structure or even rules and principles that have been followed. Aesthetic considerations relate to these abstractions.

As a whole, the task of accomplishing a spatial form can be seen as the integration of a series of processes, involving the externalisation and transformation of

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1 See the discussion in: Bijl, Aart, 1991.

abstract verbal concepts into spatial entities, the specification and articulation of these entities with respect to their geometric and physical properties, the evaluation and verification of the resulting spatial form in relation back to conceptual models. These processes can be considered in terms of the cognitive activity of designers.

Spatial Composition and Cognitive Operations

To talk about spatial composition emphasises the articulation of the spatial form of design objects by virtue of fractional components, such as geometrically defined solids or shapes. This account is reinforced by the fact that at least architectural design objects are constructed in a similar fashion, that is by structuring different building elements.

This view might seem to justify the approach followed by computerised systems in which drawings, and in consequence spatial forms, are assembled by virtue of pre-defined primitive elements.[1] It should be noticed, though, that, on the one hand, this analysis is a final stage of spatial composition which as a whole follows a top-down direction, moving from the abstract to the concrete, like for example from rough spatial volumes to specific structural elements. This can be otherwise expressed by saying that spatial composition involves firstly the synthesis of the spatial form and then its analysis into components. On the other hand, both spatial forms and the components from which they are composed are not given, but they are in fact required, and they are constantly conditioned by the conceptualisations that they accept in relation to models.

As a consequence from considering these aspects, the task of spatial composition should not be compared either to a form of 'puzzle', where pre-existing components are put together, or to pure geometric reasoning, where the knowledge that is applied is solely geometric. We can say that spatial composition is based on visual-spatial thinking, a term which expresses the difference between designing and the analytic approaches in other problem solving domains.[2] This involves the appreciation of the spatial qualities of the artifact as a whole.

These aspects of spatial composition condition the use of drawings as a modelling environment and specify the limitations of computerised drawing systems as

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1 6. Drawings in Computers. Also: 7. Example of the Use of Computers in Design.

2 The involvement of visual-spatial thinking in design tasks is particularly discussed by designing tutors, like for example: Muller, W., 1989; Tovey, Michael, 1986; Laseau, Paul, 1980. For the approaches that designers adopt in general towards spatial problems see: Lawson, Bryan, 1980.

discussed in the previous chapter. Computerised drawing environments, relying on assemblages of pre-defined primitives and determined by geometric knowledge, fail to accommodate the progression from conceptual models to spatial forms.

Cognitively, spatial thinking can be described in terms of the whole range of operations that occur during verbal-conceptual cognitive activity, namely the operations of acquisition, projection, confirmation, representation, and regulation of flow.[1] Let us see how each of these are involved in the task of spatial composition, with emphasis on particular operations when their role is more significant.

In spatial composition, acquisition has as subject the earlier externalised verbal or graphical expressions. The spatial qualities of existing physical objects might also have to be examined.

Projection operates by the application of knowledge. If we could distinguish the process of transforming verbal concepts into spatial entities from the process of geometrically articulating such entities, we could describe knowledge involved in the former of these processes as being mostly intuitive, relating generally to the nature of physical objects, with some emphasis on their perceptual attributes.

It is anticipated that aesthetic considerations emerge during this process. Specifically, as we have suggested in the discussion on design concepts,[2] the mapping between verbal concepts and spatial equivalents is not determined by a one-to-one correspondence. A series of spatial entities can be related to a specific verbal concept. Despite the reduction of the number of such entities, which can result when particular assertions in the context of conceptual models direct spatial composition, the spatial forms which are implied by these assertions could be more than one. A single spatial form is selected as the final solution on the basis of its aesthetic value.

We cannot assume that there is always an explicit task of evaluating different spatial forms in respect to aesthetic criteria. Instead, in most cases, the aesthetic features of spatial forms are abstracted and generalised under design styles which in this sense can be thought of as directing the transformation of verbal concepts into spatial entities so that considered spatial forms fall within known probabilities in respect to their aesthetic value. To this extent, regulation of flow, as the operation which moderates cognitive activity, plays an important role in spatial composition. In

1 See: 4. Objects in Mind.

2 5.3. Relations between Images and Design Concepts.

other words, regulation of flow brings into this particular task stylistic preferences and, in consequence, directs projection, as well as the activation of other cognitive operations, so that the effects from their manipulation of spatial information relate to each other in respect to aesthetic qualities. There will be some further thoughts on the involvement of styles in spatial composition later.

To come back to our discussion on projection, with respect to geometric articulation, knowledge, in contrast, can be more precisely specified. The interpretation of conceptual models into drawings, and drawings into built forms, takes into account the conditions of *regularity* and *soundness* of solids. Regularity allows ease in construction, as the majority of construction techniques rely on the assembly of artifacts from regularly shaped parts. It is not always important, especially in innovative designs that approach spatial forms with a sculptural attitude. It could be not applicable at all to design fields where different construction techniques are used, like in the design of cars or plastic objects. On the other hand, soundness describes the 'realisticness' of the spatial form. It expresses the fact that the form has to be physically possible, that it can actually exist in reality within three dimensional space. Knowledge to achieve regularity and soundness is concerned with specific geometric and topological rules.

During spatial composition both of the processes of composing and articulating appear interrelated. There does not seem to be a clear demarcation between the aspects of knowledge that are applicable each time. Examples that will be discussed later demonstrate this fact.

Confirmation evaluates spatial arrangements with respect to various verbal-conceptual models, and verifies the internal consistency of the spatial form. Internal consistency here refers to factors internal to the spatial composition, such as the attributes of the elements that compose the spatial form and the conditions that have to be fulfilled, and does not have to do with the correspondence between the spatial form and conceptual models. Conceptualisations of the spatial form can arise from a variety of possibly contradicting points of view, and there could be cases where conflicts might appear. In a corridor of a building, for example, there might be a need for a door to ensure fire safety which can contradict a demand for ease of circulation. Such conflicts are usually resolved in favour of one of the aspects that act upon them, on the basis of designer's evaluations of their significance. However, the internal consistency in the spatial attributes of the object has to be always maintained.

Inconsistencies in the spatial form might lead to problems in the physical realisation of the artifact during its construction.

Representation in spatial composition relies extensively on graphical modes of expression and occurs mainly externally. It could be assumed that geometric articulation does not necessarily have to be accommodated in an environment that is based on graphical descriptions, since geometric rules can also be expressed by the use of symbolic mathematical notations. However, as was already indicated, spatial composition is not simply geometric articulation. More importantly, geometry itself is not seen in designing as an abstract theoretical discourse, but is rather considered in its pragmatic and functional counterparts. The discussion on examples of spatial composition that follows will further clarify this point. Graphical representations during spatial composition do not constitute an additional representational medium but they are in fact elaborations of the earlier visual expressions by which spatial and perceptual qualities of physical objects are apprehended.

Finally, regulation of flow directs spatial composition towards possible and aesthetically acceptable solutions, by relating the results of cognitive operations to stylistic generalisations as we have seen, and moderates the task in respect to the overall design activity.

The discussion on spatial composition so far has specified the characteristics of this particular task by looking at the principles underlying it, its connections to conceptual models, and the manner according to which it is advanced on the basis of cognitive operations.

Spatial composition can be better apprehended by examining specific examples. In the following part of the chapter we will discuss two examples of spatial composition, the second of which is particularly interesting as it attempts to relate the considerations just surveyed to an actual design situation.

8.2. The Task of Spatial Composition: Two Examples

The first of the examples of spatial composition attempts to clarify the involvement of geometry and geometric knowledge in spatial thinking. Even though the particular geometric problem that is examined is quite simple, in relation to spatial problems in designing, the manner according to which spatial problems are expressed and approached is discussed. The second example is quite general, attempting to see how propositions in the context of conceptual models are manifested in spatial forms and especially the implications from the use of graphical representations in spatial composition. It is an example that derives from the case study.

Spatial Composition and Geometry

In the discussion on the role of projections in spatial composition, we have suggested that there are particular geometric conditions that spatial forms have to satisfy and indicated the involvement of geometric knowledge in spatial thinking. This may be seen to imply that geometric knowledge can have the form of rules which by their application to spatial forms can lead to the fulfilment of geometric conditions.

To see how geometric knowledge is involved in spatial composition, consider the case in which, after elaborations in the context of conceptual models, a need appears for an object capable of penetrating a rectangular, circular, and triangular shaped hole. The area of the rectangular and circular holes is equal and given, and the area of the triangular hole is half the given area. In passing through, its form should exactly fit each one of the different apertures.[1]

The particular example is quite abstract and in consequence it is relatively simple in relation to design situations, since the requirement is very specific in contrast to the actual composition of spatial forms which often, if not always, have to satisfy a range of conditions implied by conceptual models. In this case, the implied conditions, including the specifically required condition of an object capable of passing through three differently shaped holes, are solely geometric. Here, they have to do just with the soundness of the geometric form, since there is no regular solid that meets the required condition.

However, the example is interesting because, even if it is effectively a geometric problem, it is described in a manner similar to the way in which problems in the composition of spatial forms in designing are introduced. In other words, it does not ask us to prove the validity of a theorem, nor to specify the relations that a geometric configuration accomplishes, on the basis of geometric properties that the objects that compose it possess. It rather requires the specification of the geometric properties of a solid, and consequently its definition, on the basis of conditions.

To proceed to the resolution of the problem, it is stated that the spatial form must be capable of penetrating three different holes. This suggests that the two

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[1] The example is based on an exercise in spatial articulation, found in: Porter, Tom, 1979, p.70.

opposite projections of the solid in the direction of each of the movements, in passing through the holes, should be inscribed one to the other, and because the solid must exactly fit the holes, they should be the same. The shape of the apertures, a rectangle, a circle, and a triangle, must coincide with each of the three projections.

In order to geometrically define the solid, then, we have to start by drawing the three of its projections: starting from the circle, the radius of which can be obtained from the given area; continuing with the rectangle, which has one of its sides equal to the diameter of the circle and the other can be obtained from the given area; and concluding with the triangle, whose base is also equal to the diameter of the circle and whose height is equal to the second of the sides of the rectangle. The solid can be obtained by the composition of the three projections, as shown in *Figure 8.1*.

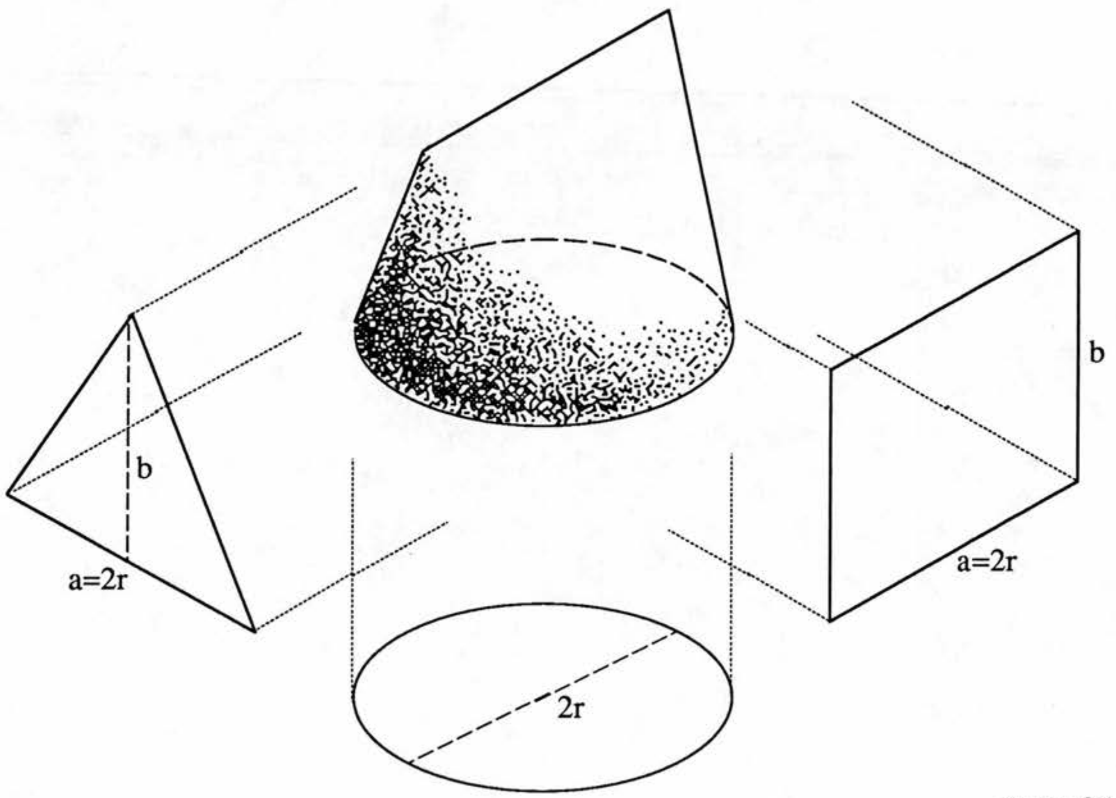

Figure 8.1

Even if the specification of the three projections can be obtained without the use of graphical representations, by using instead just mathematical formulae, it seems difficult to imagine how we can come to the definition of the solid without composing it from its projections and therefore using graphical representations.

Spatial forms can be specified geometrically on the basis of rules that define a solid in relation to its compositional parts, their vertices or faces for example, which however are taken to be known and well defined. Even so, rules take into account only certain of the relations between parts and solids, those that can be mathematically defined, resulting in specifications of usually regular polyhedra. Most likely, a mathematical definition of the solid at which we have arrived could be devised, since this solid is also composed from regular shapes. However, even in strict mathematical discourse, the definition is something that usually succeeds a discovery and proves it, and not the path which when it is followed leads to discovery.[1] In these terms, it seems plausible to say that spatial composition concerns the discovery and not its verification.

Yet, there is a differentiation in the attitude towards spatial problems between designers and problem solvers in other domains even when problems are governed by rules. Lawson, for example, sets up an experiment in which designers and scientists are asked to solve a simple spatial problem which is governed by a specific rule. The subjects know that there is a rule but they do not know what it involves. Scientists try out as many solutions as possible as quickly as possible, attempting to find the nature of the problem and the hidden rule. Designers, on the other hand, proceed by examining the qualities of the most favourable combinations until an acceptable solution is discovered. Lawson with this experiment shows that designers are mostly concerned about the discovery of a solution rather than the problem itself or the rules that govern it.[2]

The distinction between discovery and verification specifies the differences between spatial composition and the accomplishment of drawings in computers. Graphical symbols and transformations in computerised drawing systems are based on geometric rules that take into account geometric conditions. Spatial composition, however, concerns the discovery of forms that fulfil requirements implied by conceptual models. Rules that may govern the realisation of such forms are not known beforehand. If designers proceed to spatial composition using a computerised system, they find themselves thinking about spatial forms in terms of rules embodied in the system with undesirable results for designing. Examples from our case study, such as the composition of curvilinear forms on the basis of prismatic elements, demonstrate this aspect.[3]

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1 Lakatos discusses extensively this aspect of mathematical discourse in: Lakatos, Imre, 1976.

2 Lawson discusses this experiment in relation to strategies which are followed by designers during the accomplishment of design tasks in: Lawson, Bryan, 1980, pp.29-35.

3 7.3. Drawing, Modelling in Computers, and Designing.

The modelling of spatial forms in a computerised environment can be seen as their verification rather than their discovery. Spatial forms can be decomposed into well-defined geometric elements and geometric rules can be applied. They might be evaluated, in respect to regularity and soundness, and verified. This implies, however, that spatial forms have been already defined.

Spatial Composition and Conceptual Models

The following example refers to a real design situation and incorporates a series of considerations resulting from manipulations in conceptual models, such as ergonomics and construction, as well as aesthetics. It concerns the formulation and the structuring of the roof of one of the buildings that constitute the conference centre in one of the schemes by the students. The example is extracted from the work that was discussed in the fourth chapter, concerning cognitive operations, and there will be some connections in particular with projections concerning geometry. The drawings which are used by the student for the particular exploration are shown in *Figure 8.2* (*Student A; Instance 026* in Appendix B). In the figure, notations in bold and the drawings within the box are added by the author. The rest are original.

We have to be reminded that the site of the centre is on a small island exposed to winds, rain, and snow. An overt intention of the designer is to cover the building with a highly sloped roof, maintaining the morphology of traditional Scottish buildings, in order to protect the building from this weather. In relation to this intention, knowledge is acquired and projected. Such knowledge might be about the angles of the roof, materials, etc. Other projections, in the context of some model of distribution of the areas of activity, result in the decision to accommodate rooms in the roof.[1] The designer enters the task of spatially specifying the form of the roof, bringing along these considerations.

Earlier explorations of spatial distribution in the horizontal plane result in an initial plan, part of which is shown in *Figure 8.2, A*. In relation to this plan, the designer draws the section *B*. As the section is generated on the basis of the plan, we can assume that it is initially constituted from: the double lines *a*, and *b*, standing for external walls; the double lines *c*, and *d*, standing either for internal walls, or the

1 See the discussion and the corresponding figures in: 4.1. Design Actions, Transformations of Information, and Cognitive Operations; Acquisition and Projection of Information.

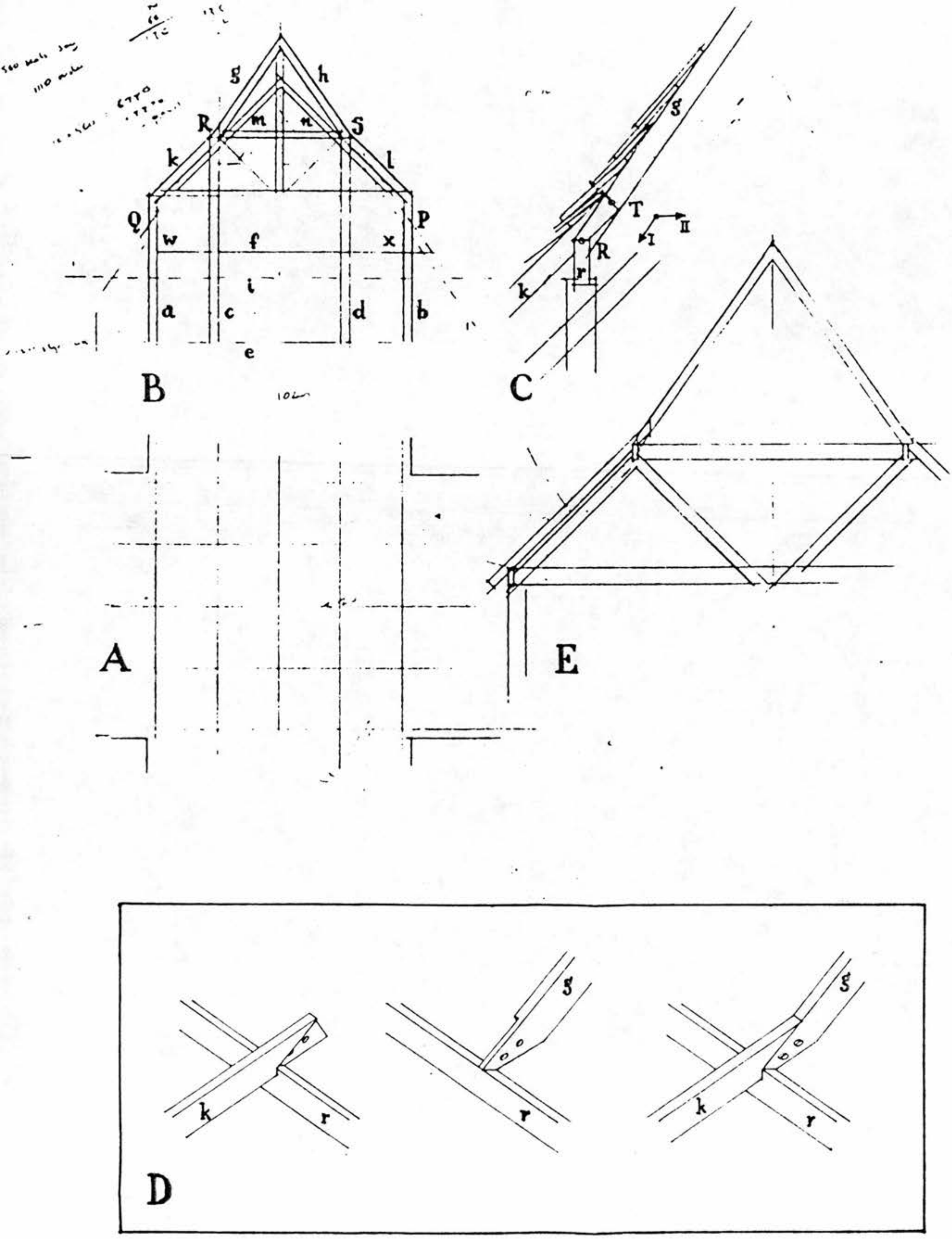

Figure 8.2

structural grid, or both; and the lines *e*, and *f*, standing for the levels of the ground and the first floor respectively. There has been already a decision that the total of the areas of activity are to be distributed in two floors. The section so far conveys established information which can be used for the spatial composition of the roof.

The designer draws the double lines *g*, and *h* for the two slopes of the roof at approximately 55° in relation to the horizontal, according to the acquired information that in Scottish buildings roofs are usually 45-60°. The position of roof, that is the topological relation between the peak of the roof and the floors, is a projection resulting from transformations of the same information, since a great deal of morphology is concerned with such relations. It can be assumed that this decision is also conditioned by his own aesthetic principles, that is how he appreciates the proportion between the span of the floor, the height of the building, and the height of the roof.

The roof intersects uncomfortably the external walls at the points *Q*, and *P*, resulting in a portion of the room being in the roof, just beside the external walls, that cannot be accommodated, since this space has height lower than a normal man; these appear in the drawing, as areas *w*, and *x*. Consequently, the designer considers lowering the level of the first floor, at the position *i*. However, this makes matters worse, because it makes a local problem general. In respect to a principle insinuated by regulation of flow, local problems should remain local, and problems should not be resolved in a way that generates new problems. The first collision is that, despite the fact that in the ground floor there are more public spaces, this floor becomes lower than the first floor where less public activities are to be located. Thus, something has to be done about the roof and not the floors, and the first thing to be changed is the angle of the roof.

A change in the angle of the roof, such as with the double lines *k*, and *l*, which would help to overcome the problem, would not coincide any more with Scottish morphology and the primary intention, since the angle of the roof would become less than 45°. A decision is taken, consequently, for the roof to be formed by using both of the angles, with a change in the slope at the points *R*, and *S*, where the structural grid or the internal walls meet the roof. The scheme resolves reasonably the problem of low height spaces, and retains the morphology of a highly sloped roof. Additionally, it provides an intuitively acceptable solution to the requirement of easy draining of rain and snow, since the rain and snow sliding from the higher part of the roof would help with their mass and speed the sliding of the quantities of rain and snow concentrated on the lower less sloped part of the roof.

By introducing an innovation to the geometric form of the roof, further aspects of construction and structure have to be considered. At this point, we have to be reminded that another early intention is to use timber frame for the structure. An initial decision is to have an infrastructure that follows the newly introduced angles, shown with the double lines *m*, and *n*. However, the structure has to be examined in greater detail so that the soundness of the geometric forms of the beams that support the roof can be determined.

A new detailed section *C* is made, retaining the established information. At the position *r* is the section of a horizontal beam which supports the beams *g*, and *k*, that hold the covering of the roof. The beams *g* and *k* should firmly seat on *r*. Since the beam *r* is a central structural element, as it connects the infrastructure with the outer structure of the roof, it is better for it to be regular in shape, with no cuts and hinges, in order to maintain maximum stability. In consequence, the beams *g*, and *k* should be formed relative to it.

Forces from the loads on the beam *g* at the point *R* occur in the directions *I* and *II*. If the beam *g* will simply seat on the beam *r*, the beam *r* would take the forces along the direction *I* but there would be a strong tendency for the two beams to be disconnected because of forces along the direction *II*. Instead of the introduction of a complicated connection between the two beams, and in order for the scheme to be elegant and simple in respect to the geometric forms of the beams and the construction, the designer considers the receiving of the forces along *II* by the beam *k*. Thus, he extends the beam *k* further beyond the point *R* to the point *T*, and connects it to the beam *g*, enforcing in this way also the stability of the connection between the beams *k* and *r*. As a result, the beams *k*, and *g* are formed in the way that is shown in *Figure 8.2, D*. The elaborations change the initial decision for the infrastructure into the new one shown in the section *E*.

As a whole, we can observe that the task has the form of a trial and error process which is accomplished by the use of drawings. Drawings act as models of the spatial form in which the various assumptions and propositions are expressed in order to evaluate their implications. An apparent instance of this aspect can be seen in the section *C*, where the feasibility of the form, in respect to the covering of the roof with tiles, is established simply by graphically representing the tiles and their positioning in relation to the angles of the roof.

The example demonstrates that thinking about spatial objects and thinking about drawings are interconnected. Explorations of the form of the designed object determine the drawing. Such explorations are driven by intentions which result from conceptual models.[1] Forms seem to be selected from a series of alternatives in such a way that they are appropriate to the abstract requirements, taking into account aesthetic considerations. Drawing operations mirror design processes. There does not seem to be an instance of thinking about the drawing, as distinct from designing. Geometric knowledge is used to verify design decisions but it does not condition either the drawing or the spatial form of the designed object. This radically contrasts with the making of drawings in computers, as we have seen in the previous chapter, where systems require thinking about the process of drawing itself.

8.3. Style and Spatial Forms

After the discussion of the principles underlying spatial manipulations and the manner through which these are manifested in the accomplishment of spatial forms, we may close this chapter with a few thoughts on the involvement of stylistic considerations in the task of spatial composition.

Style, as an idiosyncratic way of approaching design problems, is not irrelevant to the particular task of specifying a spatial form. Spatial arrangements can be approximated under a wide range of conceptualisations, and accordingly can be affected by a wide range of conceptual models. As new efficient building technologies become available, greater numbers of acceptable alternatives can be reached by the developments within the context of specific conceptual models. Style is offered as a system of constraints that can be imposed on the spatial form of the designed object in order to reduce the uncomfortably large number of degrees of freedom in its accomplishment. More importantly, style sets personal criteria that aid in resolving the inevitable conflicts that appear when the effects of the development of several conceptual models are considered in the elaboration of the single spatial form. Style can be seen as a pattern of coordination of the influence that conceptual models impose on spatial characteristics and it thereby contributes in innovative designs.

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1 A discussion on the geometric properties of design objects and their suitability to particular intentions can be found in: Pye, David, 1978, ch.4.

The realisation of a spatial form in respect to various conceptual ones can be seen as a typical ill-defined problem where a satisfying solution can be accepted rather than an optimal one. Akin offers an excellent example to illustrate the differences between satisfying and optimal solutions. Consider a flat plateau with multiple peak points on it as the search field with the possible solutions. In well-defined problems, the problem solver has a representational domain, which allows her or him to objectively codify the problem domain, and an objective function, with which she or he can measure the altitude of each peak and select the most appropriate. In the case of designing, there is neither a universal representational scheme to codify the whole problem domain, nor a metric to compare solutions. The only criterion for measuring the success of a given solution peak point is the altitude it yields compared with a certain benchmark, that is a desired altitude. If a peak point reached is above the benchmark, then it provides a satisfying solution.[1]

The basis of the criterion or benchmark for a satisfying spatial form could be its correspondence to conceptual models. Many spatial forms might fulfil this, but not all would be the 'best' ones, at the higher peak points. The goodness of a design solution, then, has as a second coordinate the stylistic choices of the designer in order to limit the search domain but more importantly to identify and set the benchmark she or he is working from. The view that criteria in design are defined by the proposed solutions[2] expresses exactly this fact.

8.4. Summary

Spatial composition, the task with which drawings are primarily connected, was the subject of this chapter. We have discussed the relations between spatial forms and conceptual models and suggested that drawings serve as a means of organising the effects on spatial forms of manipulations of information in the context of conceptual models. This is attributed to three functions that drawings fulfil during designing, which flow from their analogical character. These are namely: a denotative function, by expressing abstract verbal concepts; a referential function, by conveying information about spatial forms; and a connotative function, by evoking design knowledge which is not directly expressed.

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1 Akin, Ömer, 1986, pp.95-96.
2 See: 3.3. Models and Design Tasks.

The attributes of drawings in respect to these qualifications will be examined in the following chapter. However, in order to have an understanding of the objectives that characterise the employment of drawings, we have continued by looking at the principles that underlie the task of spatial composition and the ways through which it is advanced in relation to cognitive operations. The main outcome of this discussion is that spatial composition is characterised by a top-down approach, from abstract conceptualisations to concrete spatial forms, in which drawings have a central role serving as an intermediate stage between them.

Finally, these issues have been clarified by the examination of two specific examples of spatial composition. In the first of them, emphasis has been laid on the manner according to which problems in the accomplishment of spatial forms are approached. The second, which is an example from the case study, has addressed most of the issues above, such as the relations between conceptual models and spatial forms, the involvement of cognitive operations, and in particular the way according to which drawings are used in the task. Both examples indicate conflicts between the mode of thought which is imposed by computerised drawing systems and designers' explorations of spatial solutions.

The chapter connects spatial composition and the use of drawings to an approach to designing that has been put forward in previous chapters. It also sets the grounds for a discussion on the structural properties that drawings acquire as a consequence of their use, which will continue in the following chapter.

9. Drawings and Design Activity

As indicated by discussion on design expressions so far, the thesis takes the view that a comprehensive approach to drawings should take into account the role that drawings play within design activity. Use determines the manner according to which drawings are realised and structured.

In the previous chapter we have connected this role with spatial composition. We have suggested that drawings are closely connected with the task of externalising and transforming conceptualisations, in the context of design models, into physical spatial forms. Drawings, serving as an intermediate stage between conceptualisations and spatial objects, offer a modelling environment for the accommodation of this task. In this chapter we will examine the features of drawings which contribute to this role.

We have already indicated that this role is attributed to the analogical character of drawings which has been qualified into three functions that drawings obtain during their use: their denotative, referential, and connotative functions. These were specified, respectively as: the function according to which drawings express abstract concepts; the function according to which they convey spatial information; and the function according to which they evoke conceptualisations that are not explicitly expressed. These functions result from designers' intentions about representations of designed objects. Here, we will further specify these functions and relate them to the different kinds of drawings that are met in design activity. Then we will continue by examining specific attributes of drawings that support these functions. The discussion will take into account aspects of structure, graphical symbols, and drawing operations. We will relate these aspects to intentions about designed objects and we will exemplify them by looking at drawing practices in the traditional drawing environment.

The chapter attempts to connect our account of designing in earlier chapters to issues about the structure of drawings, and to this extent it can be seen as an extension of discussions in those chapters. It develops a view about the making of drawings by focusing on the qualities of drawings that support the accomplishment of design tasks. This view will be related to computerised drawing environments in the following and closing chapter. There, we will examine the implications that the use of drawings in designing have for the systematic representation of drawings.

9.1. Accommodating Spatial Composition

It should be clear from the discussion in the previous chapter, that spatial composition is a task central to designing. The objective of accomplishing a spatial form differentiates designing as a whole from other cognitive activities. Historically spatial composition has been performed through the modelling of designed objects by means of drawn representations or by the use of physical models. However, there are distinctions in the manner according to which drawings or physical models are made and used within design activity. These distinctions are indicated by the difference between drawings and models as well as by differences in the various kinds of drawings.

The different manners of accomplishment of drawings can be approached by examining the functions that design representations in general serve within design activity. These functions have been identified, in the previous chapter, as the denotative, the referential, and the connotative functions and are directly entailed by the purposes for which they are used. In this part of the chapter we will examine how these functions apply to design activity. In the following three parts we will connect each of them to design intentions and specific drawing operations.

The Sequence of Expressions in Designing

In our discussion on the approaches underlying the development of computerised drawing systems, we have seen that most of them are based on the assumption that drawings are primarily used in order to represent spatial objects.[1] Drawn configurations depict spatial arrangements of building elements such as walls, doors, roofs, etc. This might indeed be the case. However, in order to increase the effectiveness of the operations through which drawings are made, we have seen that

[1] 6. Drawings in Computers.

the implementation of such systems is conditioned by an attempt to specify the relations through which graphical symbols are put together independently from the qualifications that drawings obtain during their use. A system whose development is based directly on the assumption above was the system used by the designers in our case study.[1]

This results in a dissociation of drawings from the abstract conceptual operations involved in the manipulation of designed objects. Systems cannot support the accomplishment of drawings which are used not so much to convey established spatial information as rather to explore tentative design concepts. Such are the rough and sketchy drawings, occurring in early stages in designing, which only loosely appear to be conditioned by geometric knowledge.

If we look at the handmade drawings produced by the students during the development of their projects, we can observe differences both in the way they are made, as for example the kind of symbols used and the relations between symbols employed, and in the way knowledge seems to condition them.[2] In the early stages of the design task, as well as the first stages of each of the developments, expressions are mainly used in order to express verbal concepts in the context of particular conceptual models and they usually employ verbal forms of representation. Expressions like these can be seen in Appendix B, as for example with *Student A; Instance 001*, *Student A; Instance 002*, *Student A; Instance 005*.

In contrast, descriptions towards the completion of a development, including the final presentation of the designed object, being either perspectives or orthographic drawings, are usually expressed in visual form, and depict spatial and visual manifestations of the designed object. Consider, for example, the drawings in *Student A; Instance 189*, *Student B; Instance 242*, *Student C; Instance 186*.

There are also intermediary stages in which drawings have diagrammatic forms and seem to express relations that hold between verbal conceptual entities rather than exemplify geometric attributes. Consider, for example, the diagram at the top of *Student A; Instance 002*. It is an enlistment of utilities of the designed object which is realised in a way that allows also the expression of commonalities between them. The expression is differentiated from solely verbal expressions, like the one that follows in the figure, because it employs a spatial medium in order to represent these

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1 7. Example of the Use of Computers in Design.

2 See the discussion in: 5.4. Drawings as Representations; Evidence in Design Expressions.

relations, and consequently takes its diagrammatic form. A similar case occurs with *Student B; Instance 127.*

The drawings in *Student A; Instance 014* are seen as developments of diagrammatic expressions which make additional use of the possibilities offered by the spatial medium in order to indicate the spatial distribution of such utilities. These in turn are further developed into drawings, like those in *Student A; Instance 022*, which begin more precisely to elucidate spatial relations.

It is suggested that these differences in the ways in which drawings are made are a direct implication of the objective in spatial composition to find and specify spatial forms which satisfy requirements implied by conceptual models.

Top-Down Processes

As we have seen, spatial composition involves the organisation of the effects on spatial arrangements of abstract manipulations of information by cognitive activity. In order for this objective to be met, there is a need for an expressive environment which can capture both the abstractness of design conceptualisations as well as the concreteness of spatial attributes. This principle specifies the functions that drawings as an expressive environment have to serve, the denotative, referential, and connotative functions, as defined in the previous chapter.[1]

The denotative function entails the mapping of concepts to specific symbols of the graphical representation, which for early stages in designing could be also verbal symbols, that are used subsequently in order to denote these concepts. The referential function entails the assignment on symbols, which may be the same symbols that are used in order to denote verbal concepts, of spatial properties so that the configuration as a whole obtains reference to actual physical objects. We may, then, say that graphical symbols denote concepts and refer to objects.

The distinction between denotation and reference attempts to capture the differences between graphical and verbal symbols. In considering the signification of verbal symbols, denotation and reference might appear to mean the same thing. A word, for example, denotes or refers to a concept, particularly when this word is a noun, in contrast to a verb. The denotation of a graphical symbol, however, is not simply the concept which can be attached to the symbol. Graphical symbols are used

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[1] See in particular: 8.1. The Accomplishment of Spatial Forms; Conceptual Models, Spatial Forms, and Drawings.

by virtue of properties which are realised in the objects they denote. This may otherwise expressed by saying that graphical symbols become objects themselves which are mapped to denoted concepts. This quality in the relations of signification of graphical symbols is captured by the distinction between denotation and reference.

According to the connotative function, the graphical representation evokes knowledge which is not explicitly represented by particular symbols but still plays an important role in the accomplishment of spatial forms. This knowledge relates to considerations that emerge on the basis of denoted concepts or referred objects, such as with considerations about aesthetic qualities.

The connotative function of drawings is the most difficult to examine since it is not based on the employment of specific symbols or properties and relations between symbols, but on the mapping of knowledge to symbols and properties that have already a role in the representation in respect to the denotative and referential functions. In other words, to knowledge that is not involved in the representation of what is represented.

The connotative function of drawings is related to the context within which they are used. To make this point clear, let us see an example. Consider the apple, the symbol that is used as a logo of Apple computers. The symbol explicitly represents a half eaten apple. The connotative meaning of the symbol emerges if we connect the represented concept with the context within which it is used, that is with Apple computers. As such, we may say that Apple computers themselves, and not just apples, are something to be 'eaten', in other words they are ready to be used, apprehensible, direct in their approach, etc.

Since through their connotative function drawn representations are connected to their context, the role of this function becomes particularly important during the interpretation of drawings which are made in early stages in designing but are reconsidered or developed later. This aspect is reinforced by the fact that in most cases even verbal concepts are denoted in drawings by graphical symbols which are often susceptible to more than one interpretation. To this extent it can be said that the connotative function of drawings is not used in order to realise distinctions only in respect to the abstract qualities of drawings, but also in respect to the components of conceptual models which are not explicitly represented. This is the case particularly for an environment like drawings which cannot be used universally to represent all aspects of all conceptual models. Thus, for example, the indication by the magnitude of spatial volumes that the represented designed object might be expensive relates to a connotative interpretation of the drawing.

This approach to the functions that drawings serve during their use develops our early account of graphical representations and clarifies their analogical character.[1] It should be noted though that, despite the distinctions which can be realised in respect to these functions, they occur in all kinds of design representations from early sketches to final presentation drawings. That is particularly the case for the connotative function of drawings, while for the denotative and referential functions there may be differences in their degree of involvement in either the accomplishment or the interpretation of drawings. In order to examine in more detail drawing operations which result from these functions, we will continue our discussion on the basis of these distinctions. Before doing so, let us see a characterisation of the different kinds of drawings and their sequence in design activity in respect to the qualifications above.

The diagram in *Figure 9.1* is an attempt to illustrate the relation between the sequence of the various forms of design expressions and the two main functions that they serve: the denotative and the referential. The connotative function is not indicated since, on the one hand, there are no particular structures in drawings which are developed to support it and, on the other, it can be assumed that all kinds of drawings equally serve it.

In the diagram, the area in between the two horizontal parallel lines represents the field of expression in designing. The curved line stands for the progress in the design task in relation to its manifestation in expressions. Designing might begin before any expression; however, developments which are not manifested externally are not captured by the diagram. Possible forms of expression are shown as nodes on this line and their relation to the functions is depicted by their distance from the two parallel lines.[2] That is, the longer the distance within the field that indicates denotative function, the greater is the involvement of this function in a specific representation, and similarly for the referential.

Expressions at the beginning may have verbal forms and be used for the expression of verbal concepts. Later diagrammatic forms are introduced which begin to implement analogical mappings, to refer to spatial objects, and move towards three

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[1] See the discussion in: 5.4. Drawings as Representations.

[2] The diagram shows commonly used forms of design expression, but further forms may be considered. In between perspectives and physical models, for example, we may have colour perspectives or photographs of models.

dimensional expressions, like physical models, which act as complete analogues of the designed object in terms of its spatial distribution and may be in respect to other perceptual features, like colour, texture, etc.

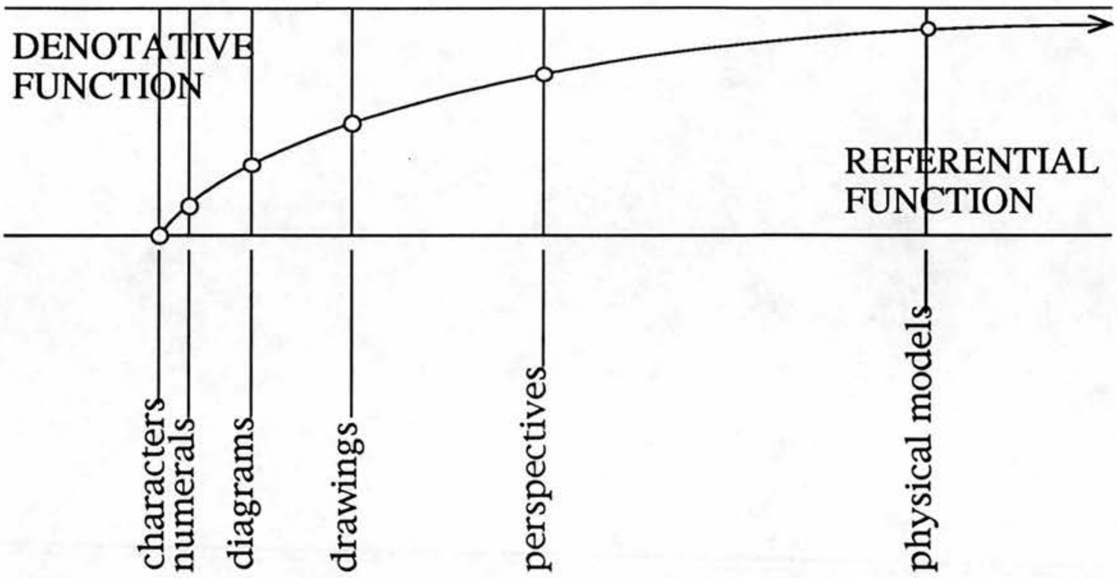

Figure 9.1

The two extremes of the sequence can be thought of as standing for the representations which are used, on the left side, solely for the denotation of conceptual entities with no reference to spatial qualities, such as lists of requirements, charts, etc., and, on the right, for representations which fully employ analogical mappings in respect to spatial properties and relations, such as models. This latter sort of representation can be thought of as capturing the majority of the qualities of an analogical system, where for example intermediate states in the representing configuration stand for intermediate states in the represented world.[1]

Consider that there is no representation which can be regarded as a complete analogue of an object. In relation to our earlier discussion on analogy,[2] this would mean that all aspects of a target object, from all points of view, are analogically mapped to another base object. This is a condition that can be met only by a base object which is absolutely identical to the target object. An object like this can only be the target object itself, and the analogy becomes useless. This condition is captured by the diagram as there are not any nodes which do not have even a minimum distance within the field of the denotative function. In other words, representations in design always require a denotation in order to be accomplished and interpreted. This indicates

1 See: 5.2. Kinds of Representation; The Representation of Images: Analogical Representations.

2 5.4. Drawings as Representations; Analogies in Drawings.

the fact that drawings maintain their connection to conceptual models even if they might have visual forms.

By relating the forms that design expressions have with the functions that they obtain during design activity, the diagram suggests that the structure of drawings is not independent of the way in which they are used. The movement in the development of design tasks through different levels of abstraction, from verbal concepts to spatial forms, is reflected in the employment of different kinds of drawings. Designers may initially express assertions in the context of conceptual models by the employment of symbols which do not refer to spatial qualities, but, as eventually the application of these assertions to spatial forms is attempted, there is an assignment of spatial properties to representing symbols so that representations begin to convey spatial information. A good example of an intermediate stage in the process is the diagram at the top of *Student A; Instance 002*. Here, we can see how verbal symbols, such as words, are placed on the paper in such a way that spatial distinctions between the concepts that the symbols denote are expressed.

This view on design representations suggests that drawings, through the particular ways according to which they are used, as these are specified by the denotative, referential, and connotative functions, obtain forms which are related to conceptual manipulations in designing. In the following parts of the chapter, we will attempt to see which are the conceptualisations that regulate the use of drawings and in relation to these which are the particular techniques employed in their accomplishment. This will be the case particularly for qualifications in drawings in respect to their referential and denotative function. In the last part of the chapter, we will examine how different interpretations of drawings emerge in respect to their connotative function.

9.2. Drawings and Spatial Objects

To the extent that the objective of spatial composition is the definition of a spatial form in a way that can be built, we may firstly see how drawings model the spatial attributes of the designed object in order to aid the exemplification of spatial properties and relations. This function has been specified as the referential function according to which drawings act as analogues of spatial forms allowing explorations in respect to their correspondence to conceptual models. We may leave aside for a while, however, the discussion about the manner according to which aspects of design models are denoted in drawings – and for that matter the conceptualisations the spatial forms receive in respect to design models – and see which are the design intentions about spatial forms, how spatial forms themselves are conceived, and how drawings obtain reference to physical objects. As such intentions may vary in different design domains, the main field of reference will be architectural design, even though similar considerations may also apply to other design fields.

Qualifications of Spatial Forms in Designing

From the point of view of spatial apprehension, a designed object is conceived as a collection of physical elements that define the non-material aspect of design, space. This conception of spatial forms is based on the duality between the container of space and the contained space. By virtue of this duality, space is modulated by various systems of enclosure. We may say that the essence of architectural space manipulation relies on the bounded fragment of space and what graphical symbols in drawings depict is boundaries of space.[1]

Boundaries of space in architectural spatial forms can be conceived in two ways: as being the limits of an enclosed fragment of space, therefore distinguishing enclosed space and open space, and as being the limits of the spatial distribution of solid elements, therefore distinguishing matter and void.

The first conception of boundaries is applied to spatial forms in the first stages of designing and architectural objects are treated as assemblies of bounded spaces. In this case, boundaries do not have mass or other physical properties and are confronted as abstract geometric entities, roughly corresponding to vertical, horizontal or diagonal planes, within a three dimensional space. 'Roughly' expresses that spaces are not simultaneously conceived in their complete three dimensional form but they are rather approached in two dimensions at a time.

The nature of boundaries is usually not specified in the first stages of designing. Boundaries may turn out to be absolute, that is allowing no connection between the spaces they separate (like a solid wall, or a floor), they may be partial, that is allowing kinaesthetic or perceptual relations between spaces (like a row of columns, a series of trees, or a glass wall), or may be implied, that is simply defining an area (like a change of level, or a projecting wall or roof).

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1 This view on spatial manipulation is developed and applied on formal treatments of architectural plans in: Oxman, Robert, Radford, Antony & Oxman, Rivka, 1987.

When the nature of boundaries becomes incorporated in designing, which indicates the application of verbal conceptual models to the spatial elements, the second spatial conceptualisation is applied to the spatial distribution of the designed object. In this case, boundaries can be conceived as obtaining mass and matter and the designed building is confronted as a composition of three dimensional solid objects.

The passage from the first to the second conceptualisation of spatial forms is reflected in the shift from rough sketches to structured orthographic drawings. This may appear to be discontinuous, involving, for example, the 'translation' of sketches to line drawings. It can be assumed that both conceptualisations may be applied to both kinds of drawings. Let us see how drawings represent three dimensional information, since their value in respect to the referential function seems to be based on this capability.

Tools for the Description of Space

Descriptive geometry can be seen as the primary methodological tool in design practice, especially in architecture, that is used in order to describe spatial forms. It helps designers to maintain the internal geometric consistency of spatial forms in respect to the conditions of regularity and, particularly, soundness.[1]

Descriptive geometry is based on the principle that spatial objects can be described by the specification of their projections on planes which cut the three dimensional space.[2] This fundamental principle of descriptive geometry of defining geometric objects by their projections offers an excellent vehicle for the description of spatial objects which do not yet exist, such as designed objects. In architectural delineation this principle is reversed so that the comprehension of the spatial properties of designed objects results from the study of one of a series of projections at a time, and their correlation. The surface of each specific drawing, which in early stages of

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1 See: 8.1. The Accomplishment of Spatial Forms; Spatial Composition and Cognitive Operations.

2 Descriptive geometry is concerned with the study of *conical*, and *cylindrical* projections, although *spherical* projection can also be studied. The elements of a system of projection are two, the *centre of projection* and the *plane of projection*. The projection of an object is the tracing of the points of the plane of projection where *projecting rays* which connect the centre of projection and corresponding points of the geometric object cut the plane of projection. In conical projection the distance between the centre and the plane of projection is taken to be finite, and the projection results in perspective drawings. In cylindrical projection the distance is assumed to infinite, and the projecting rays are parallel. This results in orthographic drawings including obliques and axonometrics. In spherical projection the plane of projection is not flat but is part of the surface of a sphere. Spherical projection simulates the effects of visual perception but is difficult to study. Furthermore, visual perception results from the integration of two projections from the two eyes. For a discussion of the principles of descriptive geometry see: Ince, E. L., 1933.

designing is usually either a plan or a section, is seen as a hypothetical two dimensional plane which penetrates the spaces. Spatial forms are projected on the plane as sets of spaces defined by their enclosing boundaries represented by lines. Spaces are represented as having the geometric properties of length and width, and boundaries the property of length. However, it is implied that spaces and boundaries have also the property of height along the third dimension in relation to the surface of the drawing.

A description of an architectural object in most cases requires the accomplishment of several projections, depending on the complexity of its form. As a consequence, the complete spatial representation of an object appears in a set of drawings, rather than a single one, which includes at least plans, sections, and elevations in various numbers in relation to the complexity and the amount of the information.

As a result of multiple projections, the reading of drawings is not linear and sequential, i.e. in one dimension, but spherical, i.e. in three dimensions. Thus, in contrast to verbal expressions, not only the accomplishment of design drawings but also their interpretation and usage, proceeds by different layers which can be thought of as a consequence of the three dimensional nature of the represented information. The two dimensions of the spatial information are interpreted on the basis of the particular two dimensional drawing in hand, being either a plan, a section, etc., while a third dimension in the interpretation is implied by the requirement to see further drawings from other points of view. The comprehension of the spatial information about the object comes as an outcome from the correlation between multiple two dimensional drawings. Such drawings are related to each other on the basis of conceptual knowledge about the represented objects.

The implications of the use of descriptive geometry in architectural delineation were already shown in the discussion of the example in *Figure 8.2*. In this case, we can observe how spatial articulation proceeds drawing by drawing, that is projection by projection. The process starts from an initial vertical projection, the plan view *A*, and continues by the specification of a new horizontal projection, the section view *B*.

Drawing operations based on descriptive geometry are demonstrated in the example of *Figure 5.2*. The spatial configuration, in this case, is constituted by the composition of three simple geometric objects: a prismatic body of a small building, a hemispherical dome, and its cylindrical base. The regularity of the solids allows their initial description on two projections in relation to their geometric properties: height, width, etc. The problem appears in the specification of the intersection between two of the solids, the prism and the cylinder, in the third projection. This is accomplished by connecting the projections of specific points which belong to both of the solids.[1] Consider that knowledge about the represented objects takes part in the description. Such knowledge, for example, specifies which are the points which are projected.

Scaling is another methodological tool used for the proportional mapping of properties of the drawn objects to corresponding properties of the represented objects. It allows the maintenance of the spatial relations that these properties entail, such as with the orientation of objects.

Grids are a method of correlating points on the surface of the drawing with corresponding points in a two dimensional space. In the construction of a grid, a set of points on the drawing, which are separated by a specified distance, are connected to each other with a net of parallel lines usually in two directions. Grids can be seen as a form of two dimensional measurement, in that they offer a means of transferring the analogical properties of space into a system of points or numbers.

Unlike conventional measurement, in which the units of magnitude of distance are abstract and general, serving several purposes, in grids distances are taken to correspond to magnitudes which are entailed by conceptual models, structural in particular. A common grid, for example, used in concrete constructions is a square grid 120 by 120 cm. The interval of 120 cm is a distance in which a single door or window can fit, two intervals can accommodate a double door, three or four intervals can be the distance between two columns, etc.

There could be *orthogonal* grids, with dissimilar sizes of interval in the two directions; *non uniform* (or tartan) grids, with different sizes of interval succeeding one after the other in the same direction; *triangular* or *polygonal* grids, with more than two directions which are not perpendicular to each other; *intersecting* grids, where the diagonal distance of two points on the grid form the interval of a new grid; *discontinuous* grids, where two grids are related to each other by virtue of factors which are completely external to the geometry of the system; etc.[2] Examples of different grids are shown in *Figure 9.2*.

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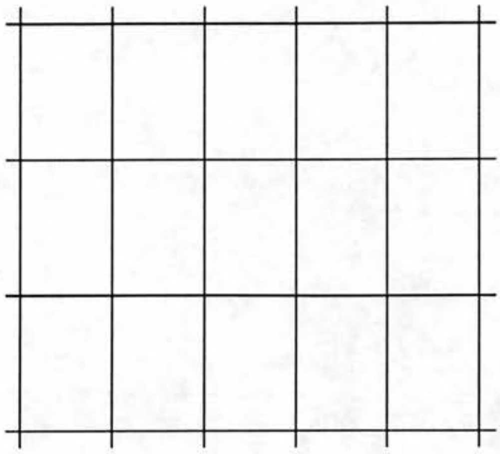
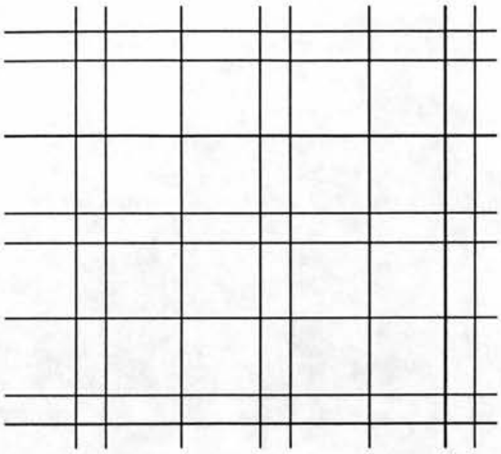
1 A comprehensive account about the use of descriptive geometry in architecture can be found in: Lee, Leslie A. & Fraser Reekie, R., 1943.

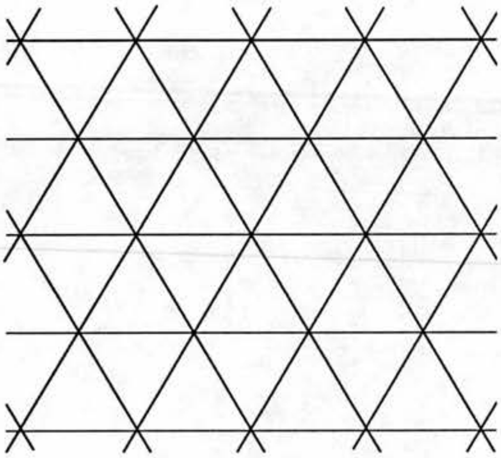
2 Grids, among other drawing techniques, are discussed in: Fraser Reekie, R., 1969.



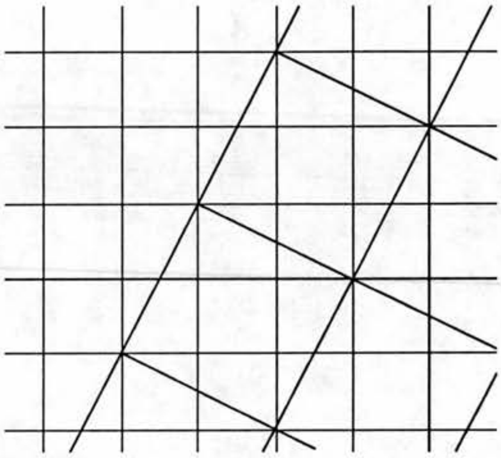
A: Orthogonal Grid



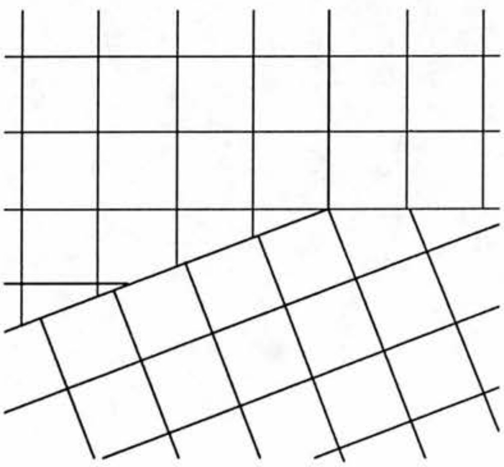
B: Non-Uniform Grid



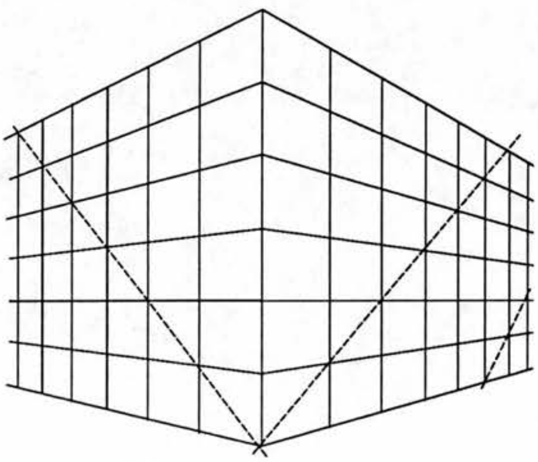
C: Triangular Grid



D: Intersecting Grids



E: Discontinuous Grids



F: Perspective Grid

Figure 9.2

A distinctive case is perspective grids in which points on the surface of the drawing are correlated to points in a three dimensional perspective space. Perspective grids allow the easy construction of perspective drawings as building elements are placed directly within space.

Grids are an important aid towards the externalisation of spatial concepts. Grids can be seen as a means of relating topological assertions in conceptual models into a spatial configuration with considerable precision. The precision offered by grids makes them almost indispensable in complicated structures like reinforced concrete or steel frames.

Construction lines can be seen as the abstraction of initial sketches which are transferred into working drawings, especially in plans, bringing along earlier considerations about the spatial form of the designed object. Initially, construction lines are taken as the depiction of boundaries of space[1] and later they are used to locate the graphical symbols standing for the various spatial elements.

In some respect, grids can be seen as sets of construction lines which however satisfy particular geometric conditions. Grids indicate a particular perception of space and geometry, showing great emphasis on structure and construction. Construction lines, as an irregular pattern of lines, seem more closely to follow the spatial qualities of the specific design artifact.

This difference is apparent in the accomplishment of drawings. Grids are often imposed initially on a drawing to help spatial composition which is achieved by following grid patterns. In the positioning of every single construction line, however, particular effort is given to relate the specific graphical symbol, and the building element that it stands for, to other elements of the spatial configuration in respect to the conceptualisations that condition it. Generally speaking, both grids and construction lines may appear on the same drawing.

Methodological Tools and Conceptual Knowledge

The drawing operations entailed by the methodological tools just described are not independent of how spatial forms are conceived. This is particularly true of grids and construction lines, but also descriptive geometry.

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1 See the discussion under: 9.2. Drawings and Spatial Objects; Qualifications of Spatial Forms in Designing.

The choice of a particular grid pattern is conditioned by design intentions and conceptualisations of the particular designed object. Different grids may be used in different kinds of buildings, different stages of design activity, different models of distribution, etc. Grids used in hospital layout, for example, are derived from the dimensions of hospital equipment. Particular kinds of grid might also be connected to particular styles in spatial composition. Deconstructivist architecture, for example, shows an emphasis on intersecting or discontinuous grids.[1] Other styles, like organic architecture, may not use grids at all, relying mostly on spatial articulation by the use of construction lines. Designing may generate new unforeseen requirements for different grids. Late decisions in relation to the structural model of a building, for example, may entail the use of new grid patterns, other than those initially used.

Construction lines are even more closely related to conceptual assertions about spatial forms. They express tentative ideas about the relations between spatial elements, implied by conceptual models.

Drawing operations based on descriptive geometry are accomplished in accordance with designers' conceptual knowledge. Even though descriptive geometry is used in order to achieve geometric consistency, it is in fact a 'neutral' tool for the exemplification of spatial descriptions. It does not rely on geometric definitions and conditions, geometric analysis, or assumptions about the geometric form of spatial objects. Descriptive geometry does not deal, for example, with questions such as when two lines are parallel or how a rectangle is decomposed, but it offers operations for the description of spatial objects which are otherwise specified by conceptual knowledge. This coincides with the way the geometry of spatial forms is approached in designing, as discussed in the previous chapter.[2] It contrasts, however, with drawing operations met in computerised systems. In this case, graphical symbols and transformations rely on geometric assertions embodied in systems.

These issues indicate that designers are able to structure drawings according to their own perceptions of spatial forms. They also point to the importance of the denotative function of drawings even in the representation of spatial objects. There is first of all a denotative function so that a particular graphical symbol denotes a spatial element, and then a referential function through which the properties of this symbol are

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1 For a review of recent projects following the principles of deconstructivist architecture see: Johnson, Philip & Wigley, Mark, 1988.

2 See, in particular: 8.2. The Task of Spatial Composition: Two Examples; Spatial Composition and Geometry.

related to corresponding properties of physical objects. Attributes of drawings in respect to their denotative function are discussed in the following part of the chapter.

9.3. Drawings and Conceptual Models

We have seen how drawings convey spatial information and obtain reference to the physical world through methodological tools that support their referential function. Since, however, spatial forms are manipulated in respect to conceptual models, we have to examine drawings as an environment for the externalisation of conceptualisations. The role of drawings in respect to this issue is based on their denotative function.

Components of drawings in respect to their denotative function are treated as symbols that denote concepts in the context of various design models. Drawings as a whole manifest distinctions that are imposed on spatial forms from intentions implied by conceptual models.

Conceptual Distinctions in Design Drawings

As has been mentioned, the development of the spatial form of the designed object is based on clarifications and elaborations of it under the tendencies that are imposed on spatial elements from verbal conceptual models. The manipulation of the spatial form according to conceptual models refers to distinctions that are imposed upon it which have to do with spatial relationships, groupings, operations, and qualitative attributes of spatial elements. Each of these determines particular drawing operations resulting in the resolution and modification of drawn objects and accordingly the corresponding spatial objects that they depict.

Distinctions in *spatial relationships* involve the identification of individual spatial elements and the specification of topological relations between them. The identification of a spatial element refers to the distinctive conceptualisation that a spatial element accepts under a certain conceptual model. This relates to the clarification of location that the element has within the semantic structure which describes the domain of the conceptual model. Relations result from the associative connections between this element and the rest within the structure.[1] The same element can be subject to various conceptualisations under different models. A spatial element, for example, might be conceived as being: a partitioning element, therefore belonging to a system of

[1] See: 5.3. Relations between Images and Design Concepts.

enclosure; a load bearing element, therefore belonging to a system of structure; or a thermal storing element, therefore belonging to a system of energy performance. These various conceptualisations may entail various spatial relations.

Such distinctions are closely connected to *groupings* of elements in which sets of spatial elements are conceived as composing more complete or comprehensive elements. Spatial relations might refer to the connections under which these elements are composed into one. For example, a series of columns connected to each other by their close distance might compose a partitioning element. Groups, confronted as a single element, can be related to other groups or individual elements within the domain of the conceptual model. In a steel construction, for example, spatial relations refer to the inclinations and connections that occur between individual steel sections, i.e. struts and stanchions, as a consequence of stresses from loads. They also refer to the relations between the beam that the sections compose and the rest of the structural elements, such as the columns on which the beam rests or other beams in the structure.

An interesting aspect in the specification of a group is that it is not definite. It is not a case in which once the group is distinguished it is always confronted as a single element. Varied conceptualisations may occur in relation to varied models. Varied spatial relations may emerge among the elements of the group as a result from the relations of the group with other groups or elements, even in the context of a single model. In our previous example, a modification in the relations between the beam and another beam may entail changes in the relations between the steel sections. This aspect of grouping is evident in almost all kinds of groups of spatial elements. In the less complicated example of walls defining the boundaries of a room, a moving of the room to a new position may entail re-specification of the relations between the walls which compose it. Under another conceptual model, about the load bearing structure for example, the grouping of the walls into a room may not occur at all.

Operations refer to the application of knowledge in the context of conceptual models and non-spatial information upon groups or individual spatial elements. These are the factors upon which the specification of spatial relations is based. Operations result in the modification of the spatial distribution of spatial elements or their transformation, and they occur within the context of distinctive conceptual models. In our previous example, the application of loads upon the structure, and the stresses that they entail, results in the specification of the inclinations of the struts.

Operations on spatial elements are nothing else but the effects of the activation of cognitive operations under distinctive conceptual models to the extent that these refer to spatial elements and not abstract entities. Aspects of such operations are explicitly denoted in drawings by the employment of graphical symbols which themselves do not play any role in respect to the referential function of the drawings. Such is the case of arrows to indicate the forces that act upon spatial elements, for example.

The *qualitative attributes* of spatial elements emerge also as a consequence from the application of cognitive operations upon them and they can vary from highly abstract to concrete in relation to the models according to which they are construed. In drawings, there is a symbolic representation usually of those properties which refer to the matter of the element. Notations, symbols, patterns, and varied thickness of lines are employed to denote the material of the construction of a specific spatial element, to indicate its texture, or to annotate its role within the context of a distinctive conceptual model. A thick line may denote a solid element, hatching may signify concrete, a solid black pattern may indicate a structural element, an arrow may denote the main entrance, a piece of text or simply some characters may show that a particular element is important from the point of view of an energy performance model – 'TW' standing for 'Trombe Wall', for example.

Symbols are also used to denote moving spatial elements which for the case of architectural design are usually only doors and windows. Therefore, we can include them in the qualitative properties of elements. Moving elements are represented by lines showing the path of movement. It could be also the case that a moving element is depicted in more than one position.

We may now discuss the attributes that drawings obtain when they are used in order to express the conceptualisations that we have just seen.

Drawings in respect to their Denotative Function

From the point of view of the referential function all drawings as projections are essentially equivalent and similarly important, to the extent that a global description of the geometry of the designed object is required. From the point of view of the denotative function this might not be the case. Specific kinds of drawing, or even particular projections, might be more important or useful. In architectural design, for example, emphasis is given to plans, since the greatest impact on structural models of buildings is usually forces of gravity. However, in relation to a model of energy performance, section appears to be the most useful projection for the representation of aspects like sun rays, wind direction, etc. This is a direct effect of the involvement of conceptual models in the manipulation of drawings, since distinctive models refer to particular aspects of the designed object.

In an attempt to examine the impact that conceptual manipulations have on drawings, we may put forward a categorisation into synthetic, analytical, distributional and zoning, flow, intentional, and operational drawings, examples of which are shown in *Figure 9.3*.[1]

It should be noted that, even though different kinds of drawings might be distinguished, these are fluid and change according to design intentions. This categorisation is not all embracing, since according to the interests of particular design projects specific kinds of drawing may be used that cannot be approached outside the context of these projects. Also, it does not distinguish between drawings that are used in relation to intentions implied by several conceptual models and drawings that are specific to particular models, with the exception of synthetic and analytical kinds of drawing which are often used in the context of more than one model.

Synthetic drawings are simplified representations of the designed object or parts of it which stress the impact of operations under conceptual models on spatial relationships, and spatial and qualitative properties of elements. They help designers to articulate the spatial form in response to the specific factors in models that have a physical counterpart or can be exemplified, such as sun and air movements, wind directions, views, lighting, noise, thermal distribution, loads, etc. These drawings are composed by annotating simple orthographic projections or axonometrics with notes and graphical symbols, usually arrows in different forms, which indicate the force that these factors deliver to the object. The example in the figure shows a section which exemplifies the conditions underlying spatial composition in respect to energy efficiency. However, similar drawings may be used for the expression of components

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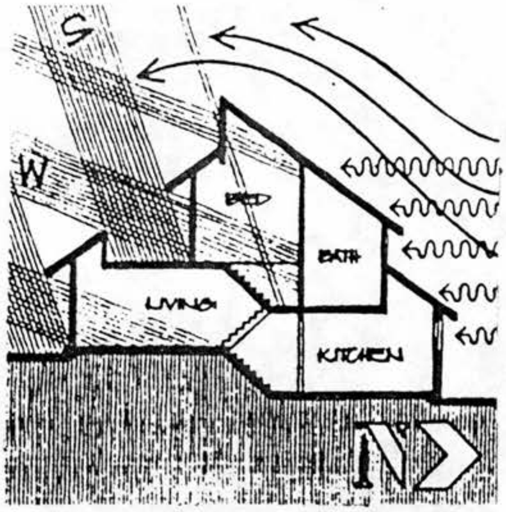
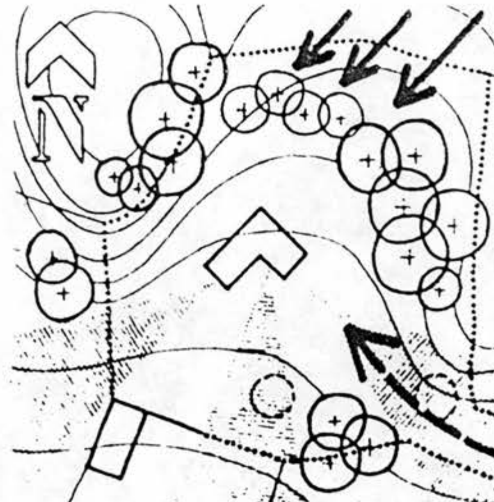
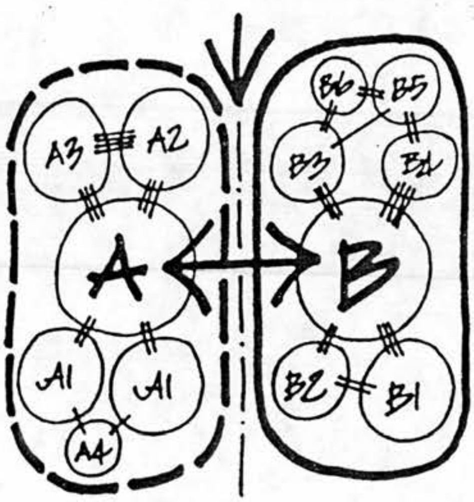
[1] A similar categorisation of conceptual drawings appears in: Porter, Tom, 1979, pp.62-65. The drawings A, B, and C, in the figure, are by the architect William Tilson from the same source. Drawing D is from the work of Le Corbusier for Villa Savoye in Poissy, France; source: Benton, Tim, 1987, p.196. Drawing E is by the architect Bernard Tschumi for the new National Theatre of Japan, Tokyo; source: Tschumi, Bernard, 1989, p.12. Drawing F is from the work of Santiago Calatrava for the Jakem Warehouse in Münchwilen Aargau, Switzerland; source: Blaser, Werner (ed.), 1989, p.70.



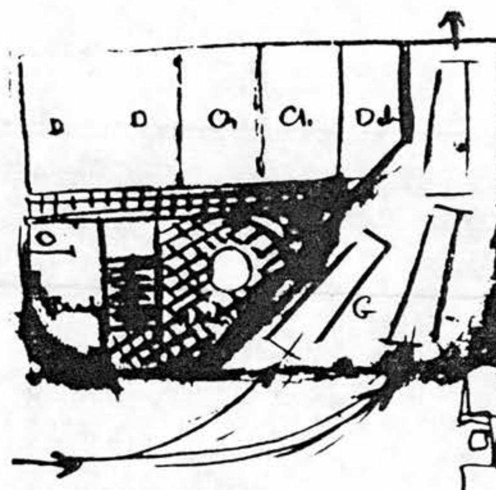
A: Synthetic Drawing



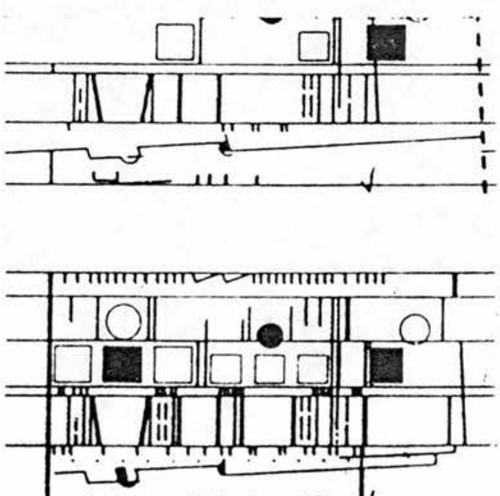
B: Analytical Drawing



C: Distributional Drawing



D: Flow Drawing



E: Intentional Drawing

F: Operational Drawing

Figure 9.3

of other conceptual models or incorporate factors which could be applicable to the context of various models.

Analytical drawings are used in early stages in designing to visually identify and connect the information which is related to the designed object. They have a direct influence in the evolving conceptualisation of this information, and they help to initially specify design intentions. Their function lies in the investigation of the nature of the existing constraints and conditions, rather than evaluating their effect in the spatial form, and they often refer to the physical environment of the designed object. They are usually plans of the site, where the building appears only schematically, and graphical symbols represent plantation, slopes, orientations, access possibilities, etc. Such information may turn up to be important for several design models.

Distributional drawings identify the proximity and the kinaesthetic relations of areas of activity. In early stages in designing they may have the form of 'bubble diagrams', like the one shown in the figure, representing areas in rough round shapes, which become more finite as the design evolves. While they most often refer to the horizontal distribution of the building, they are also used for distribution in the vertical direction.

Similar to distributional are the *zoning* drawings which are used to specify different zones in the distribution of a building, like zones of private and public areas or other. Zoning drawings are usually specific to particular models involving a division of space relevant to aspects of these models. Such is the case of drawings showing zones of warm and less warm spaces, a categorisation of areas related to thermal performance.

Flow drawings, like operational ones, incorporate the fourth dimension in attempting to indicate changes in time. They are used to study directions, intensities, conflicts, and possibilities which arise when movement is considered between one point and another inside or outside a building. They often refer to pedestrian or vehicle circulation, but they can be used also to study the flow of information, air distribution in air conditioned buildings, water and heating currents, etc. Flow drawings emerge from the superimposition over orthographic drawings, usually plans and sections, of diagrams representing the relevant information.

Intentional drawings as a term is used to classify a wide variety of drawings which are used to communicate or exemplify intentions which refer to factors that do not have explicit physical or perceptual counterparts. They may indicate abstract concepts which are taken into account in the development of the designed object that could relate to philosophical theories, symbolisms, obsessions with geometry or specific architectural ideas, references to the work of famous architects, etc., which are relevant to aesthetic considerations. The drawing shown in the figure, for example, attempts to indicate a relation between the spatial distribution of a building and music notational schemes. Such drawings mostly employ artistic forms of expression, such as the incorporation of pictures or photographs in drawings, the superimposition of multiple views in a single graphical form, the use of unconventional or even non-architectural notational systems, etc.

Operational drawings are used to exemplify changes in time or sequences in the operation of, usually, parts of a designed object. They are perhaps the most rarely used for static objects, like buildings, but they may be used to explain the order of construction or the mechanics of the object. Operational drawings focus on the detailed articulation and structure of components of the designed object. They often appear in axonometrics or perspectives and they may employ specific drawing techniques such as 'sequential', 'exploded' or 'x-ray' drawings. (When the same element is shown multiple times in a single drawing modified each time in relation to the conditions that are applied to it, as in the figure, when the components which compose the object are depicted as they have been taken apart, and when projections in several planes are incorporated so that the viewer is as if were looking through the object, respectively.) Operational drawings appear to take into account conditions specific to a single conceptual model.

Usually these kinds of drawing are made in order to explore the connections between spatial forms and specific conceptual models. However, a single drawing may incorporate information that is important from the point of view of more than one model. This is a result from the interconnections of conceptual models which become evident when they are applied to spatial forms.

When drawings are used in the context of particular design models, taking forms similar to those that we have just seen, graphical symbols are employed that denote specific aspects of the model in hand, like for example the direction of sun rays, the direction of winds, etc., in addition to the symbols used to denote spatial elements like walls, doors, and so on. There are symbols which may have a conventional meaning attached to them, like for example a particular pattern standing for a particular material for the construction, say brick, or concrete. These symbols indicate distinctions that are imposed on spatial elements from conceptual models.

However, with the exception of this particular kind of symbols, we can say that, even in cases of conceptual drawings in as much as all other kinds of design drawings, there is no a clear distinction as to which are the conceptual entities that are represented. In other words, there is nothing in the drawing telling us that an arrow, for example, stands for the direction of sun rays and not for the direction of views from the building. This is particularly the case for spatial elements which may even have diverse forms of expression. A wall, for example, can be denoted by one, two, four lines, etc. Generally, we can say that graphical symbols explicitly denote spatial concepts, like for example, boundaries, directions, orientations, axes, densities, etc., and indirectly verbal concepts by the application of qualifications in respect to conceptual models to symbols. To this extent, to say that a line denotes a wall is a qualification of a boundary that is explicitly represented by the line. Qualifications are also expressed by relations between such symbols. When a designer, for example, draws an arrow pointing to a line, she or he wants to express a condition that holds between the concepts that the arrow and the line represent.

This points to two important implications. On the one hand, relations between graphical symbols take part in the denotative process, in a way which contrasts with a verbal notational system in which the relations that specify the form of the expression are specified by syntactic rules that are independent of the meaning that this expression has. On the other hand, as there is no conventional meaning attached to symbols, there might be problems of ambiguity in the interpretation of the expression. How, for example, do we know that a boundary is seen as a wall and not something else?[1]

However, if we consider the role that drawings play in designing, both of these aspects can be regarded as the virtues of drawings. As the objective of spatial composition is the fit between spatial forms and various conceptual models, on the one hand, there must a way of expressing spatial relationships, and, on the other, there must be a representational scheme of spatial forms which can accept qualifications in respect to various conceptualisations and not be determined by a particular view. We

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1 Both of these aspects are discussed in a more general way, in the context of an examination of the differences between verbal and graphical representations, in: 5.4. Drawings as Representations; The Features of Drawings and their Structure.
For the condition of ambiguity in drawings see: Lee, John R., 1988. A general discussion on ambiguity in linguistic systems can be found in: Scheffler, Israel, 1972.

have seen how inflexible become drawings when they are determined by a particular view, as in the case of computerised systems.

How are graphical symbols and relations between them specified, and how do designers interpret drawings without problems of ambiguity? This can be examined if we consider the context within which drawings are used. In other words, their connotative function.

9.4. The Connotative Function of Drawings: Significant Schemes

The connotative function of expressions is approached in the field of semiotics as a relation of signification between an expression and its meaning, and further meaning. In other words, connotation occurs when both a signifier and its signified become at a second level a new signifier that points out to a new signified. This second signification is based on what an interpreter knows about the first one.[1] *Figure 9.4* attempts to illustrate this relation and the example with Apple's logo in the beginning of this chapter demonstrates how it can occur. As such, the symbol as an expression at a first level (the lower level in the figure) signifies a half eaten apple. At a second level (higher in the figure), the half eaten apple points to concepts associated with the use of Apple computers rather than apples.

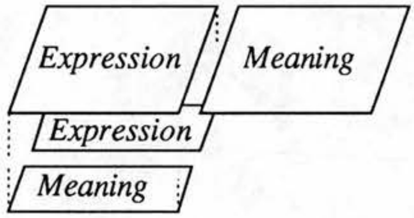

Figure 9.4

This definition of connotative relations suggests that connotative signification is not necessarily associated with vague and obscure meaning. It also indicates that the context within which the first signification occurs is taken into account by the second.

In the context of our discussion of design drawings the first signification is achieved through the denotative and referential functions of drawings. Through the denotative function of drawings there is an expression of distinctions about spatial forms. Drawn objects, by taking properties that actual spatial objects possess through their referential function, become analogues of spatial forms. Then a second

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1 See the discussion in: Eco, Umberto, 1976, pp.54-57.

signification occurs, according to which spatial forms, and not drawings any more, accept qualifications through connotative relations. It is the connotative function of drawings which connects the two previous functions and allows design knowledge in the context of various conceptual models to be applied to spatial forms and in consequence to drawings.

Physical Forms and Significant Forms

To see how the connotative function of drawings emerges and how design knowledge can specify the relations between graphical symbols, we have to look at the ways in which drawings are interpreted during their use. We may introduce a model of the interpretation of drawings that takes into account the context of discourse within which the interpretation occurs. This can be specified by the attention and the intentions of the interpreter.[1] To the extent that the denotative, referential, and connotative functions of drawings are interconnected during the use of drawings, this approach will clarify relations between the different distinctions that are imposed in drawings in respect to these functions, and will indicate the ways according to which ambiguity is reduced during the use of drawings.[2]

We can assume that a first interpretation of drawings is based on their denotative and referential function which allow the interpreter to initially correspond drawn configurations to spatial objects and comprehend the spatial form of the designed object. However, as we have seen in the discussion on the interpretation of drawings, interpretative processes occur at different levels.[3] The connotative function of drawings establishes further relations of signification between the spatial forms and the conceptualisations according to which they are manipulated. In other words, further interpretations of the same drawings develop, the context of which is provided by verbal conceptual models, to the extent that manipulations of spatial forms depend on them. The manner according to which conceptual models organise the spatial information occurring in drawings relates to the manner according to which they

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1 The semantics of graphical information as an outcome of some established context of discourse are discussed in: Bijl, Aart, 1988.
For a discussion about the attributes of discourse, in general, see: Grosz, Barbara J. & Sidner, Candace L., 1986.

2 This discussion builds upon our early approach to the interpretation of drawings by relating it to theories of meaning from the field of semiotics. A comprehensive theory about meaning in designing, which is taken into account here, is provided in: Bonta, Juan, 1980.

3 See the discussion in: 5.3. Relations between Images and Design Concepts; Levels of Interpretation and Components of Meaning.

organise the perceived information during the presentation of the design task in the initial stages of designing.[1]

This indicates that relations between specific graphical symbols can vary since different qualifications are applied to them in respect to different conceptual models. It is suggested that this is indeed the case, but if the context of the interpretation is given, in other words if one conceptual model is taken to condition the interpretation at a time, then it can be assumed that certain relations become more evident than others.

To see how the context of the interpretation is involved, let us say that the totality of the features which are directly or indirectly perceptible in a drawing constitute the *physical form* of it. These are all the graphical symbols that compose the drawing, such as lines, points, shapes, etc., as well as their properties, such as length, width, thickness, colour, etc. Within a specific context only a subset of these features has some meaning. The colour of a line, for example, might have no meaning in the context of a structural model of the designed object. We can say then that the *significant form* of the object is an abstraction of the physical form which includes some of its features, those which have meaning within a particular context, and excludes the rest.

Significant schemes, as discussed earlier,[2] define the ways according to which significant forms are abstracted from physical ones. Significant schemes, acting as binders of cross-level relations between the different levels of interpretation, connect conceptual models and graphical symbols. Within a specific context, a significant form is the external counterpart of a significant scheme. It includes only the appropriate features of the physical form, and refers to the bottom level of interpretation. Significant schemes include components of meaning, and relations between the significant form and conceptual models. We can say that the physical form realizes or admits a significant scheme and that a significant scheme organizes or analyzes the physical form, so as to obtain the part of the physical form that relates to a significant scheme, the significant form.

To the extent that a significant scheme takes into account the relations that occur between components of conceptual models, it also determines the relations between symbols in the physical form on the basis of which significant forms are composed. In other words, certain relations between elements of the spatial form are

1 See: 3.2. Models of Discourse.
2 5.3. Relations between Images and Design Concepts; Significant Schemes.

conditioned by the particular conceptual model that specifies the context of the interpretation, and these relations are recognised in drawings.

One single significant scheme can correspond to diverse physical forms. For example, the symbol of the north direction can be drawn in a number of different ways but whatever its appearance its meaning could remain the same. The significant scheme characterises in all of the cases that orientation is the only feature of the symbol that belongs to the significant form, and takes part in the signification. Similarly, for a particular significant scheme it might make no difference whether a window on a plan is drawn with two, three or four adjacent parallel lines, in as much as the meaning of the lines is simply 'window'.

What is important for the case of drawings is that various significant schemes can correspond to a single physical form. This is because the features of the physical form are distinguished and abstracted according to some particular meaning, determined by a conceptual model, and meaning regulates the components of significant forms.

Even a specific geometric figure can have different significant forms. Consider, for example, the case in which we are interested in the construction of a certain oval metallic section. If we are thinking in terms of construction by pressing, we recognise in the depiction of the element in the drawing the feature of being an oval. In other words, there is a significant form which takes into account only one feature in the physical form, that of being an oval. If we are thinking, however, in terms of construction by hammering, we might conceive the depiction as being a flattened circle. In this case, there is another significant form which recognises two features, that of circularity and flatness.

Example of Significant Forms

To examine the connections between physical and significant forms, as well as the manner according to which relations between graphical symbols are realised in drawings, let us consider a worked example which has to do with a presentation drawing to indicate that the distinctions put forward above hold not only for drawings that explore particular aspects of spatial forms but also for drawings that incorporate a variety of information. Although the following discussion suggests particular ways of interpreting drawings, it should be noted that significant forms are abstracted according to designers' intentions. They are not stored as parts of drawings, retaining relations of signification, but they come and go throughout design process.

The drawing in *Figure 9.5* is the final plan of the ground floor of a small house. Someone can initially perceive on the drawing marks with ink on a paper which is the physical form. The context of the first interpretation of the drawing is obtained through the denotative and referential function of the drawing, so that we can recognise that the physical form of the drawing realises the spatial form of a building. Accordingly, we can distinguish in the drawing graphical symbols, their properties, and relations between them which constitute the significant form of the drawing in respect to the significant scheme of a spatial model of the building. The significant form corresponds to components of meaning within the spatial model, such as boundaries and spaces, and properties of them, as discused earlier. Note that the rest of the features in the physical form, for example, characters, texture, etc., do not take part in this signification.

Once the spatial form of the building is recognised, further interpretations of features of the spatial form occur in relation to verbal conceptual models. In respect to a structural model, for example, a new significant form of the drawing is abstracted which recognises in the physical form only those features that correspond to components of meaning within the structural model of the building. A possible abstraction of a structural significant form of the drawing can be seen in *Figure 9.6*.

Consider that the significant scheme in relation to structure organises not only the relations between different graphical symbols in the drawing, but also between primitives of graphical symbols. Four lines, for example, are grouped together to realise a concrete column, and the square that they compose is connected to the lines realising a brick wall, since concrete columns support brick walls.

Another significant form can be abstracted in respect to the distribution of areas in the house. According to this, other features like the names of activities are taken into account, as in *Figure 9.7*. In this case, consider that relations between lines composing a column, as well as lines composing a wall, are not realised in the drawing, but instead the whole set of these lines are grouped together to denote an area and realise the shape of it.

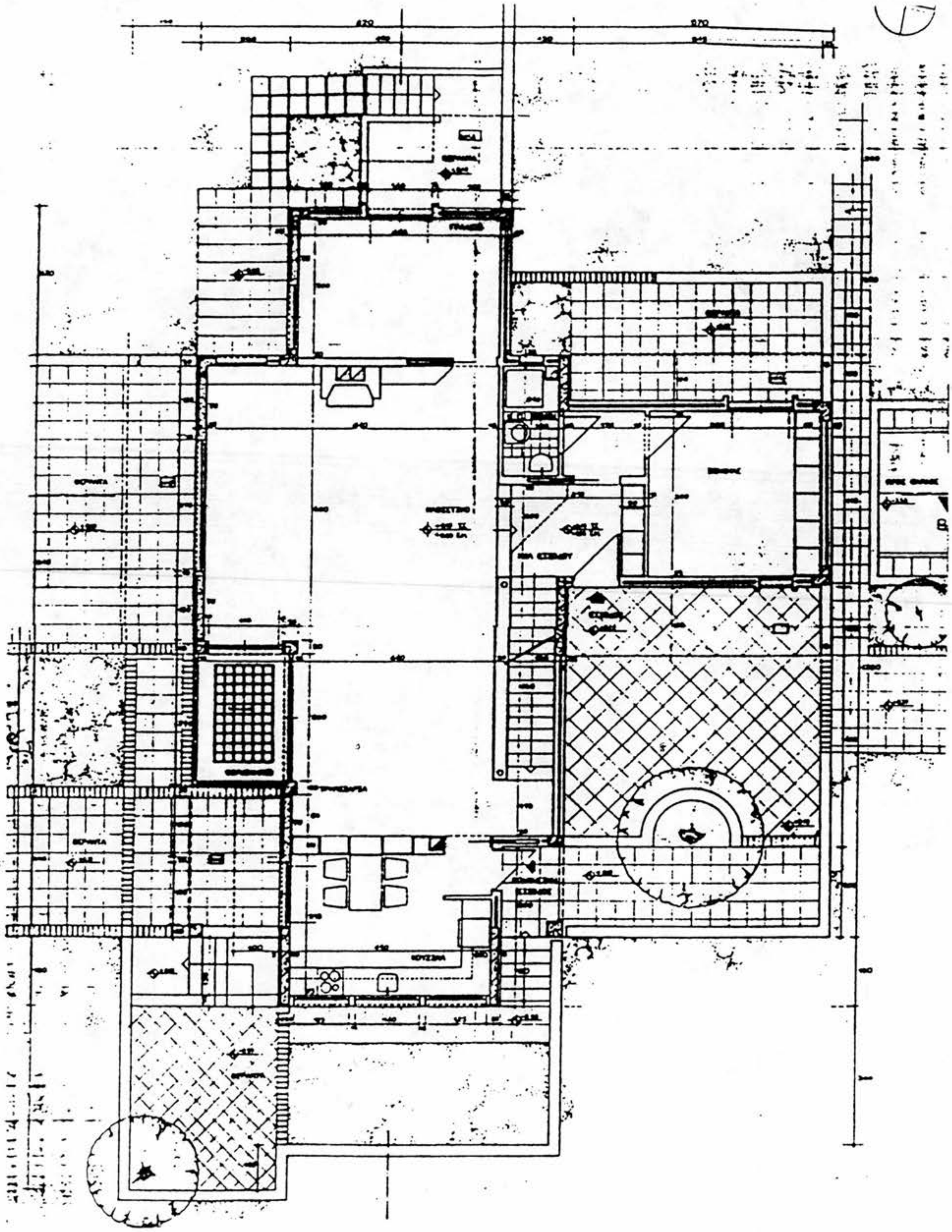

Figure 9.5

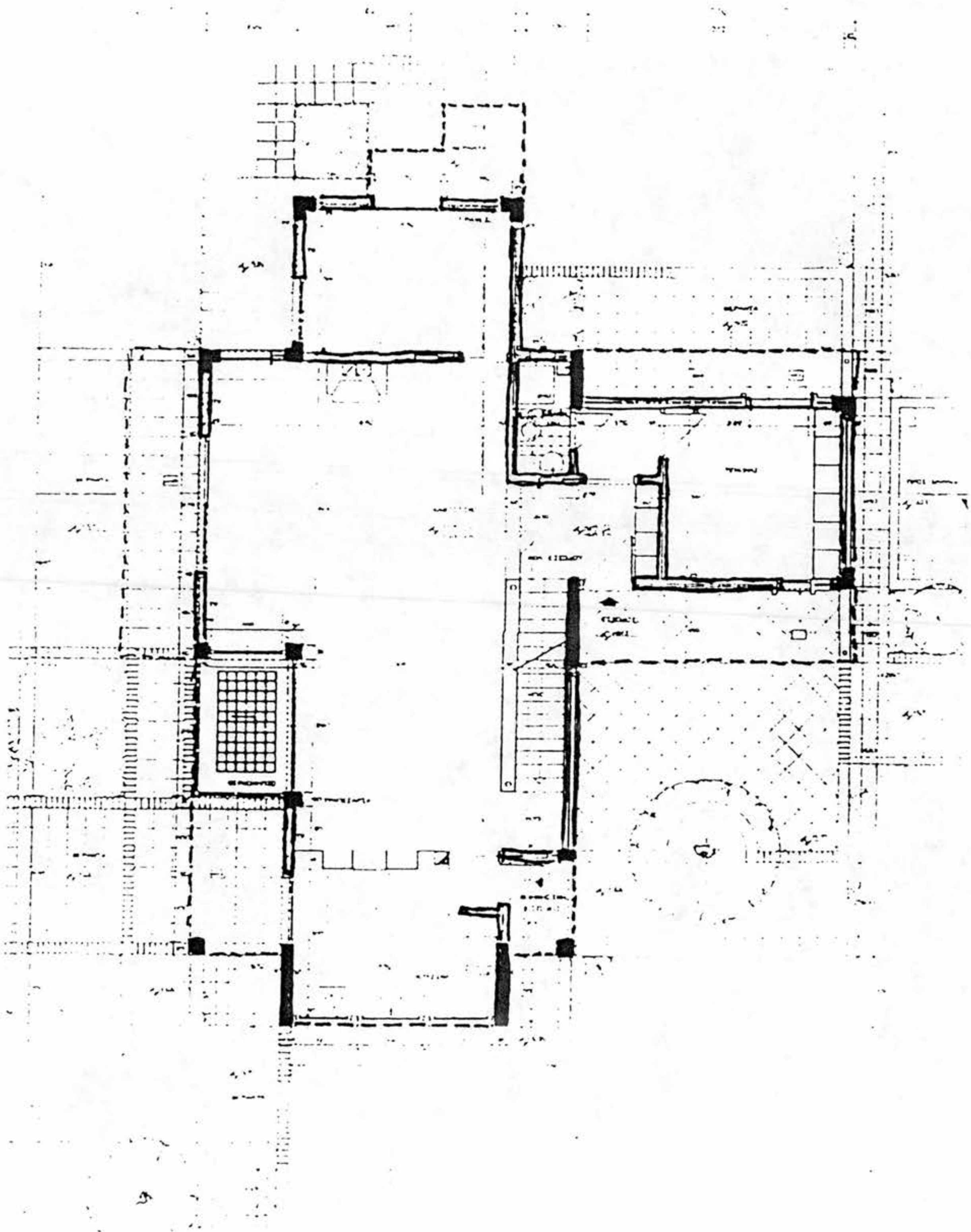

Figure 9.6

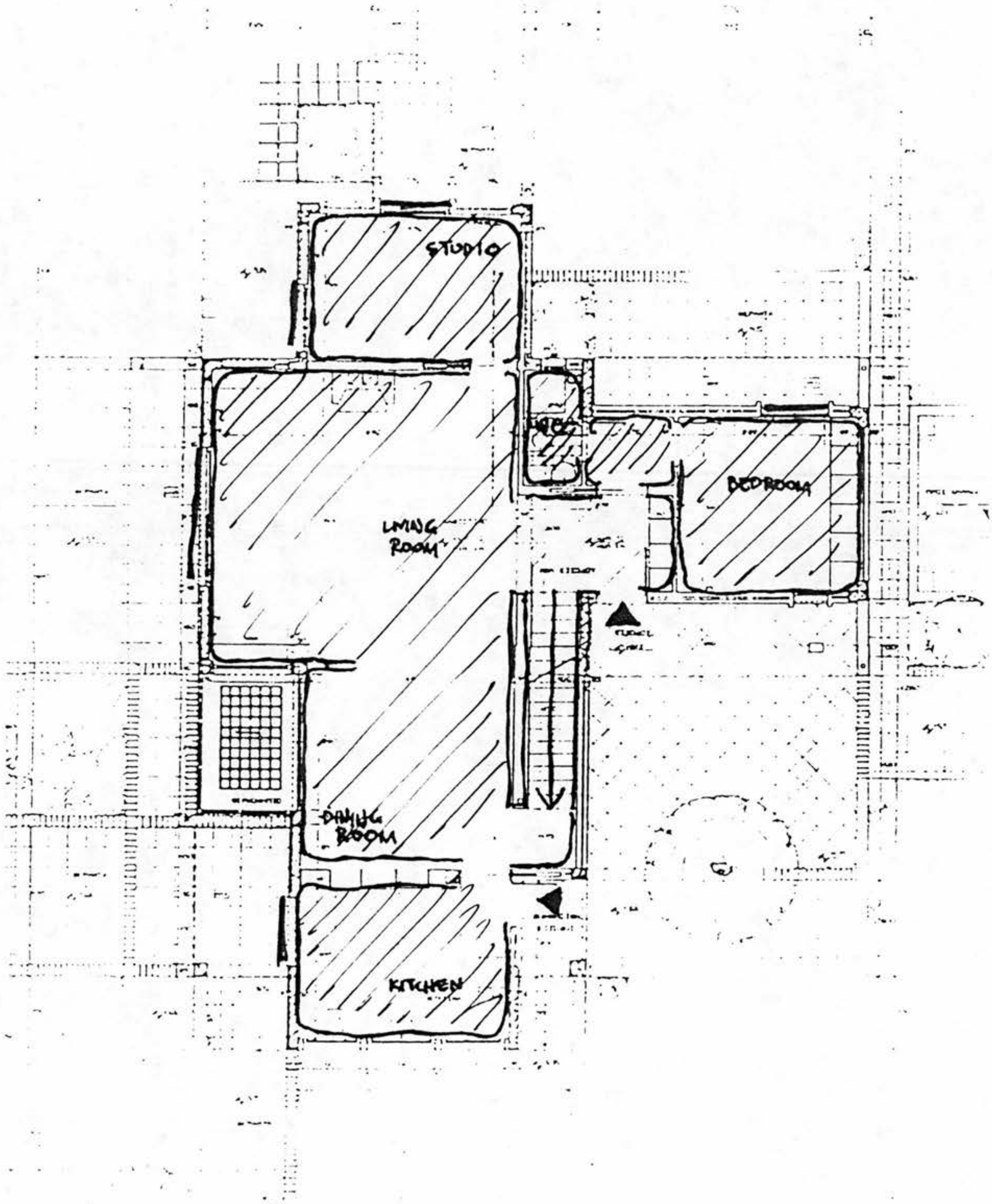

Figure 9.7

Another significant form in respect to the thermal performance of the building, appears in *Figure 9.8*. Here, we are concerned ourselves more with the outer skin of the building rather than lines realising columns or even areas. Note how significant schemes specify not only which symbols in the drawing belong to the significant form, but also which properties of the symbols take part in the signification. For example, while certain depictions might belong both to a significant form that corresponds to the structural significant scheme and to another one that refers to thermal performance, the orientation of the symbols in respect to the former could be irrelevant although the same property is highly relevant in respect to the latter.

This discussion on the interpretation of drawings suggests that structural assertions in drawings depend on the context of use of drawings. Different qualifications of the features of drawings apply during different stages in designing, according to designers' current interests. To justify our view that the context of the interpretation specifies the relations of signification in drawings, we can compare the significant forms in *Figure 9.6*, and *Figure 9.8*, to conceptual drawings made to explore possibilities in the spatial form solely in the context of a structural model, shown in *Figure 9.9*, and in the context of a model of thermal efficiency, *Figure 9.10*. These were produced much earlier in the sequence of design expressions.

There may be some difficulty in approaching the features of the physical form that take part in the signification, since significant form is seen as the set of features that affect meaning, and meaning as the values susceptible to being modified by changes taking place in the form. And some circularity is involved: there must be a context, a conceptual model, in order to distinguish the features in the physical form that constitute the significant form, and the components of the model are modified once the significant form is abstracted. To express this in other words, something in the drawing tells us that relations in the context of a model of structure, for example, are expressed – which in most cases can be attributed to those graphical symbols that have a conventional meaning attached to them, like patterns denoting concrete – and once this conceptual model is taken to condition the interpretation, further distinctions in respect to this model are realised. But, nevertheless, this condition is a reflection of the suggestion upon which the approach to the use of drawings is based from the beginning of the thesis: the structure of drawings tells us something about the way drawings are used, and the way according to which they are used specifies their structure.

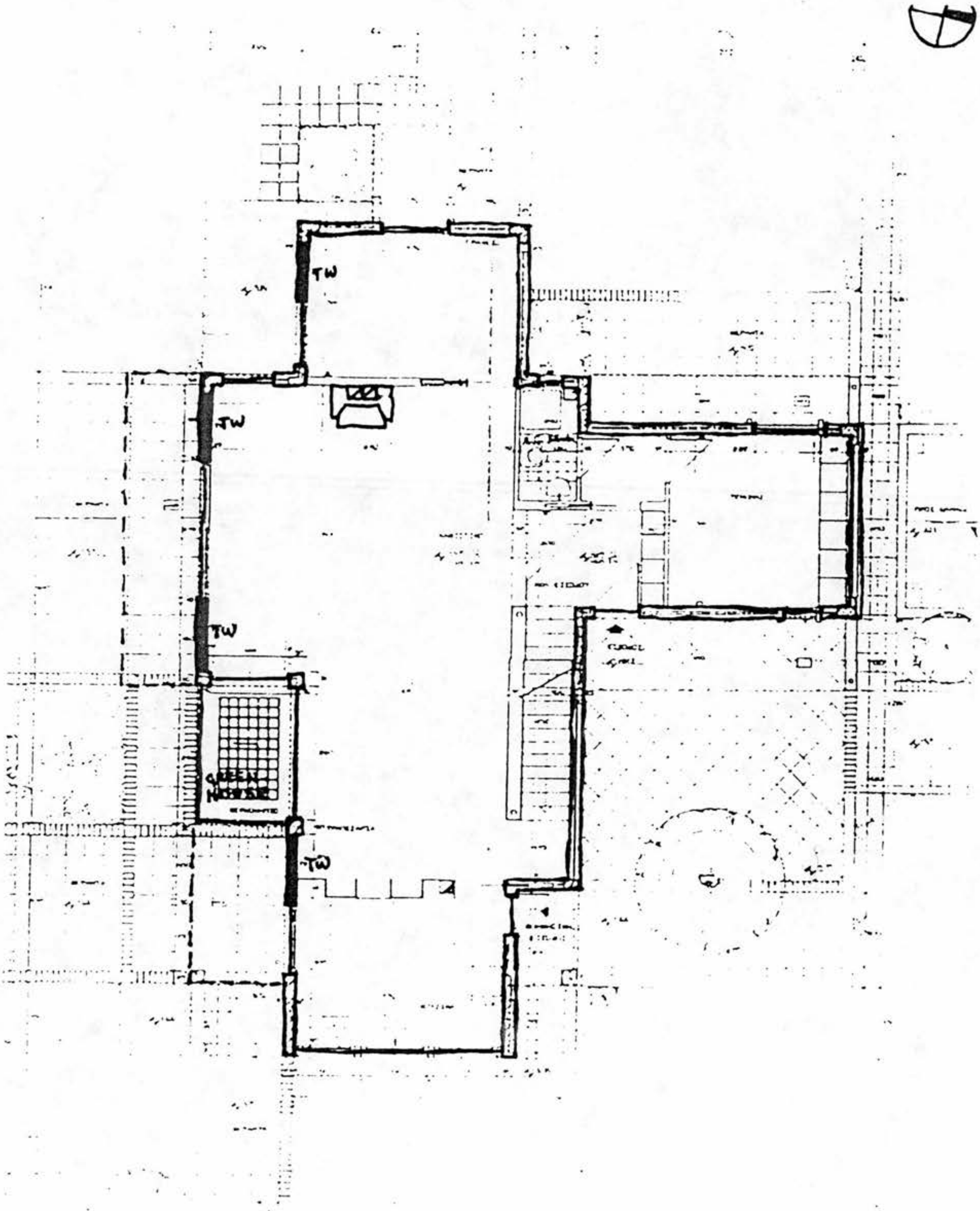

Figure 9.8

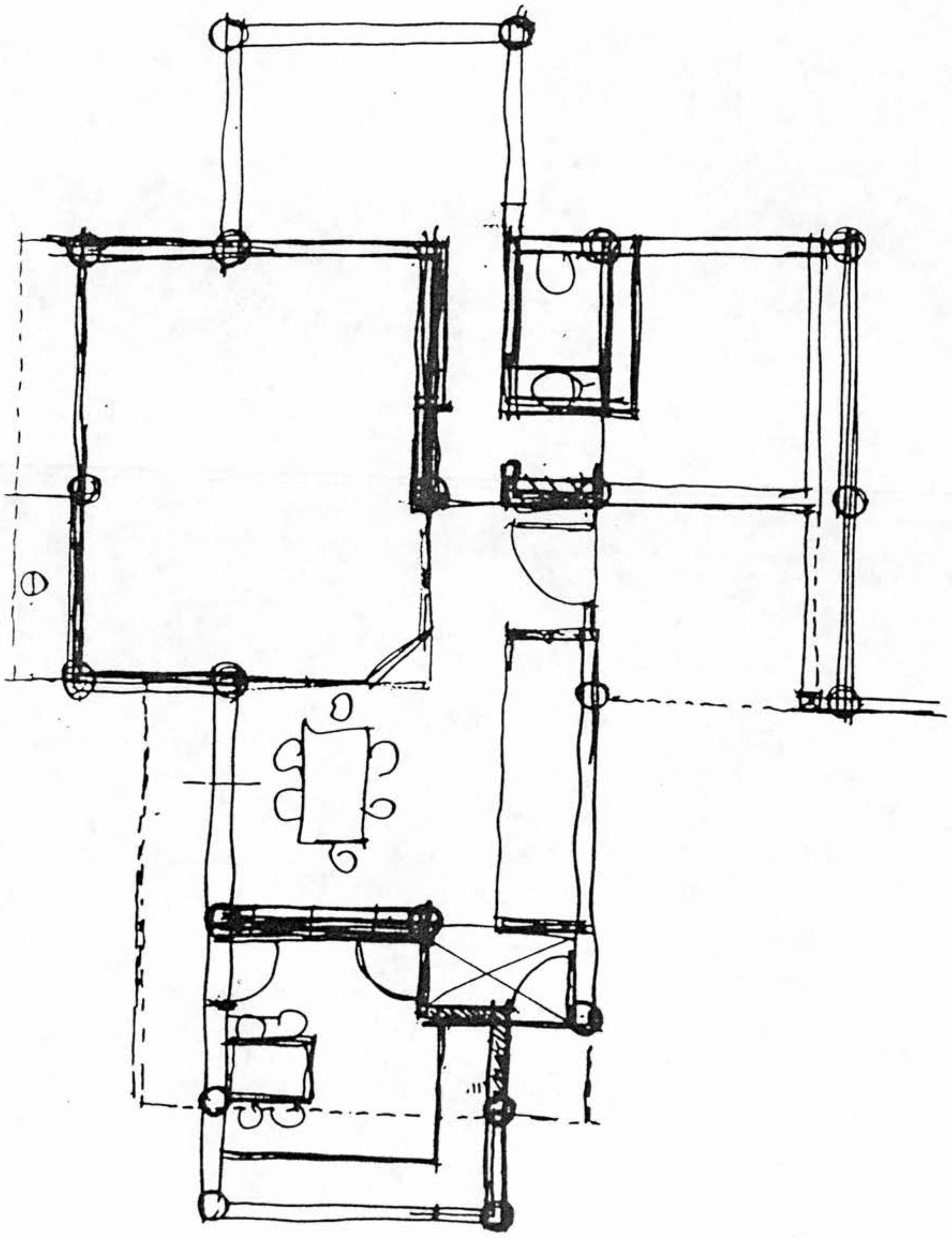

Figure 9.9

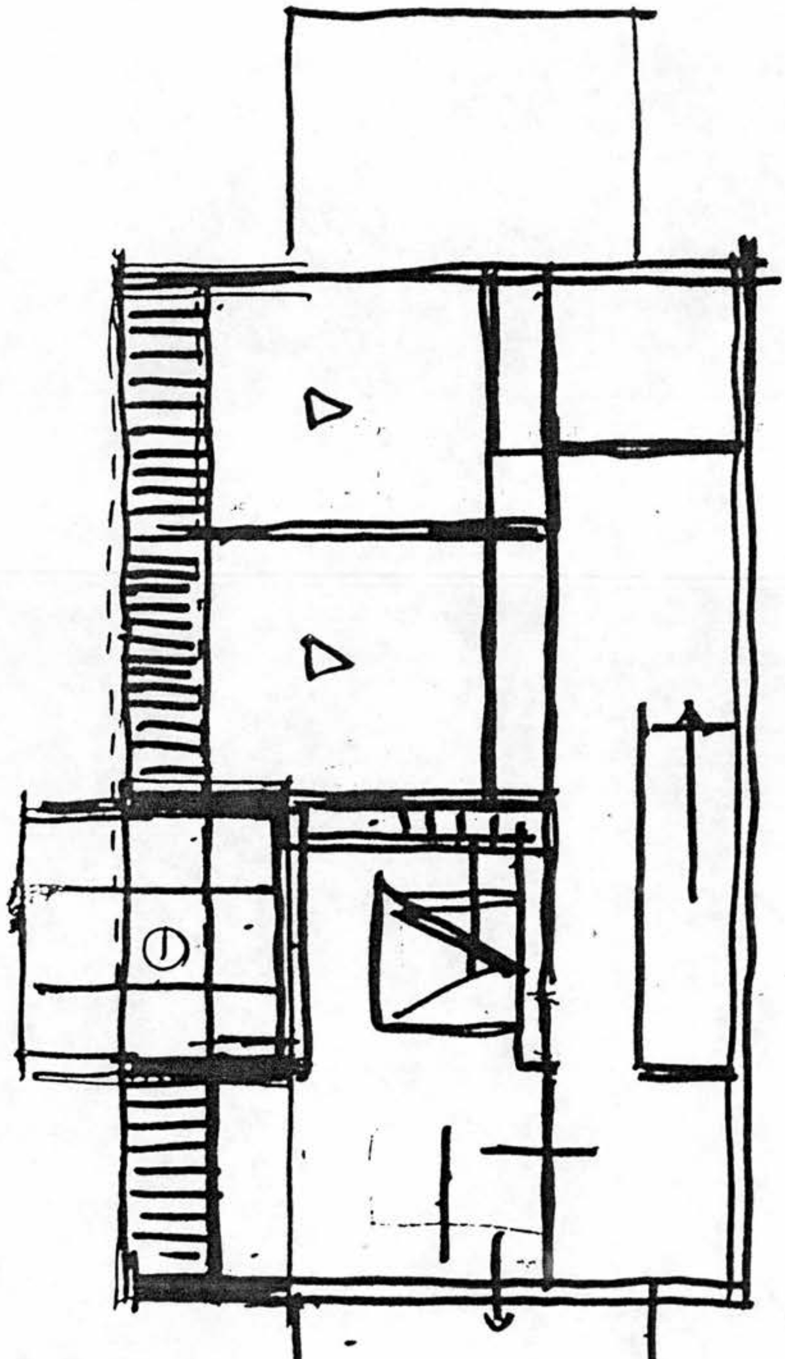

Figure 9.10

Ambiguity and Polysemy

Before closing this chapter, let us go back and discuss the phenomenon of *ambiguity* in respect to the distinctions above. Ambiguity can appear at both the physical form level and the significant form level. In the first case, it emerges as an inability to attach a particular context to the features of the physical form according to which a significant form can be abstracted. This is a case that rarely occurs in design drawings, where the intentions of the interpreter are usually transparent and where analogical mappings of knowledge to drawings are obtained in relation to certain conceptual models. Conceptual models can be specific to individual designers and their components might be difficult to capture. However, the clarification of the relations in drawings which are mapped to corresponding relations between such components can be achieved, as it has been indicated.

Ambiguity at the significant form level, appears when a single significant form admits various meanings. It is a case where within a specific context of meaning, specified by a specific conceptual model, certain features of the significant form are not clear as to which components of meaning correspond. This kind of ambiguity emerges mainly in the context of the spatial form where certain depictions in a drawing might correspond to different and even diverse spatial arrangements in a designed object. What in most cases appears in drawings is the phenomenon of *polysemy*. Polysemy occurs at the physical form level, when a single physical form realises various significant forms each of which corresponds to one context of meaning. This refers to the case where several significant schemes could apply to a single physical form so that several significant forms can arise.

To understand the differences between polysemy and ambiguity, consider the example where someone has different dictionaries, each one specific to a particular context, in order to find the meaning of words in a text. Polysemy is the case where the reader knows that more than one dictionary applies to a given word, and a single meaning is assigned to the word in relation to each of the dictionaries. The first case of ambiguity appears when the reader does know which dictionary the word refers to. It might be known that more than one dictionary applies, but she or he does know which to choose for the specific case. The second case is when the reader knows the dictionary that applies to the word, but in this dictionary more than one meaning is assigned to the word.

Ambiguity is an unwelcome condition that leads to problems in the interpretation of drawings. Polysemy, however, is a highly desirable condition for designing as by virtue of it the manipulation of a single spatial form, as it is represented in design drawings, can be achieved in respect of several conceptual models.

9.5. Summary

In the previous chapter, the role of drawings in designing has been connected to the particular task of examining and developing the spatial form of the designed object in accordance with implications that result from operations within the context of verbal conceptual models. The spatial form of the designed object becomes the plane where distinctions in relation to conceptual models are realised, and drawings exemplify the fit between spatial arrangements and conceptualisations. It has been suggested that drawings manifest the exploratory task of spatial composition through the referential, denotative, and connotative functions that they acquire during their use.

To see how these functions are developed, in this chapter, we have examined the sequence of drawings in design activity and we have characterised different kinds of drawings in respect to the referential and denotative functions. Subsequently, we have studied the different attributes that drawings manifest during their use, and the methodological tools on the basis of which drawings are made, in relation to these functions. An approach about the connections between the structure of drawings and the manner according to which they are used has been developed.

The referential function of drawings becomes more evident towards the completion of the design task but it may emerge from early stages in designing. It is based on qualifications of drawings that are implied by design conceptualisations about spatial objects and it is exemplified mainly by the employment of drawing operations derived from descriptive geometry, grids, and construction lines.

The nature of spatial properties and relations are taken into account by the denotative function of drawings. The denotative function continues to characterise drawings in final stages of designing even though it is the one that emerges earliest. It is based on distinctions in the context of conceptual models and there may be kinds of drawings that are made in order to explore relations between components of distinctive models. Even though drawings capture such distinctions, the graphical symbols by which they are composed remain abstract in character, explicitly denoting spatial entities rather than verbal conceptual. This might lead to problems in the interpretation of drawings and ambiguity.

To see how such problems can be resolved, we have looked at the connotative function of drawings which takes into account the context of use of drawings. If drawings are confronted against an established context of discourse, the qualifications that they accept in respect to their referential and in particular denotative function become more transparent, and properties and relations of graphical symbols are realised. A model of the interpretation of drawings that incorporates their context of use has been proposed based on the notion of significant schemes.

The chapter develops and integrates our early approaches about the structure and the interpretation of drawings by taking into consideration qualifications that drawings obtain during their use. In the following and closing chapter, the implications of this account will be related to the systematic representation of drawings in computers.

10. Design and Computerised Drawing Systems

In the previous chapter we have developed an approach to the qualifications that drawings obtain during their use, in respect to the functions that they serve in designing. Such qualifications impose distinctions on the attributes of drawings and the manner according to which they are decomposed and interpreted. In this chapter, we will discuss the implications of this approach on the systematic representation of drawings in computers.

Although observations on the employment of computerised systems have already been made in our earlier examination of the use of such systems in design tasks, this chapter will present a theoretical discussion of the limitations that drawing systems manifest. These will be linked to the task of initial specification of the features of drawings that systems might represent.

This chapter concludes the thesis by suggesting possible directions for future research. This part of the discussion takes into account systems that link the accomplishment of drawings with abstract conceptual design processes, or employ rich representational schemes that recognise the qualifications of symbolic structures in drawings related to design knowledge.

10.1. Design Expressions in Computers

In our early discussion on representation, we have seen that Palmer's view on "feature" representations characterises the systematic representation of drawings in computers. This approach recognises that drawings are composed by graphical symbols whose properties and relations are mapped to corresponding properties and relations in the represented world.[1]

At a theoretical level, we have accepted that this approach can form a basis for the systematic representation of drawings. However, by looking at the attributes of computerised drawings, we have seen that practical aspects in the implementation of drawing systems entail distinctions with respect to this approach. The concern for effectiveness of drawing operations leads to a series of considerations that have to be taken into account.[2] These considerations can be generalised under the following two issues. Firstly, which are the properties and relations between symbols that take part in the representation, and secondly, how can mappings between these features of drawings and represented objects be specified beforehand? The latter point is critical since features of designed objects are in fact what is required in designing.

To address these issues most drawing systems take the view that graphical representations are geometric configurations. There is a specification of the structure of drawings according to which properties and relations of drawn objects are determined by generalised geometric knowledge. This view includes assumptions about the decomposition of drawings into graphical symbols, equivalent to geometric objects, as well as the decomposition of graphical symbols into primitives.[3]

Recognising, however, that drawn configurations accept mappings to designed objects, drawing systems offer a range of transformations on the basis of which, on the one hand, modifications can be made, and, on the other, relations between graphical symbols can be accomplished, like the implementation of groupings. These transformations take into account aspects of organisation of drawings in the form of sub-models or layers.

Despite the fact that such transformations are specified by designers, it became clear, from our discussion on the use of computerised systems in designing, that issues about properties of symbols, decompositions, and transformations are interrelated to each other. So, for example, transformations depend on views about the decomposition of drawings and affect the geometry of the configuration. To this

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1 5.2. Kinds of Representation; The Representation of Images: Analogical Representations. See also: 5.4. Drawings as Representations; The Features of Drawings and their Structure.

2 See: 6. Drawings in Computers.

3 From this account, we may exclude bit-map systems which we can say accept drawings as geometric configurations, so they offer graphical symbols that stand for geometric objects, but there is no provision of relations on the basis of which such objects are composed.

extent, we may say that the view that drawings accept qualifications mainly in terms of geometric knowledge does determine what can be done by drawing systems. Groupings are specified on the basis of conceptualisations that do not concern geometry, but even they seem to depend on geometric decompositions.

This issue contrasts with our approach on the qualifications that drawings accept in relation to their referential, denotative, and connotative functions. The main aspect of this approach is that during designing knowledge in the context of conceptual models conditions how drawings are used and specifies their structure. This aspect becomes apparent by examining handmade drawings in which there are no structural assertions embodied in the drawing environment.

In a subsequent part of the chapter, we will see what our approach entails for the systematic representation of drawings. At this point, however, following the discussion on the functions of drawings in the previous chapter, we will look at the implications for designing of using computerised drawing systems.

Computerised Drawings and Spatial Composition

In our discussion on the accomplishment of spatial forms, we have seen that spatial composition is characterised by a search for a fit between spatial forms and conceptual models. Within this task, geometric articulation is a final objective. Geometric knowledge is applied to spatial forms mainly in order to achieve geometric consistency, in order for the condition of soundness of spatial forms to be satisfied. However, even the geometric features of spatial forms are initially approached through aspects of conceptual models.

Sequences of design expressions indicate that drawings are initially used in order to manifest conceptualisations, to express relations between components of conceptual models, to explore the effects of conceptual models on spatial forms, and finally to exemplify geometric properties and relations. This progression follows a top-down approach to the specification of spatial forms, with drawings acting as an intermediate stage between forms and conceptualisations. Drawings are models of spatial forms upon which knowledge in the context of conceptual models is applied.

The view that drawings are conditioned by geometric knowledge recognises only the qualifications that spatial forms accept in respect to geometry. Drawings, and in consequence spatial forms, are disconnected from assertions in conceptual models, with certain implications for both spatial composition and the making of drawings.

To be reminded of drawing operations in computers, consider, for example, that graphical symbols are chosen from palettes by virtue of their features. To the extent that symbols stand for distinctive components of spatial forms, this first of all implies that there is an analysis of spatial forms into geometric elements. However, a definite analysis of spatial forms is met only in late stages in designing. The geometric features of spatial forms and their components are approached in relation to tendencies in various conceptual models. Thus, the choice of a graphical symbol will have to be conditioned either by a single conceptual model, in which case there will inevitably be subsequent changes, or several models, a case which implies that the spatial form is already established.

Changes can be encountered by transformations. However, on the one hand, as we have said, transformations rely on the decomposition of the configuration. There are interrelations between transformations and symbols, so that transformations that can be used for the modification of spatial forms in late stages depend on the initial choice of symbols. On the other hand, the consequent increase in number of changes entails that there is no gain from the functionality of the system. The progress of the task might be slowed down despite the expanded effectiveness of drawing operations.

The initial specification of the features of graphical symbols affects also the accomplishment of associations between drawn objects, such as with groupings, sub-models, etc. Relations between spatial elements, derived from conceptual models, do not always take into account the properties of the graphical symbols that represent them and their values. Thus, for example, four double lines can be used as a group to represent the plan of a room. The length, however, of these lines, or otherwise the width and the length of the room, could remain to be specified at a later stage. A change of these values, in the case of a layer oriented computerised system, would involve the disassembling of the object, the accomplishment of the modification, and its reassembling. This is because the application of a transformation to the group would modify indiscriminately the values of its properties including properties that would be required to remain unchanged, such as the distance between the double lines. Similarly, in the case of a component oriented system, parts of the group would have to be modified individually. Accordingly, groupings appear to be more effective in cases of already specified drawn objects, where in fact they are less needed.

In computerised drawing systems, there is also a shift in the methodological tools used for the accomplishment of drawings. Grids, for example, are used in designing in order to exemplify the top-down approach to the composition of spatial forms by connecting conceptualisations to spatial distinctions. In computers, the role of grids is mainly to achieve a correspondence between the display of drawings in the screen and the database.

Descriptive geometry is a tool for the accomplishment of consistent mappings between drawn objects and spatial objects and the description of the geometric properties and values of drawings. In drawing systems, this correspondence is given to the extent that drawn objects are seen as geometric objects incorporating already their geometric features. This has as a result the elimination of the importance of descriptive geometry as a tool. Although, functionalities of particular vectorial drawing systems, such as snapping, might allow the easy implementation of the basic procedures of descriptive geometry, it seems that the value in using such procedures is diminished.

Modelling systems incorporate principles of descriptive geometry for the projection of views of models into orthographic or perspective drawings. Yet, this is something that follows the specification of the spatial form of the designed object. Such a specification is also accomplished through the assemblage of geometric elements, in the form of two dimensional shapes or three dimensional primitive solids.

Generally, the initial specification of the features of drawings can be seen as an imposition of a bottom-up approach to designing. At early stages of design activity, when designers attempt to explore the connections of presented information, this might appear helpful in aiding the modelling of distinctive aspects of information. Later, however, when designers attempt to explore the correspondence between spatial forms and conceptual models, the approach above seems to impose limitations.[1] During spatial composition, designers conceive spatial forms in their totality so that a fit between spatial forms and various assertions in the context of conceptual models can be achieved. A given decomposition of drawings, in these stages, implies that spatial forms have to be known prior to their representation, and drawings have to be known prior to their accomplishment. This knowing has to go down to the level of decomposition at which the most appropriate symbols can be used.

If designers proceed with the specification of the spatial form of the designed object using a computerised system, they have to rely more on their imaginative

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1 This became evident from the examination of the examples of our case study. See in particular: 7.2. Computers in Use; Focus on One Project.

abilities to visualise spatial objects in their mind and comprehend their geometric features prior to their description in the computerised environment. Despite the differences between individual designers, generally such abilities are limited, and this is precisely the reason for using external representations such as drawings.[1]

To this extent, a computerised system can be seen as insinuating a means for generating spatial forms on the basis of established geometric components. These components are either in the form of palettes of graphical symbols or libraries. A psychological bias of designers towards extensive use of established forms, because of limitations of their own internal memory system, may lead to repetition. This radically contrasts with the continuously changing character of designing within society, reflecting the changing needs of people.[2] Taking into account the aesthetic considerations which influence designers' behaviour,[3] we may say that the adaptation of a specific approach to geometric articulation of designed objects results in a restriction of the expressive and stylistic repertoire of designers.

To put it in other words, the emphasis on the geometric features of drawings results in limitations on depictions of abstract design knowledge by which designers approach the relation between spatial forms and people's needs. This is because such knowledge cannot any longer play a full role in the articulation of forms. Design intentions may still evoke mappings between drawings and knowledge, which does not occur in the representation, during the interpretation of drawings. But such mappings do not any longer condition the accomplishment of drawings. The only knowledge that can be readily applied to spatial forms and graphical configurations is geometric knowledge. Furthermore, even geometric knowledge has to be applied in accordance with assertions built in the systems.[4] As a whole, the emphasis on certain features of drawings is equivalent to a reduction of their analogical character.

Directions

It should be clear from our discussion of computerised systems so far that the initial and definite specification of the features of drawings causes the majority of

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1 See the discussion on the role and importance of external representations in the context of the cognitive activity of designers in: 4.1. Design Actions, Transformations of Information, and Cognitive Operations; External Representations.

2 See: 1.2. Design Practice. Also: 3.1. The Framework of Discourse; Abstractions: Designers and Information.

3 8.1. The Accomplishment of Spatial Forms; Spatial Composition.

4 Consider, for example, the case in which curvilinear forms are conceived in terms of prismatic blocks. See: 7.3. Drawing, Modelling in Computers, and Designing.

problems encountered during the use of systems in designing. Furthermore, the fact that this specification is determined by geometric knowledge entails that drawing systems can be used for the accomplishment of drawings in which distinctions related to the geometric articulation of spatial form are transparent and stable. As a result, computerised systems can be effectively used for the production of drawings that represent established spatial forms, such as presentation drawings.

In drawing practice, though, there is no clear distinction between drawings for presentation and drawings for designing. Drawings which are made by designers for their own design benefit are also presented to clients or other participants. Drawings maintain their connections to conceptual models until the end of designing, and considerable changes occur also in later stages. If a computerised system is to be involved in design activity, there arises a practical need to separate presentation drawings from design drawings. Note that presentation here includes production or working drawing, presented to builders.

Consequently, it is not strange to see design practices establishing separate departments for the production of drawings in computers, rather than introducing drawing systems into their general design activity. Designers can find themselves more often passing information to specialised technicians who operate computers, rather than themselves using a drawing system.[1]

Future research should be aimed at development of systems for the accomplishment of drawings in early stages of design activity. Such systems ought to provide a basis for successful incorporation of the benefits of advances in computerised systems, such as visualisation, effectiveness of drawing operations, etc. These benefits ought to be brought into drawing environments for designing rather than draughting.

Research towards this aim has to take into account the role that drawings play in spatial composition and the qualifications that drawings obtain during their use. A key issue that characterises the use of drawings is their connection to knowledge in the context of conceptual models. The application of such knowledge to drawn objects specifies the analogical character of drawings.

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1 See, for example, the report on the introduction of computers in a particular design practice in: Davies, Colin, 1988.

This, however, does not mean necessarily that systematic representations of drawings in computers have to involve also representations of conceptual knowledge. The nature of conceptual models in designing is difficult to describe explicitly, as such models emerge on the basis of individual abstractions of designers, previous experience, and estimations of design information.[1] Assumptions about the components of conceptual models may lead us back to the severe problems of early computer applications, which attempted to formalise the constituents of design tasks.[2] What seems to be needed, consequently, is the development of environments which allow the manifestation of designers conceptualisations without imposing restrictions on the nature of such conceptualisations, on components of conceptual models, and on the features of drawings upon which such components are mapped.

Possible directions towards this target may focus on systems in which increased effectiveness of drawing operations does not rely on some definite specification of the structure of drawings. Systems may incorporate different and interlinked representational schemes for drawings, like for example pixel and vectorial representations in the same environment, gaining from the flexibility of bit-map systems.

There may be a gradual imposition of structure on drawings by designers, depending on design considerations, that affects the decomposition and transformation of drawings. If decompositions of drawings are specified by designers in relation to the context of use of drawings, drawing operations will also become context specific without posing limitations in the externalisation of design concepts.

As the methodological tools of handmade drawing practice are influenced by the connections of drawings to conceptual models, drawing operations may take into account such methodologies. They may involve, for example, the active incorporation of construction lines or descriptive geometry procedures.

Most important of all, perhaps, is the issue of change that becomes evident when considering drawing practice. As the components of spatial forms accept different conceptualisations according to different models, there is a need for accommodation by the drawing environment of the changing perceptions of spatial forms. Systems must allow different and even diverse interpretations to be applied to

1 See: 3.1. The Framework of Discourse.

2 1.1. Design Methodology.

the same drawn objects. This might be encountered by environments in which designers can work in different modes, each of which relying on particular decompositions and accompanied with particular transformations, operating on the same drawn objects.

These directions might indicate problems either technical, that is in the implementation of systems, or practical, that is in the employment of systems in designing, which we do not yet know to solve. However, they recognise the qualifications that drawings obtain during the accomplishment of design tasks, and to this extent they provide a basis for future research. We may have a short discussion about the issues that each of these directions involves, referring to relevant current research where this is appropriate.

Suggestions

Structuring Pixels

The flexibility of handmade drawings is based to a great degree on the fact that there is no inherent structure embodied in the drawing environment. Designers impose distinctions on features of drawings entailed by interpretations specific to the contexts within which drawings are used.

One possibility is to accept that indeed this is what designers need also from a computerised drawing environment, especially in early stages in designing, which may lead us to choose a bit-map representation for drawings in computers. In bit-map systems, drawings are decomposed into pixels, the minor units of screen resolution behaving similarly to dots on a paper. Pixel arrangements are free of structure, so that designers can express and explore tentative ideas in spatial composition without restrictions from some definite specification of the features of drawings.[1]

The limitations in the use of bit-map systems, however, have to do with the limited effectiveness of drawing operations, especially during those later stages in designing in which distinctions related to the structure of drawings appear to be more stable. It seems that a drawing environment in which there can be a gradual imposition of structural assertions upon pixel formations could be an acceptable possibility.

Even though there is not yet much work along this path, an experimental system which follows it is Viewpoint. In this system pixels are used as the primary

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1 See: 6.2. Bit-map Drawing Systems; The Structure of Drawings in Bit-map Systems.

carriers of information in an apparently structured drawing environment.[1] Viewpoint has limited capacities but it demonstrates some interesting functionalities. It employs a screen fragmentation into cells each one of which is constituted of a certain number of pixels. Every cell can be individually modified and used as a primitive graphical symbol that can fill other cells. Empty cells are treated as 'non-symbols' so that areas of empty cells enclosed by filled cells can have certain properties.

This functionality, in a potentially more powerful environment, could give useful results like, for example, the construction of different levels of pixel structure so that various and global transformations could be made in different levels maintaining simultaneously the ability of individual modifications of single pixels. There may be, however, some loss in the simplicity of drawing operations associated with bit-map systems.

Extracting Structure from Handmade or Bit-map Drawings

An alternative might be the possibility of deducing structure from pixel configurations that can be used as input in a vectorial drawing environment.[2] This potentiality can be employed also in automatic conversions of handmade drawings to computerised forms, if designers continue to use traditional techniques in early stages of spatial composition. Using current technology, such drawings can be converted to binary representations which are equivalent to pixel formations.[3]

The deduction of structure from pixel configurations, is a hard Artificial Intelligence problem usually referred to as 'pattern recognition' or 'image processing'. The objective in pattern recognition is the extraction of well defined shapes from binary forms of images. Shapes are connected to conceptual knowledge so that pattern recognition has potential applications to computer vision.

Early attempts in the recognition of images try to identify shape through the classification of shape features and the construction of templates of shapes which are matched to the binary representation. As such, they usually apply to the cases where the number of classes of shapes and the variability within a class are small, as in

1 See: Kim, Scott Edward, 1987.

2 Consider that the vectorial representation of drawings does not necessarily entail that features of drawings are conditioned by geometric knowledge. It allows, however, structural assertions to be imposed upon depictions which could be determined by geometric knowledge or other. See: 6.3. Two Dimensional Vectorial Drawing Systems; Design Drawings in Vectorial Drawing Systems.

3 Input of architectural drawings in computer environments and extraction of information from them are discussed in: Koutamanis, Alexander, 1990.

optical character recognition. Current approaches accept the decomposition of shapes into their compositional parts.[1] This is similar to the structural decomposition of drawn objects met in drawing systems. Given that the output of bit-map drawing systems in designing is far less complicated in relation to the visual scene descriptions which are normally used as input in pattern recognition systems, it can be assumed that such systems can be employed for the conversion of pixel graphics to structured drawings.

However, there are limitations in the involvement of pattern recognition which are similar to the limitations entailed by pre-established definitions of the features of design drawings, such as those met in current drawing systems. Pattern recognition assumes already known objects, while the interpretation of designed objects changes in relation to varied conceptual models. We may assume that pattern recognition can have a role in drawing interpretations only if there is a way of altering the decomposition of drawings at a subsequent stage.

User Definable Decompositions

Much of the difficulties in the use of drawing systems are caused by the initial specification of the features of drawings before their use in some particular context. This specification is manifested in the decomposition of drawings into their parts, graphical symbols, and primitives, which designers can use in order to compose their drawings. At the time of making a drawing, the choice of graphical symbols may be determined by a specific conceptual model, according to which the spatial form is decomposed, and the right symbols may be used. At some other time, however, during which the same drawing is modified, different models may imply different decompositions of spatial forms. Designers are bounded by their initial choice and have to re-construct the drawing.[2]

There is a great deal of scope for future work on the ability in drawing systems to allow modification of initial decomposition of graphical representations at different stages. I am not aware of any system that addresses this issue, even though simple alterations, such as for example the cutting down of a rectangle into its compositional lines, do not seem to embrace severe difficulties. This would involve the analysis of a graphical symbol into its primitives so that the primitives become

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1 Nevatia, R., 1982.

2 Consider, for example, the case of the final development of student A in our case study, who has to re-construct his model because of minor changes in the analysis of his building into spatial elements. 7.3. Computers in Use; Drawing, Modelling in Computers, and Designing.

graphical symbols themselves. It would also require base primitives to be at a very low level, such as unsegmented lines.

There are functionalities in existing drawing systems which allow modifications at the low level of primitives, but these are connected with initial constructional properties of symbols rather than subsequent decomposition. Systems may allow, for example, the cutting of a line into two or more lines, or more drastic modifications like the ones that we have seen in the discussion of the example in *Figure 6.3*.[1] These indicate the potential flexibility that systems would gain if actual alterations in the decomposition of drawings were involved.

Context Specific Decompositions and Drawing Operations

The potential capability of systems to allow designers to change the decomposition of graphical representations, implies that designers can specify the features of drawings according to the drawing's context of use. We may foresee, for example, that a drawing generated initially in relation to a model of distribution, therefore making use of comprehensive symbols such as boxes or circles standing for areas, can be changed later according to a model of structure. Boxes may become lines and the application of a transformation may convert lines into double lines for walls.[2] Consequently, we may have drawing environments that accommodate the top-down progression manifested during the composition of spatial forms.

To the extent that transformations depend on views about the decomposition of drawings, context specific decompositions entail transformations that operate within particular contexts. Although, strictly speaking, transformations themselves are not conditioned by the context of use, the sequence of drawing operations becomes also context specific, as in the example above.

Drawing Operations based on Construction Lines

In addition to context specific drawing operations, it seems that there is a way of implementing systems in which transformations can actively take into account conceptualisations of designers. This might be achieved by the involvement of construction lines in the specification of drawings.

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1 6.3. Two Dimensional Vectorial Drawing Systems; Graphical Symbols and Transformations.

2 See the discussion in: 9.4. The Connotative Function of Drawings: Significant Schemes; Example of Significant Forms.

An experimental drawing system that makes use of the notion of construction lines is described by Szalapaj.[1] The primitives in the system are construction lines, construction points (the points of intersection of construction lines), and segments (lines which are attached to construction lines, defined by construction points). Drawings are made by virtue of construction lines which act as a means for locating segments. The system, in addition to the graphical representation, employs a logical representation of drawings, so that topological relationships between graphical objects can be expressed. The interesting point, however, is the way construction lines are used in transformations.

Construction lines are specified in the system just in direction, without fixed end points, so they do not have other definite geometric properties and values. Segments, however, are specified in length by construction points. A change in the location or the orientation of a construction line entails corresponding changes to the location, orientation, and length of the segments that are attached to it. Accordingly, the majority of transformations, such as movement, rotation, etc., can be implemented.

This reflects handmade drawing practice, where graphical objects are conceptually attached to construction lines. Construction lines are used in order to express spatial distinctions (boundaries, orientations, etc.), while segments are in fact the symbols which, from the user's point of view, denote conceptual entities.[2] Designers do not have to be precise when they firstly construct a drawing, since, on the one hand, they do not initially have to specify properties and values, and, on the other, they know that modifications will not destroy the structure of the drawing.

The same principle can be used also for the systematic representation of descriptive geometry operations. From the point of view of descriptive geometry, graphical objects are similarly specified by virtue of points of intersection of projection lines, even though they are not attached to projection lines as with construction lines. This may be extended to connections between projection lines in different views of objects, with useful results. Consider, for example, the case in which a change of the projection lines that specify the location of a wall in a plan is followed by a corresponding change in an elevation.

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1 Szalapaj, Peter, 1988.

2 9.2. Drawings and Spatial Objects; Tools for the Description of Space.

Involvement of Descriptive Geometry in Three Dimensional Descriptions

In our discussion so far, we have not explicitly mentioned modelling systems. This is mainly because, as we have seen,[1] the implementation of modelling systems is based largely on the same principles as vectorial drawing systems and to this extent most of our considerations, such as about user definable decompositions, context specific operations, construction lines, etc., apply also to them. It is worth considering, for example, modelling systems incorporating construction lines for the positioning of solid primitives in a three dimensional space.

In general, the complexity of operations in modelling systems makes them even more applicable to the construction of models of established spatial forms, rather than to designing. In our case study we initially assumed that modelling in terms of primitives could be used in early stages in designing, but the examination of the practices of the designers has shown that this possibility was embraced with difficulties. Therefore, we may anticipate that designers proceed firstly to the development of designs in two dimensional drawings and subsequently construct three dimensional models.

An issue worth examining, particularly for those systems in which models are made on the basis of initial two dimensional drawings, might be the direct transformation of such drawings into a solid form. Since designers using traditional techniques achieve a definite description of spatial forms in drawings, which, with the involvement of some conventions and instructions, can be interpreted by builders, it is conceivable that particular mechanisms can be incorporated in a system that can generate three dimensional models using as input drawings. This goal may be helped by the employment of descriptive geometry, which ensures precision and geometric consistency in the description.

This approach would involve the specification of a three dimensional description by the system on the basis of combined two dimensional projections of the object. The information that the system would require would be: geometric, concerning the coordinates for the vertices of solids, the curve geometry for their edges, and the surface geometry for their faces; and topological, concerning the network of relations which interconnect these into a solid. Two dimensional projections incorporate only geometric information concerning just vertices and edges.

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[1] 6.4. Three Dimensional Modelling Systems.

Thus, an immediate result might be a wire frame model.[1] However, devices can be conceived which would allow the description by the user of the surface geometry of faces still at the level of two dimensional drawing. After all, this is a description that some vectorial drawing systems incorporate. The incorporation of a logical representation scheme may allow the specification of topological relations. The user can have an active role, guiding the accomplishment and eliminating cases of ambiguity. This approach does not radically alter the sequence of spatial composition processes, and it does not seem to involve considerable additional complexity in operations.

Different Modes of Operating on Drawings

The possible directions described above take into account different intentions about drawings emerging at different stages of design activity and to this extent they imply systems that can be used for the accomplishment of different kinds of drawings. It can be assumed that more than one of these strategies can be incorporated in a system, which effectively could accommodate top-down approaches in the development of spatial forms, from the externalisation of tentative ideas about spatial relationships to precise descriptions of structural elements.

A point, however, that becomes evident when considering spatial composition and its impact on drawings is the need for changes. Designers might want to go back and examine the aspect of general distribution of areas, while working on structural analysis. They might want to look at the effects of window detail designing back on general principles of thermal performance.

Considerations about what the general suggests for the specific and what the specific implies back to the general, characterise design tasks and they are a direct consequence of interrelations prompted by conceptual manipulations of spatial forms. In other words, of the involvement of conceptual models in spatial composition. Different conceptual models, ranging from general and abstract to specific and concrete, imply different perceptions of spatial forms and they result in extensive changes in drawings, until a fit between spatial forms and conceptual models is achieved.

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1 This approach for the production of wire frame models is followed by STAG™, a system developed by DeCAL (Design Computer Aids Limited).

Such changes can be encountered by systems which allow different and even diverse conceptualisations to be applied to the same drawn objects. Perhaps, the key notion that can be employed in systems that address this issue is the notion of user definable decompositions of drawings. By the incorporation of this notion, designers would be able to structure their drawings according to their perceptions of spatial forms. However, the fact that different conceptual models apply to the same drawn objects simultaneously indicates that designers want systems that maintain structural assertions of drawings in relation to a specific model, while allowing the re-structuring of the same drawing according to another conceptual model. In this way, the effects of the conceptual manipulation of spatial forms in respect to one model will continue to apply while working in the context of another.

If we suppose that future systems allow changes of the decomposition of drawings, we may go further and discuss the possibility of a system that offers to designers a drawing environment in which they can work in different modes, each of them corresponding to a specific conceptual model. Particular decompositions of drawings might be specified by users and assigned to a specific mode, and, to the extent that transformations depend on the decomposition of drawings, each mode in practice will involve particular transformations.

To imagine such a system, consider the analogy of layers as a means of organising drawing information. In a layer organisation there is an assignment of parts of drawings to a specific layer, so that drawn objects which are conditioned by similar aspects are grouped together. In our speculative system, not different parts of drawings, but different means of organising drawings could be assigned to a specific mode, so that the same depiction would be conditioned by different aspects of knowledge. In effect, we will have different manners of operation on the same drawing corresponding to different conceptual models. This would be equivalent to the case of several different drawing systems employed for the accomplishment of the same drawing.

A direction towards the implementation of such a system may anticipate the involvement of a single graphical representation, corresponding to the depiction of the drawing, and several logical representations of the drawing, each one specific to a particular mode of operation. The graphical representation should include a minimal number of graphical primitives, possibly free from syntactic rules. Each logical representation of the drawing could be used for the expression of structural relations between primitives, so as to compose sets of graphical symbols specific to particular domains of knowledge. However, all of the logical representations could be applied to the graphical representation.[1]

To consider the architecture of such a system, let us be reminded of the architecture of existing drawing systems. In these systems there is a distinction between the display of the drawing and its database which holds geometric information. The database includes syntactic rules that govern the composition of drawings. There is also a means of organising the database, in terms of layers or components, which is embodied in the system. We may say that in our system there will be a single display of the drawing; a single database, that keeps information about the values of the properties of drawn objects and controls the display; and several means of organisation of the database, let us say knowledge bases, that condition the relations between drawn objects. Knowledge bases, however, are not simply different means of organisation but also include syntactic rules. Thus, our system would look, in practice, as if different sorts of groupings can be accomplished between drawn objects. Each sort of grouping would be governed by its own syntactic rules and it would be specific to a particular mode of operation.

There might be, though, a theoretical problem with this approach concerning the contradictions that appear when considering several conceptual models affecting a single spatial form. What happens, for example, when according to a certain model four lines have to be linked to represent a room, and according to another they have to remain independent to represent walls? Or, when according to a model a certain wall has to be, say, 6m long, and according to another 7m? This can be partially resolved if the knowledge bases are completely independent from each other, and only one knowledge base is active at a time. Thus, at one stage lines are linked and at another independent. If modifications occur while in a mode in which lines are independent, moved, for example, away from each other, they may retain their linkage in another

[1] A field of current artificial intelligence research follows a view on problem solving strategies which has some similarities with our approach. This has to do with the 'blackboard' model of problem solving, or 'blackboard' architectures. According to the blackboard model, there is a global database of the solution space of a problem, called the blackboard, which is organised into hierarchical levels. Each one of these levels is conditioned by knowledge sources which are logically independent of each other. The knowledge sources respond to changes on the blackboard, and they are self-activating. There is no control flow. The main difference with our approach is, first of all, that we are not concerned with problem solving but only with the accomplishment of a description, and also that there is no hierarchical organisation of the database of a drawing (see below). However, blackboard architectures may provide a vehicle for the implementation of the kind of system under discussion.
For blackboard systems see: Nii, H. Penny, 1986.

mode even if they are not visually connected. The values of geometric properties can be handled just by the database, as we have already indicated, so that there will be a single geometric representation of the drawing. Alternatively, the database may receive information from a single knowledge base at a time, the one that is active. The latter, however, may in the end be quite confusing for the user.

The possibility of incorporating some consistency maintenance sub-system does not seem to be acceptable. In this case, conflicts would have to be resolved in favour of knowledge bases which are considered more important than others. This implies some sort of hierarchical organisation of the knowledge bases, which radically contradicts the whole idea of having different knowledge bases. Specifications of the features of drawings on the basis of assumptions about their importance in spatial descriptions occur in existing drawing systems and this is what causes the majority of their problems.

The limitation that appears if only one logical representation conditions the graphical representation at a time, does not seem to pose serious restrictions. In fact, this is consistent with our account of the memory system of designers.[1] This would be equivalent to the case in which only one layer in existing drawing systems can be viewed at a time. In our case, however, different modes do not concern parts of the database of the drawing and their display, as in layers, but rather its structure. Designers may have to work in one mode at a time, but they would know that the structuring of the drawing in other modes continues to apply.

There might be other problems related either to the implementation or the use of this system which cannot be anticipated before its actual implementation is attempted. This, however, is beyond the scope of this study. The interesting point is that designers, by using such a system, can built up descriptions that correspond to the conceptualisations of spatial forms.

Instructing Computers

Our discussion now brings us to an aspect of the use of drawing systems, not only of the speculative system above but possibly all computerised drawing systems. This has to do with the manner of making drawings in computers, the apprehension of

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[1] In our discussion about cognitive activity during designing, we assumed that, because of limitations of short-term memory, information in the context of only one conceptual model can be manipulated at a specific time. See: 4.1. Design Actions, Transformations of Information, and Cognitive Operations; Representation in Memory.

the functionalities of systems, and implications that go beyond the issue of familiarity with these functionalities.

For someone who attempts to use a drawing system, the first impact is that there is an explicit and definite specification of the drawing operations that have to be followed in order to accomplish a drawing. There is an establishment of processes on the basis of which graphical symbols are selected, assembled, organised, modified.

A need arises, from the user's point of view, for knowledge about how a drawing can be made in the particular system at hand, or better how a drawing can be described to the system. This knowledge concerns sequences of transformations, interrelations between transformations and graphical symbols, organisation of components of drawings, etc., and it is interpolated between the designer and the drawing.

As a consequence of this, there is the addition of a new 'language' to the task of spatial composition. Spatial forms have to be described in such a way that they can be introduced into the system. While drawings can be potentially infinitely rich in realising design conceptualisations, this richness is reduced in order for a drawing to coincide with the drawing processes embodied in the system.

As a result of the requirement of knowledge about the system, imposed on the designer, the accomplishment of drawings is not a spontaneous activity of externalising conceptualisations. As precise instructions have to be given for each of the drawn objects that compose the depiction, the making of a drawing becomes effectively a form of intercourse between the designer and the system, as if the designer were describing the drawing in a non-drawing mode to someone else.

Our possible directions for the development of future drawing systems, in the previous part of the chapter, cannot escape from the fact that there has to be such non-graphical intercourse. This is because computerised systems are essentially formal systems and have to rely on logical relations and computer operations which are applied to design expressions.[1]

We may assume that familiarity with using computerised systems can reduce the consequences of this aspect. However, we have to realise that the problem is not simply an issue of apprehension of the functionalities of computerised systems but is

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1 The relations between formal systems and human knowledge, and their consequences in the use of computers are discussed in: Bijl, Aart, 1989, pp.211-230.

connected with the difference between thinking and describing. It has to do with the impact of externalising aspects of knowledge in mind.[1]

Handmade drawings, relying in loose syntactic structures, seem to be flexible in capturing designers' expectations and offer a means of expression that reflects design conceptualisations. Computerised drawings, however, have to be based on precise syntactic rules. This is a premise that we have to face when using formal systems.

The most promising direction for the development of future drawing systems is towards drawing environments in which designers themselves can specify the syntactic rules by which drawings are composed; environments in which they can define their own language of description to computers. This is precisely what most of our suggestions have attempted to move towards, irrespectively of the ways in which they can be realised.

10.2. Summary

In the discussion in the previous chapter of the thesis, we developed our view on the use of drawings by examining the attributes of drawings with respect to their role in designing. In this chapter, we have seen the implications of this view for the employment of computerised drawing systems.

Complications in the use of computerised systems have been related to the main issue that characterises systematic representations of drawings, that of the initial specification of the features of drawings on the basis of geometric knowledge. This makes drawing systems appropriate only for the description of established spatial forms.

Finally, we have seen how future developments can take into account the qualifications that drawings obtain during their use. The main outcome of this particular discussion has been the suggestion that designers will successfully use computerised drawing systems as designing tools, rather than for presentation, if systems offer them environments in which they themselves can specify the manner according to which drawings are structured.

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1 See the discussion in: 5.1. Knowledge or Representation of Knowledge?

Epilogue

The thesis has attempted to develop an account of the effects on drawing operations of conceptual processes in designing, and examined the implications of this account on the systematic representation of drawings in computers. We may now review some of the main arguments of the thesis to see the extent to which this objective has been fulfilled.

The thesis starts by examining the activity of designing. **Chapter 1** looks at early approaches to designing, and computer applications that have followed them. The ambition of such approaches to fully understand design processes, on the basis of the externalisation and rationalisation of design knowledge, does not correspond to observations on design practices. Such observations suggest that knowledge in design cannot be objective and is necessarily in a state of continuous change.

In contrast to these approaches, the thesis adopts a descriptive approach to designing, by focusing on design expressions. The analysis of various aspects of a case study, concerning the development of a design project by architecture students using a computerised drawing system, helps in the development of the descriptive approach. **Chapter 2**, in particular, puts forward a view about designing as a continuous process of transforming partial descriptions of states of information into an eventual spatial object, by the application of knowledge. Graphical expressions hold a central role in this process, offering a vehicle for the representation of information and the execution of transformative operations.

The examination of the behaviour of designers, in **Chapter 3**, suggests that the location of design problems under different models of discourse is an important aspect of design tasks. Models emerge by the identification of links between distinctive problems, and the structuring of such links, on the basis of abstractions by designers in presented information. Designing can be thought of as search for a satisfactory fit between conceived models and a spatial object.

In order to analyse the accomplishment of design tasks, and to locate the role of drawings within it, **Chapter 4** looks at the conceptual activity of designers. The cognitive operations of acquisition of information, projection of information, confirmation of information, representation in memory and externalisation of information, and regulation of flow of these operations are analysed. Acquisition is the selection of external information from the environment or the recall of information from memory. Projection is the application of knowledge to distinctive pieces of information according to design intentions. Confirmation is the comparison between distinctive pieces of information. Representation is encoding of information in memory. Conceptual models are specified as different organisational patterns of knowledge, and information is represented by forming associations with such knowledge structures. Externalisation is the process of accomplishing an external representation as an output of the current manipulations of information by cognitive operations. Regulation of flow is a function applied to the rest of the operations coordinating their activation and direction.

The approach to designers' cognitive behaviour explains the importance of drawings in designing. Acting on distinct states of information, cognitive operations achieve their structuring and organisation which is represented externally in graphical forms. Graphical representations manifest the dependencies between spatial forms and conceptualisations of information under models.

After the establishment of the approach on designing, **Chapter 5** focus on the manner according to which representations are structured and interpreted in accordance to cognitive activity. The distinction between propositional and analogical representations characterises the structure of representations of verbal concepts and images respectively. Semantic networks, as a model for the organisation of knowledge based on propositional representations, explain the associative character of design knowledge and the structure of conceptual models. Drawings are approached as symbolic representations. Graphical symbols that stand for spatial concepts are composed on the basis of graphical primitives. However, design intentions entail analogical mappings to depictions of knowledge in the context of conceptual models other than this represented. In this respect, drawings act as analogues of designed objects.

The examination of the interpretive mechanisms of drawings provides an account of the ways according to which depictions are mapped to images, conceptual entities, and abstract associative structures of knowledge in memory. Significant schemes, in particular, act as binders of relationships between different levels in the interpretation and indicate the manner through which conceptual models regulate the interpretation of drawings.

The implementation of computerised drawing systems, which are discussed in **Chapter 6**, relies on the view of drawings as symbolic representations. The functionality of drawing systems is based in assumptions about the use of drawings. Such functionalities are approached in a general way with the introduction of the notions of effectiveness and restrictiveness. Effectiveness refers to the objective of minimising the number of drawing operations, manifested by the provision of specific graphical symbols and comprehensive transformations for their manipulation. Restrictiveness has to do with limitations in the applicability of symbols and transformations to depictions which do not fall within a pre-defined range. It is suggested that systems should combine maximum effectiveness with minimum restrictiveness.

After the evaluation of various drawing systems, including bit-map, vectorial, and modelling systems, it is assumed that a three dimensional modelling system, in which the construction of models is made on the basis of solid primitives, can be involved in the development of a design project by the designers of the case study.

The detailed examination of the practices of the designers, in **Chapter 7**, shows that systems that rely on a definite decomposition of drawings, before the use of the drawings in a particular context, impose restrictions in the accomplishment of design tasks. These are evident particularly in early stages in designing.

Restrictiveness is connected to the analogical use of representations. A given specification of the features of drawings entails complications in the application of design knowledge to depictions. Accounts of the structure of graphical representations cannot be specified independently of the manner according to which drawings are used in designing.

Chapter 8 starts a discussion on the conditions that characterise the use of drawings. This time we focus on the handmade drawing environment in order to find out the qualities of drawings which are missing from the computerised ones.

The relations between drawings and conceptual models are examined in the context of spatial composition. Drawings are characterised as intermediate states between conceptual models and spatial forms. The analogical character of drawings is attributed to three functions that they serve during designing. These are: the denotative function, by which they express distinctions in the context of conceptual models; the referential function, by which drawings convey spatial information; and the connotative function, by which they evoke conceptualisations other than those explicitly represented.

Chapter 9 looks in more detail at the attributes of drawings and their structure in relation to these functions. The referential function of drawings is exemplified by the gradual imposition on graphical symbols of spatial properties and relations that correspond to spatial properties and relations found in spatial forms. Mappings between drawn objects and spatial objects are implemented so that drawings convey precise spatial information. The use of methodological tools for the accomplishment of drawings is connected to this function.

The denotative function of drawings refers to a specific use of graphical symbols so that drawings capture distinctions in conceptual models. This function might be exemplified by the use of particular symbols, such as arrows, patterns, etc., which are directly connected to components of models. However, the nature of graphical symbols remains abstract, in the sense that graphical symbols do not have a single predominant meaning attached to them, independently of the context of use of drawings. This might lead to problems of ambiguity.

The context of use of drawings can be approached by looking at their connotative function. Drawings, acting as models of spatial forms, evoke knowledge that is not directly expressed. This function is manifested by the application of design knowledge to depictions which have been already made on the basis of the two previous functions. Relations between graphical symbols and their meaning become more transparent if drawings are confronted against a given context of discourse, provided by conceptual models. A model for the interpretation of drawings that takes into account this function is put forward.

The functions that drawings serve during designing impose qualifications in respect to their features and their structure. The implications of these qualifications for the systematic representation of drawings in computers are discussed in **Chapter 10**. It is suggested that computerised drawing systems can be successfully employed in designing and aid spatial composition if they provide environments in which designers themselves can specify the manner according to which drawings are structured.

Appendix A: Tables

1. Presentation of the project:
    a. Brief
    b. Map
2. Questions and declarations on the brief in relation to:
    a. The requirements in space and area
    b. The island of Cramond
    c. Greenpeace
3. Search for a more detailed map
4. Selection of a location for the site of the building
5. Visit to the island:
    a. Survey on the island
    b. Change of the site
        Photographs of the island
        Photographs of the site
        Photographs of views from the site and the island
        Notes on the map of the position of the photographs
        Declarations on the map of elements on the site
        Sketches of important elements on the island, by the site
6. Studio work:
        Instance 001
        ...
        Instance 006
        Instance 007 | presented map of Cramond Island
7. Second visit to the island
        Declarations on the map of further elements on the site
        Notes about elements on the site
8. Studio work:
        Instance 008 |
        ... |
        Instance 013 | work on the site map
        Instance 014
        ...
        Instance 062

...

Table A.1; Extract from Sequence of Actions, Student A

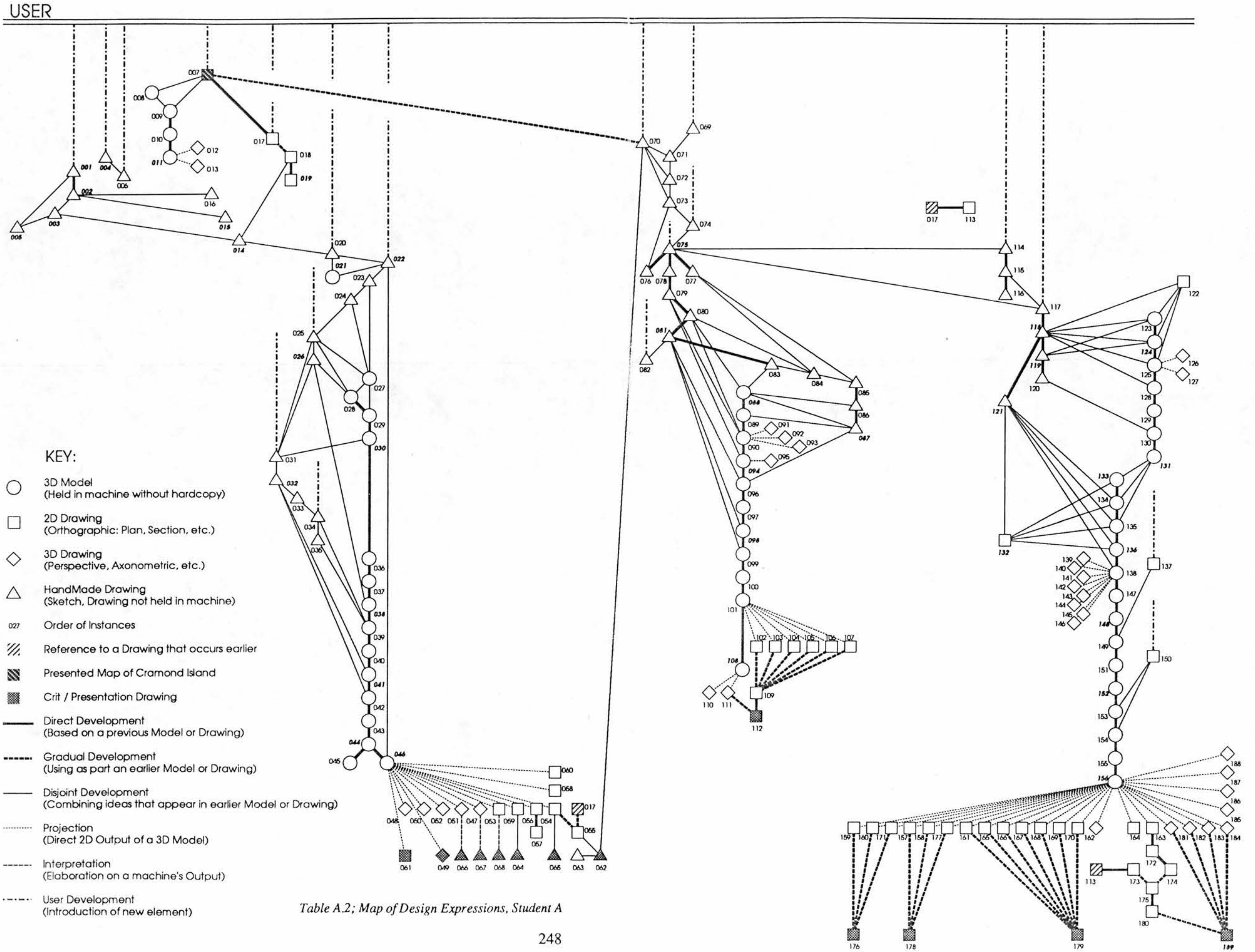


Table A.2; Map of Design Expressions, Student A

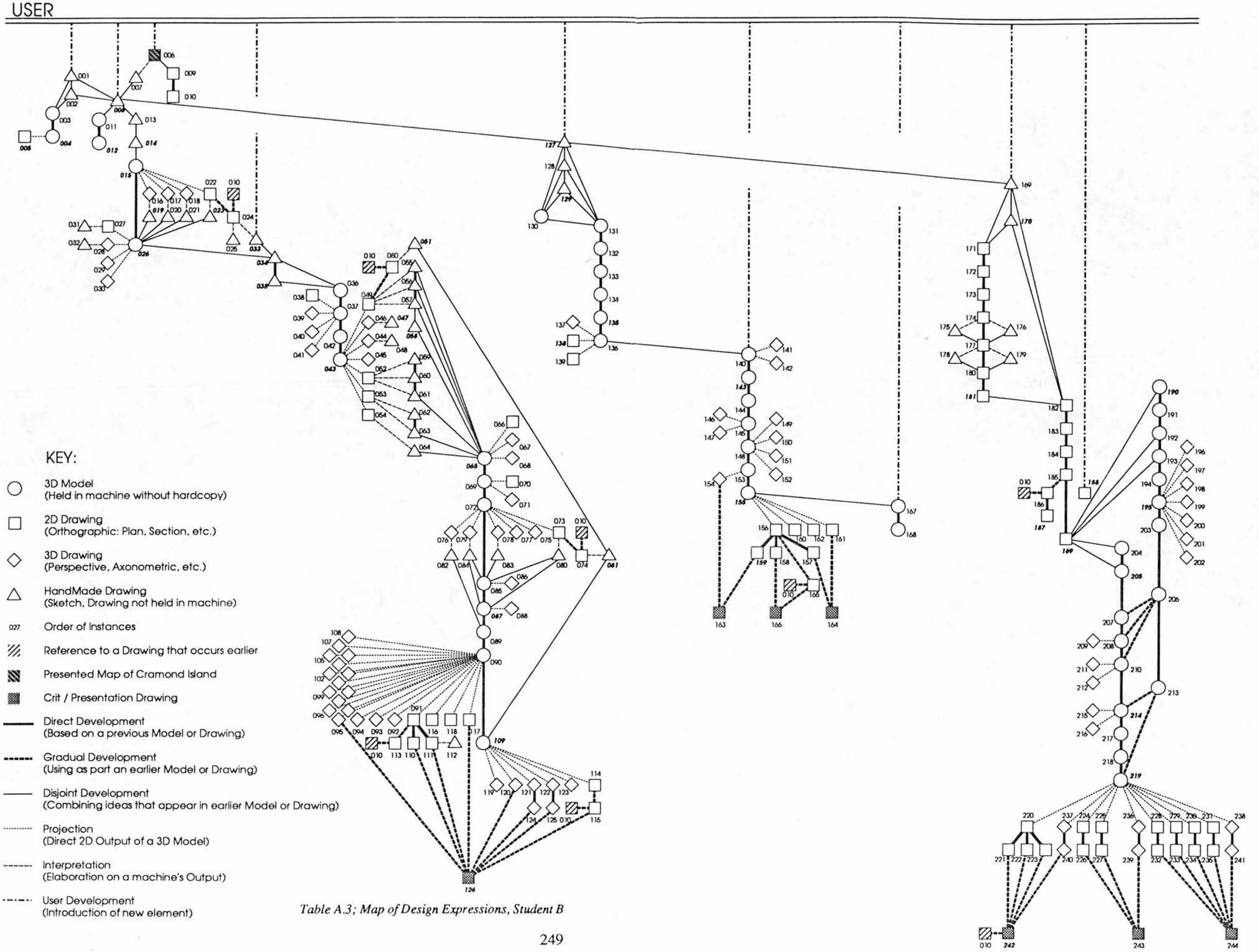


Table A.3; Map of Design Expressions, Student B

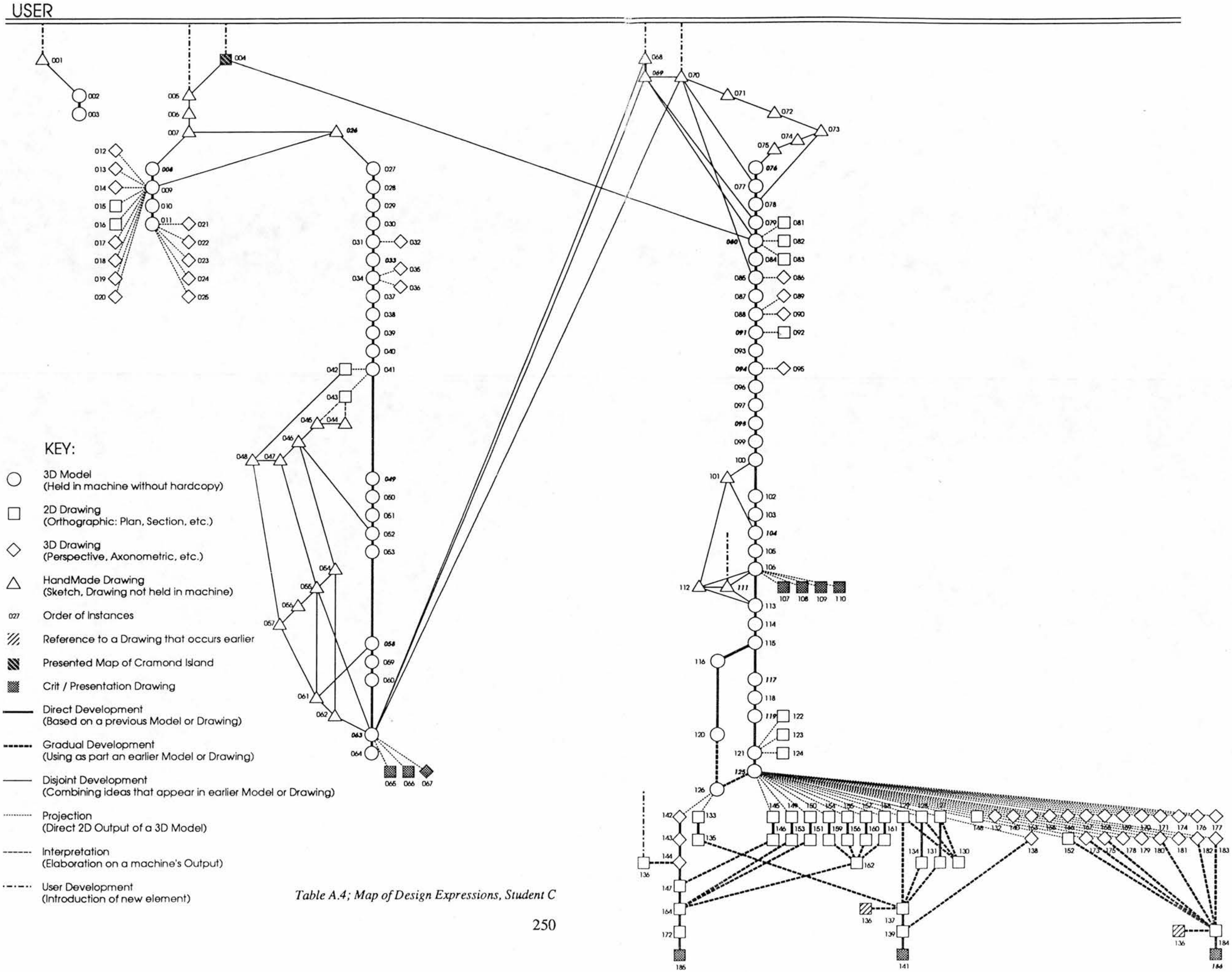
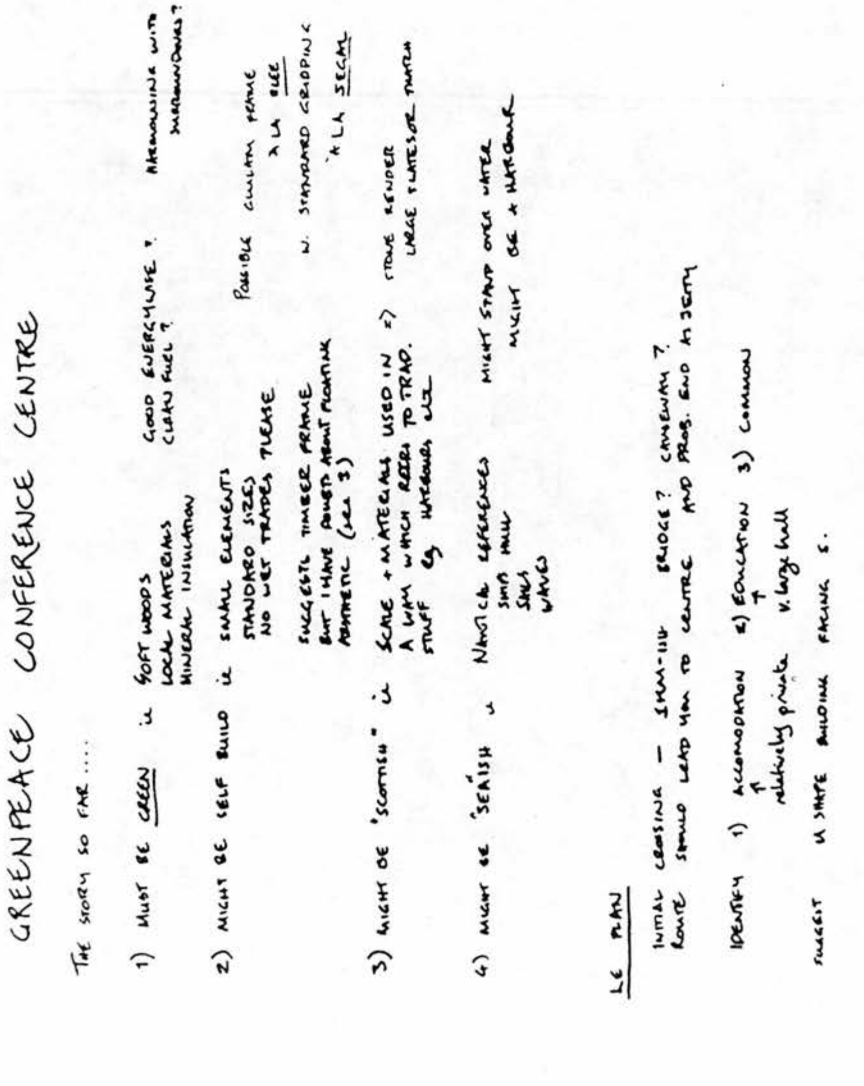


Table A.4; Map of Design Expressions, Student C

Appendix B: Instances of Design Expression (Drawings from the Case Study)

B.1. Student A



Student A; Instance 001

Main Entrance

Exhibition ← Reception → common room ⇐ Kitchen
Lecture theatre
Offices + Toilets
restaurant

Library + labs
conf. rooms etc

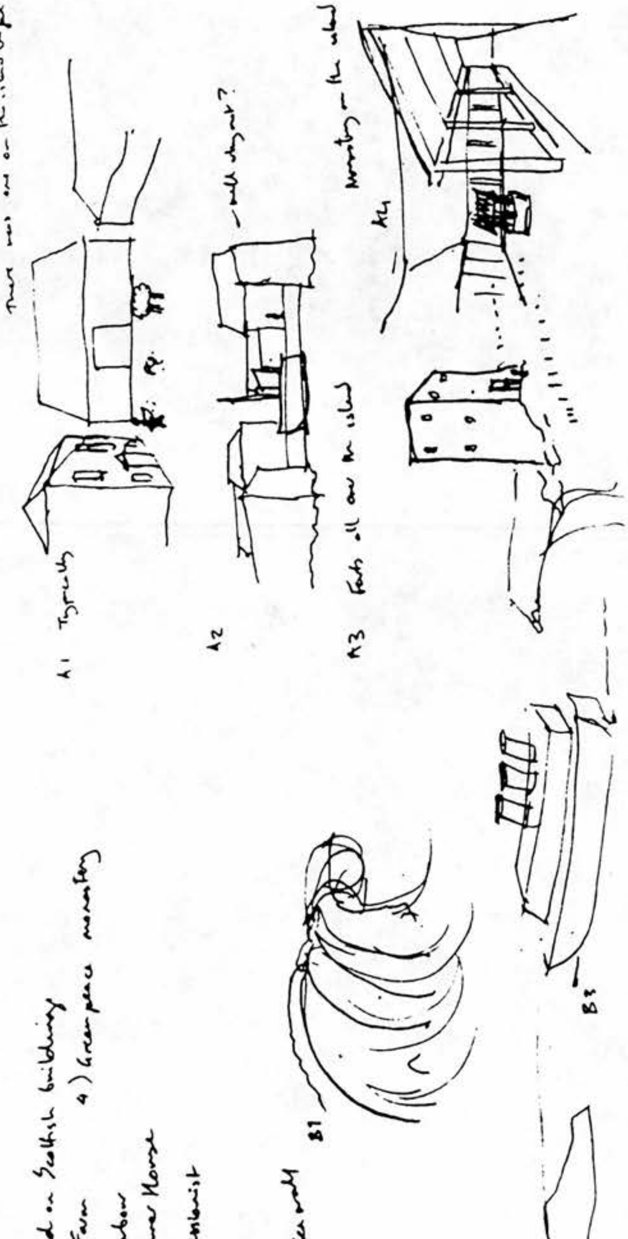
Lecture theatre room for 150 adult suggest seats 600 × 800
→ seating block 10 rows of 15 = 9000 × 8000

Offices say 40m²
Exhib 100m²
Labs 60m²
L.b 40m²

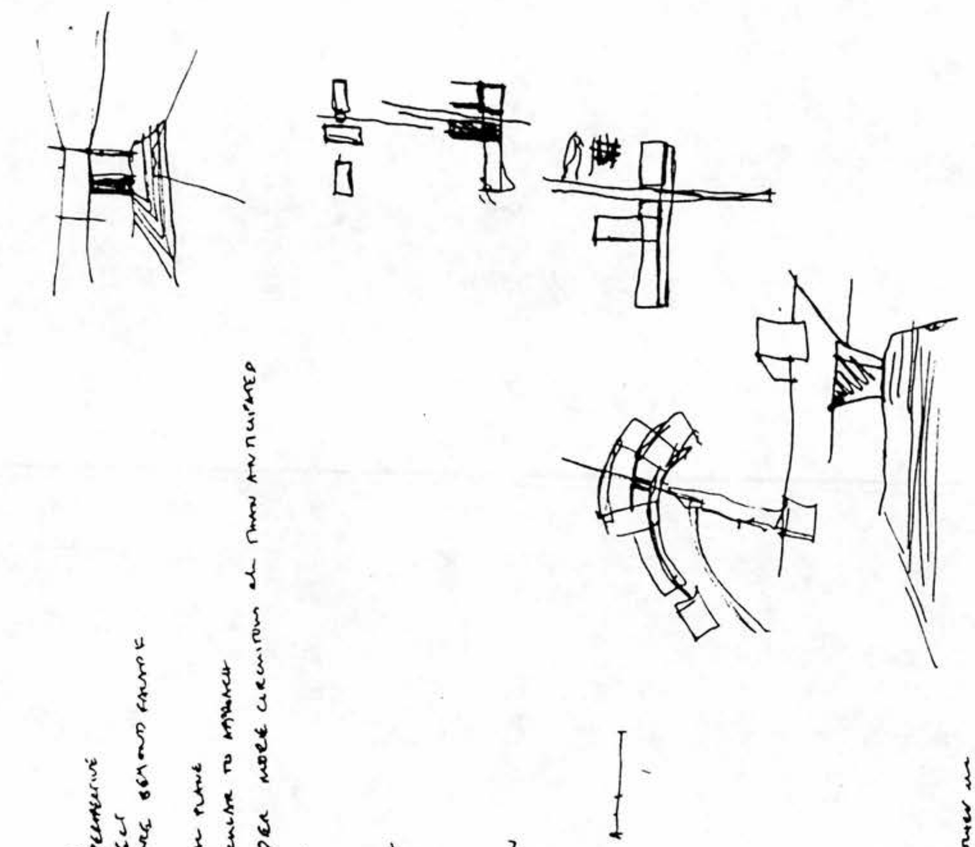
Residential - suggest staff house for 5 persons
hotel style rooms for 10
Dormitory space for 10

Common room say 40m²
Boat garage 40m²
Reception/ ~~[illegible]~~ area
Toilets etc

Catering for 100 inh. say table + 4 chairs in 2500 × 2600
20 of these 10m × 12.5m
Kitchen about the same incl. servery



Student A; Instance 003



Student A; Instance 004

Purposes

Meeting
Study
Teaching

Providing an identity ⇒ some very distinctive quality or thing

Qualities

Peaceful
Natural

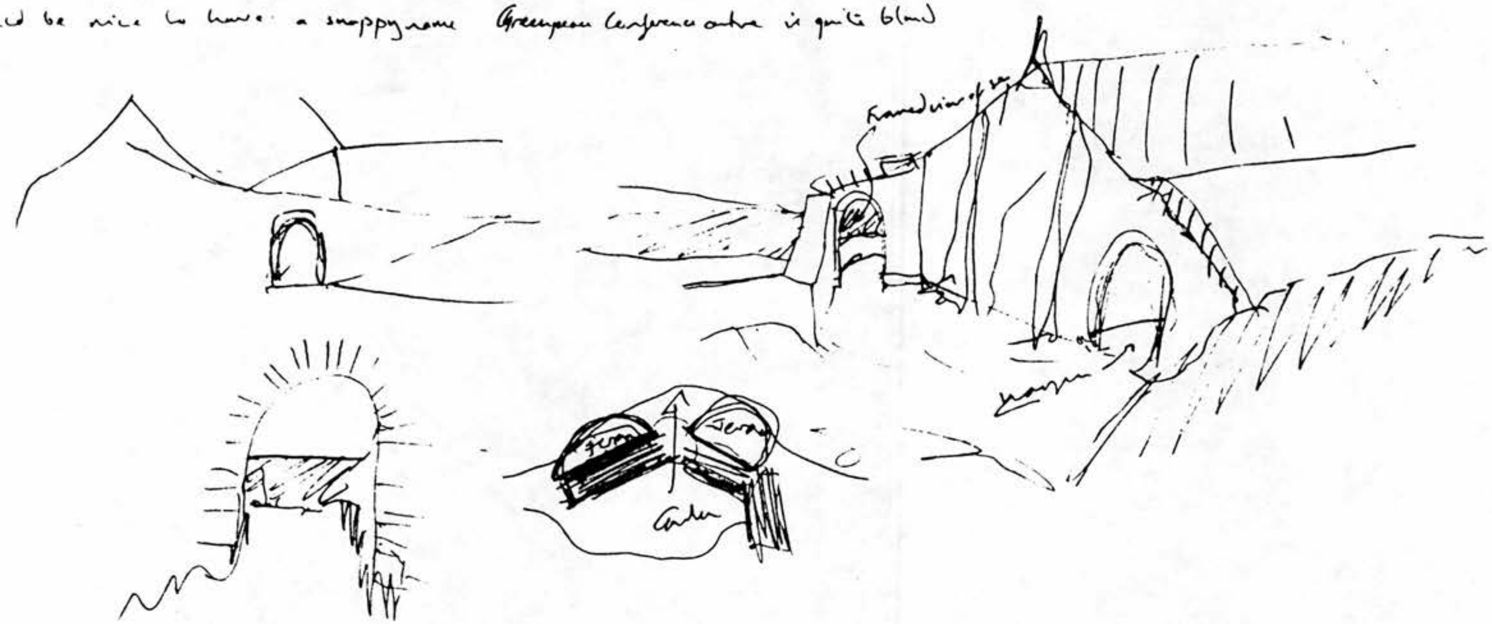
I would suggest a building that embraces the landscape (sounds good) but (and) provides shelter. (tricky)

Contrast exterior + interior?

Using fall of site — perhaps contouring or going against contours to use hillside as a wall.

Informality rectilinear not curved though

It would be nice to have a snappy name Greenpeace Conference centre is quite bland



Student A; Instance 005.a

Organiser

Progression of privacy

Restaurant common room exhibition lecture theatre lab. lib. accomodation staff house

(boat house ?)

Enter

Structure + materials

Say stone slate softwood minimum metal concrete

(Consider thermal response of heavy structure tho.)
vs light internal lining! - maybe just (?)

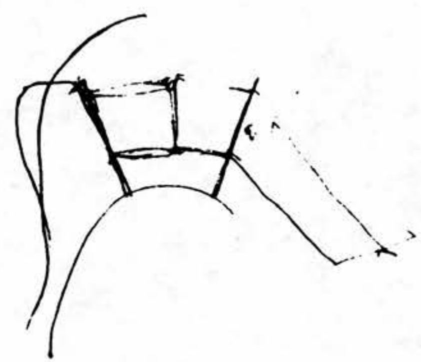
Trusses span up to 15m–18m

Pitches – 45–60° – ie rooms in roof (roof twice as high as its wide ie)

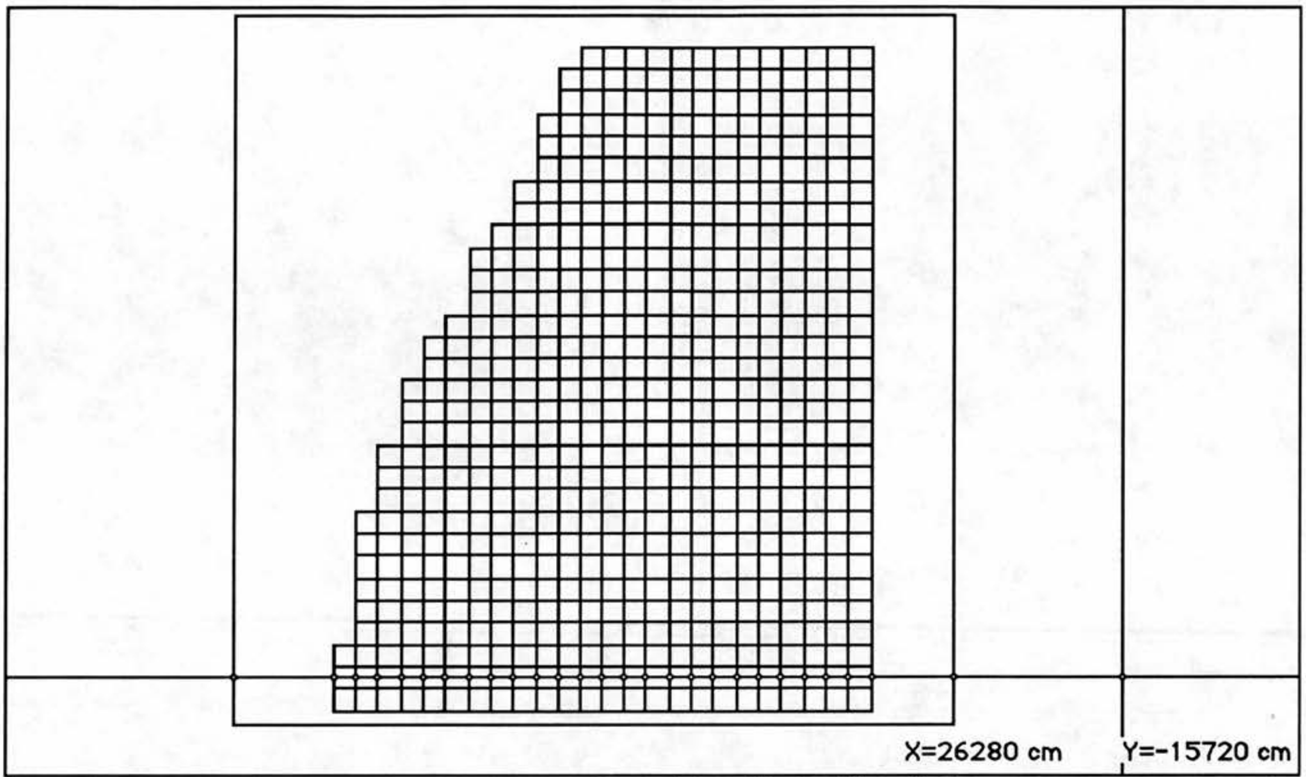
Site

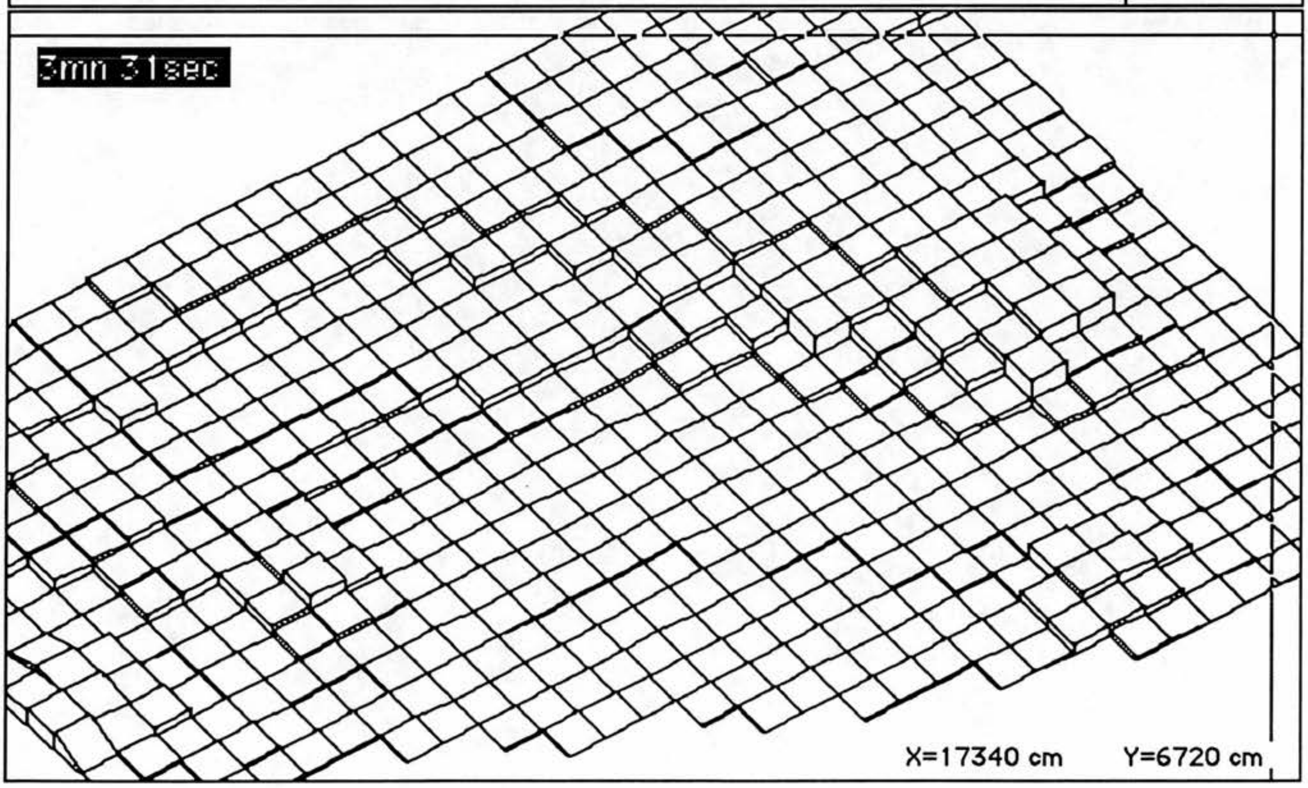
Faces W. generally to. own levels

Steepish slope towards sea

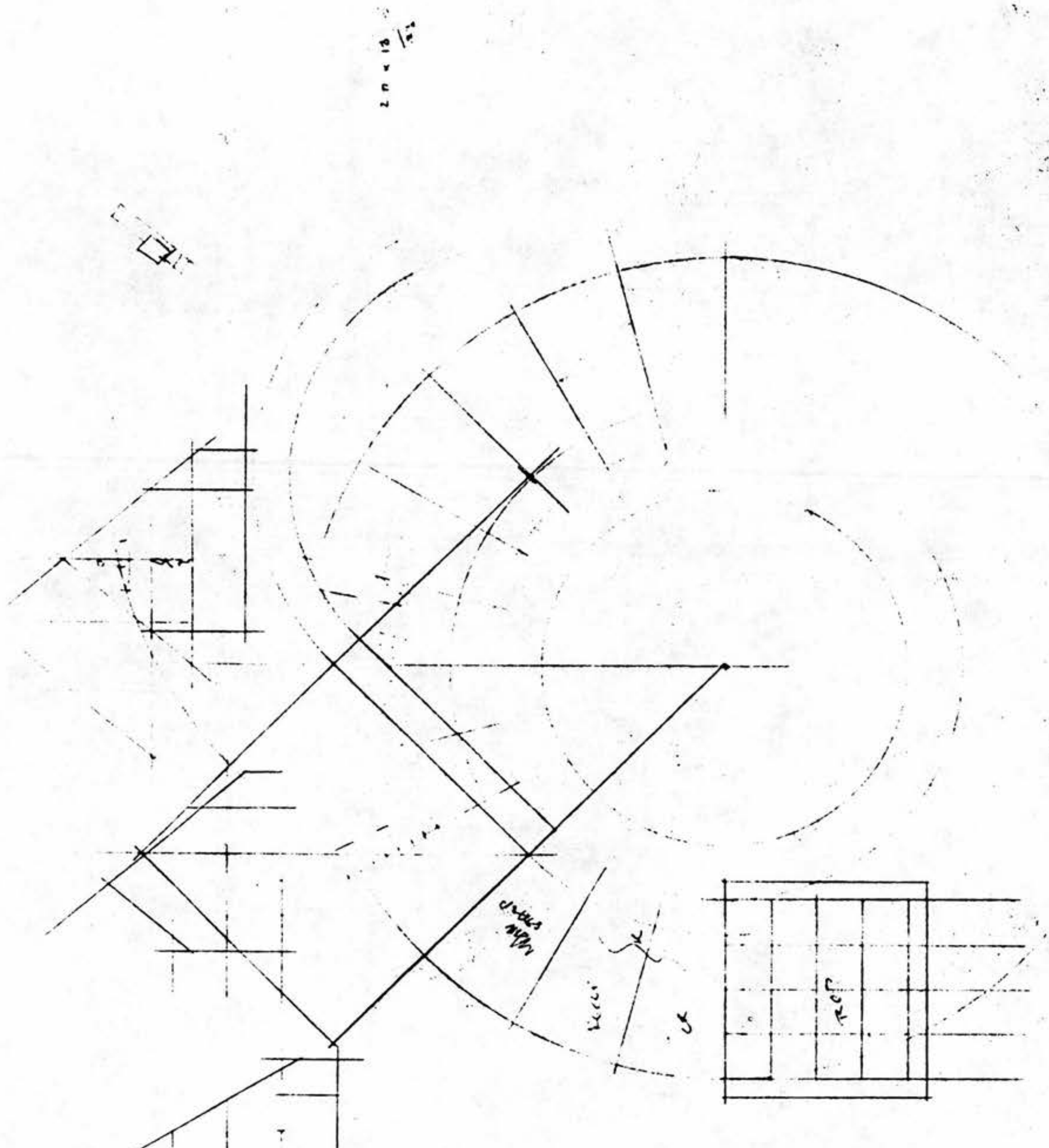


Student A; Instance 005.b

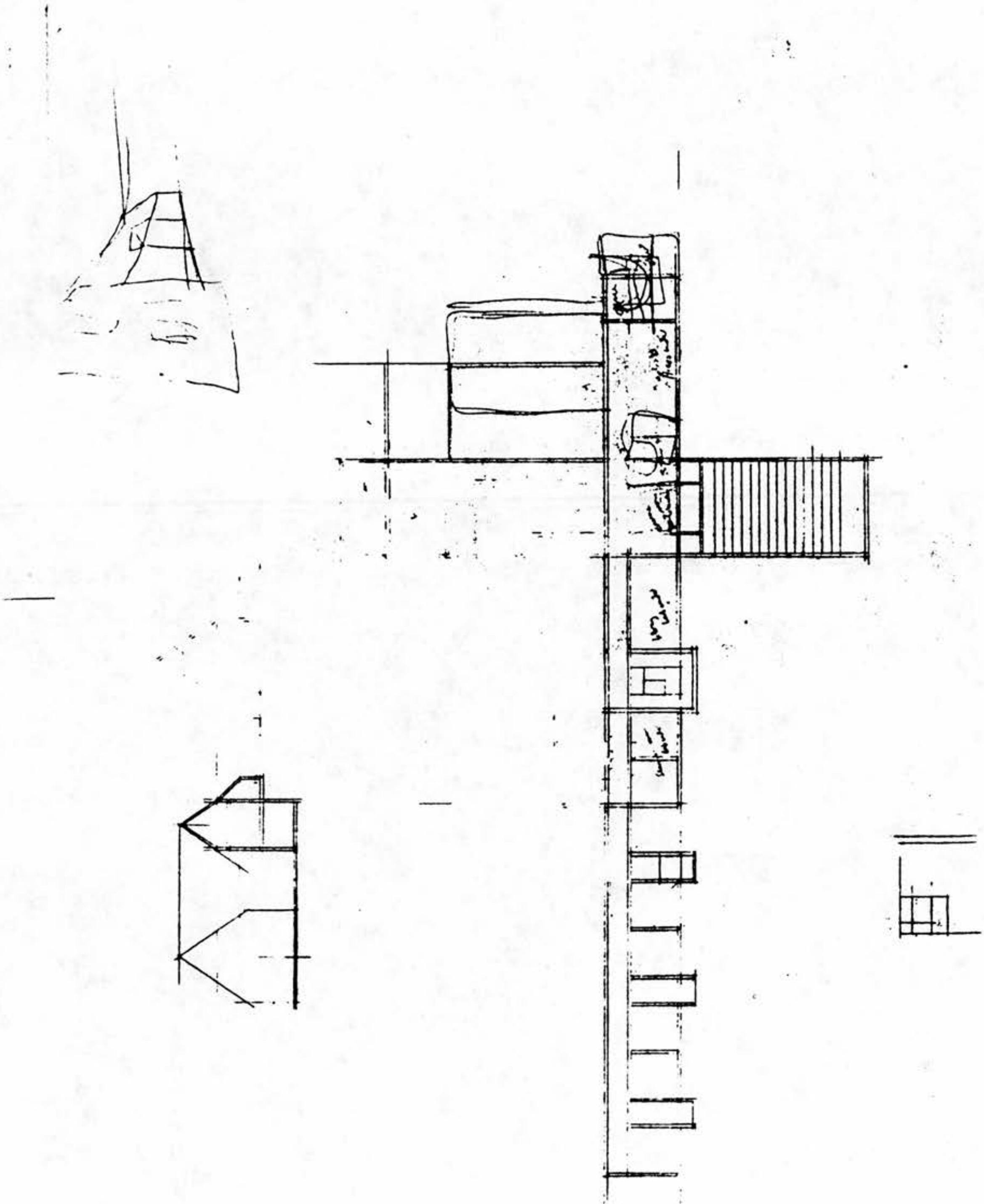




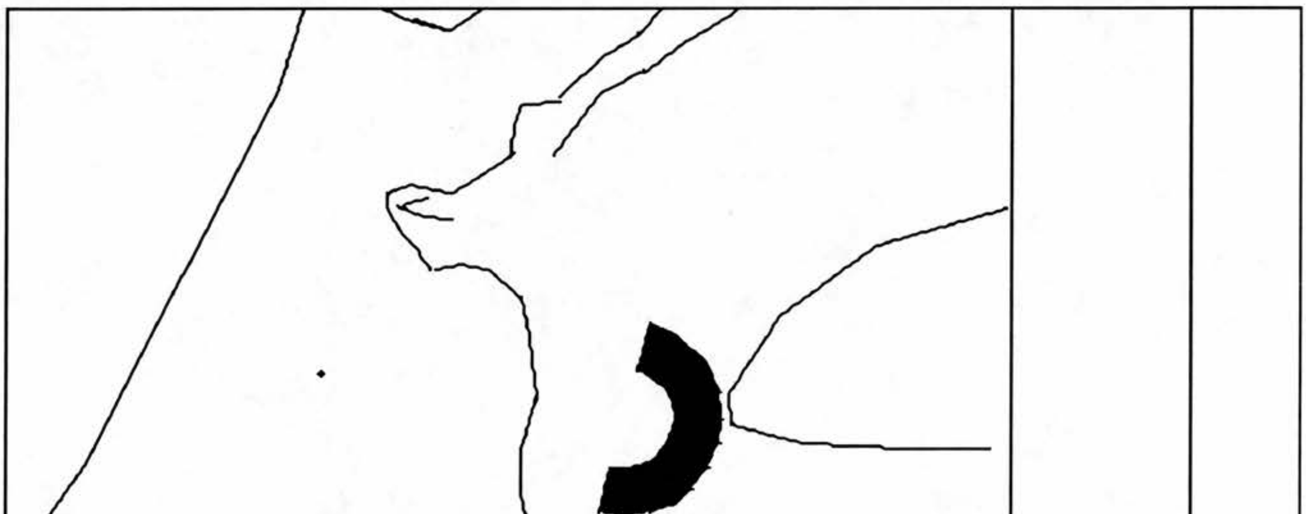
Student A; Instance 011



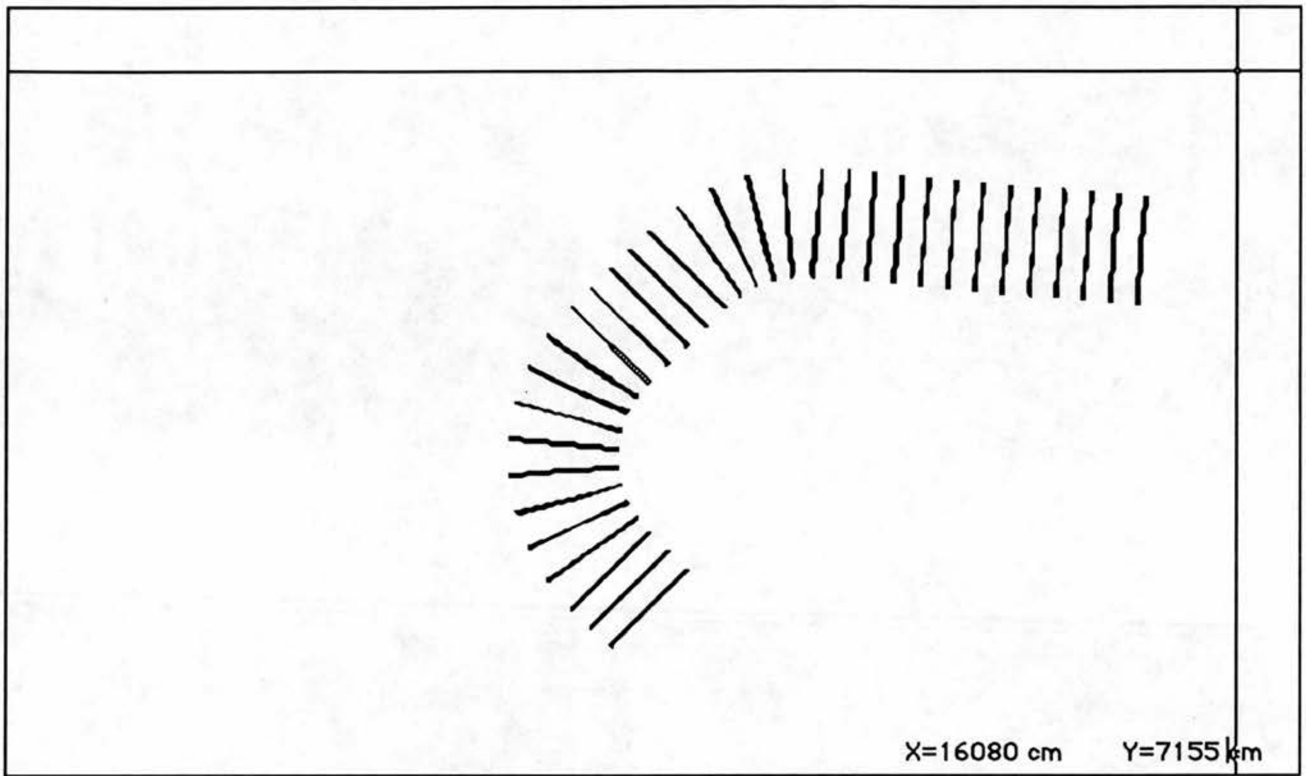
Student A; Instance 014

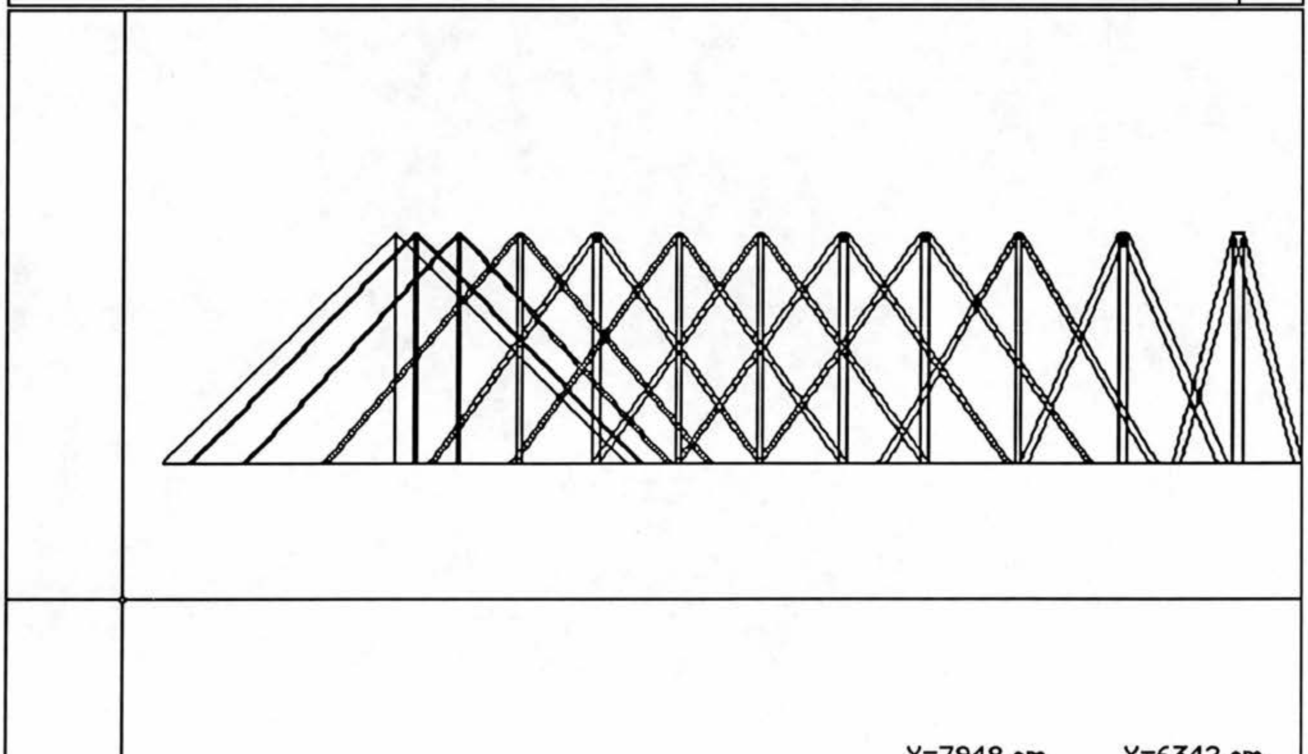


Student A; Instance 015

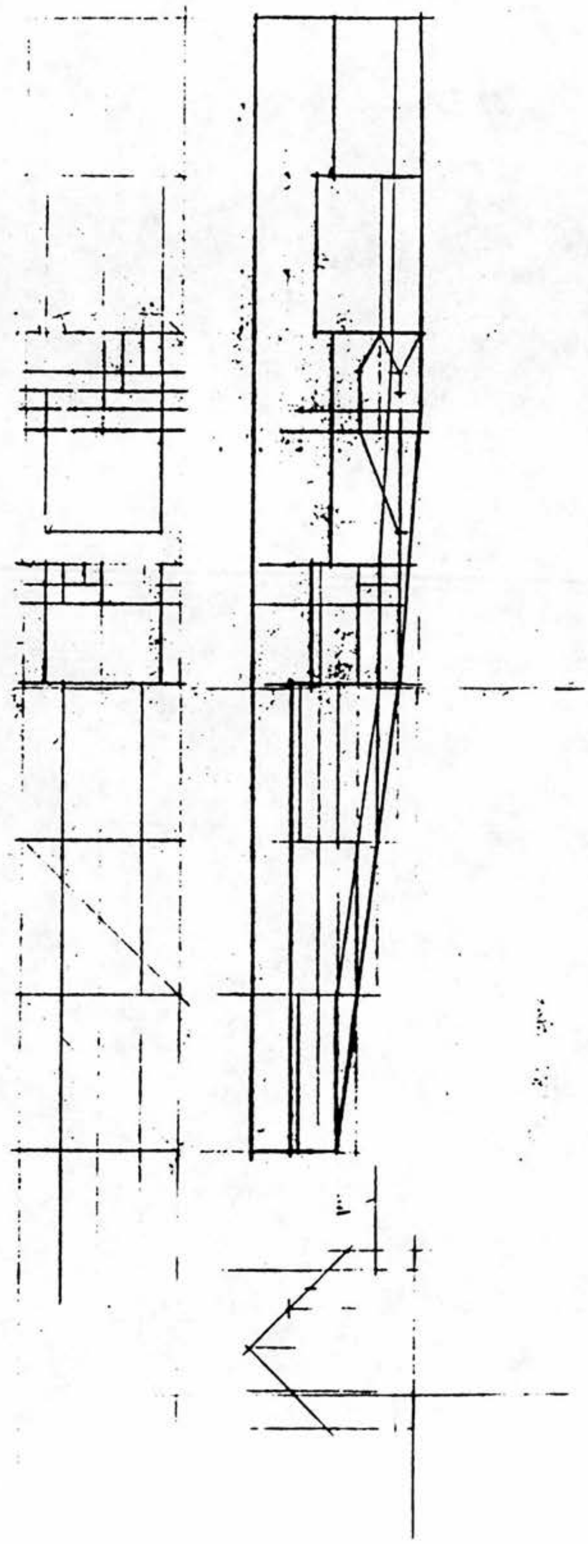


Student A; Instance 019

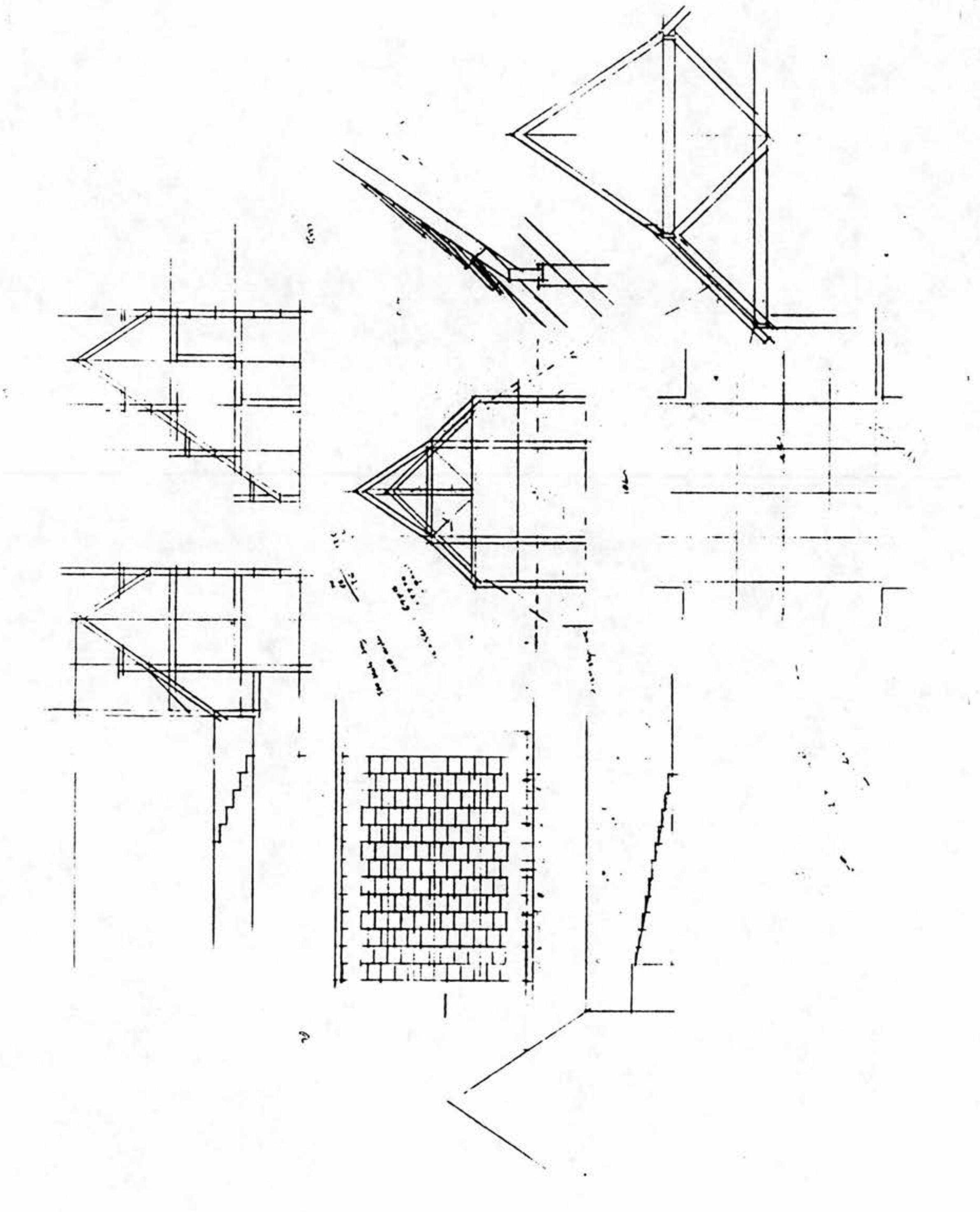




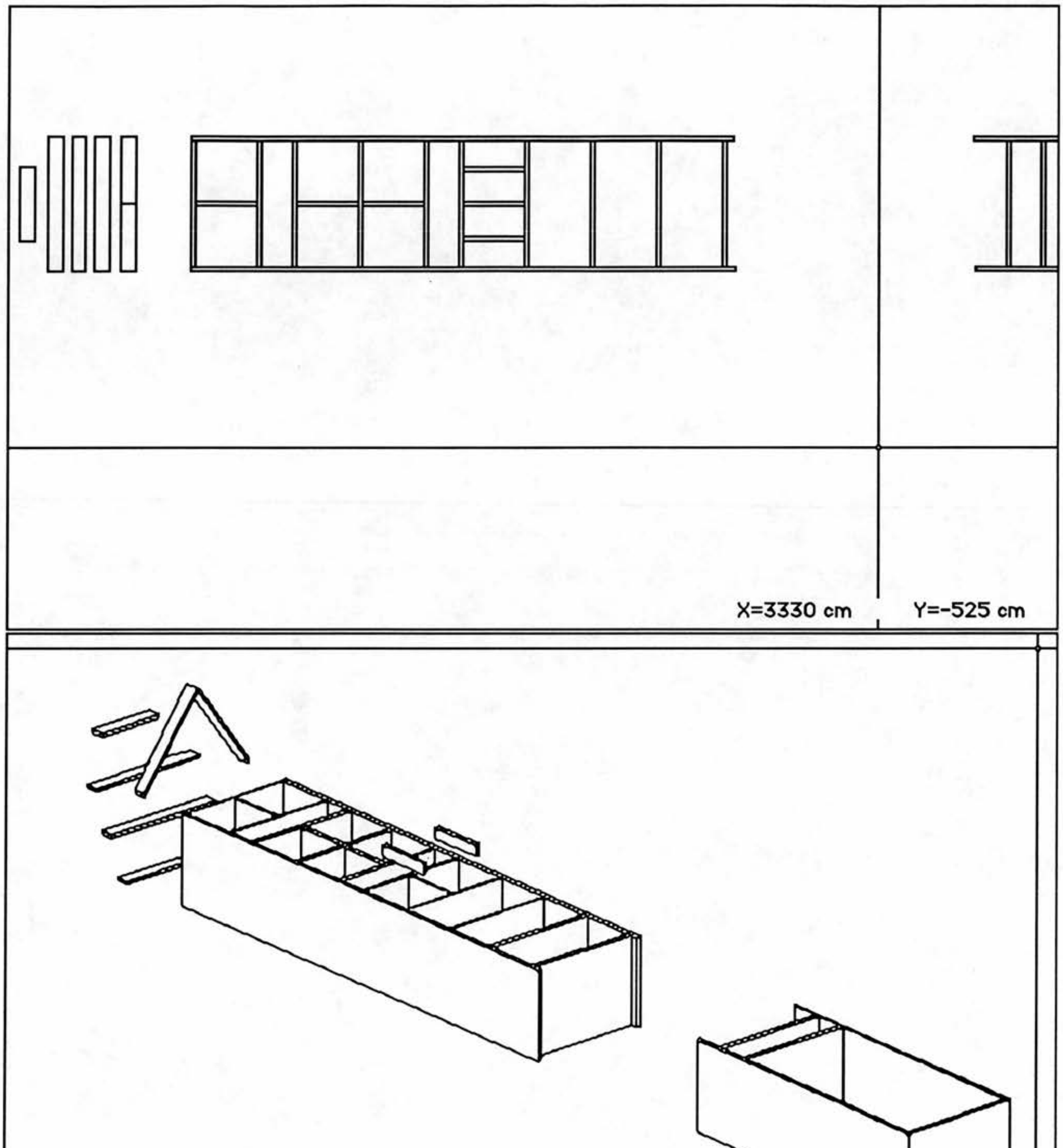
Student A; Instance 021



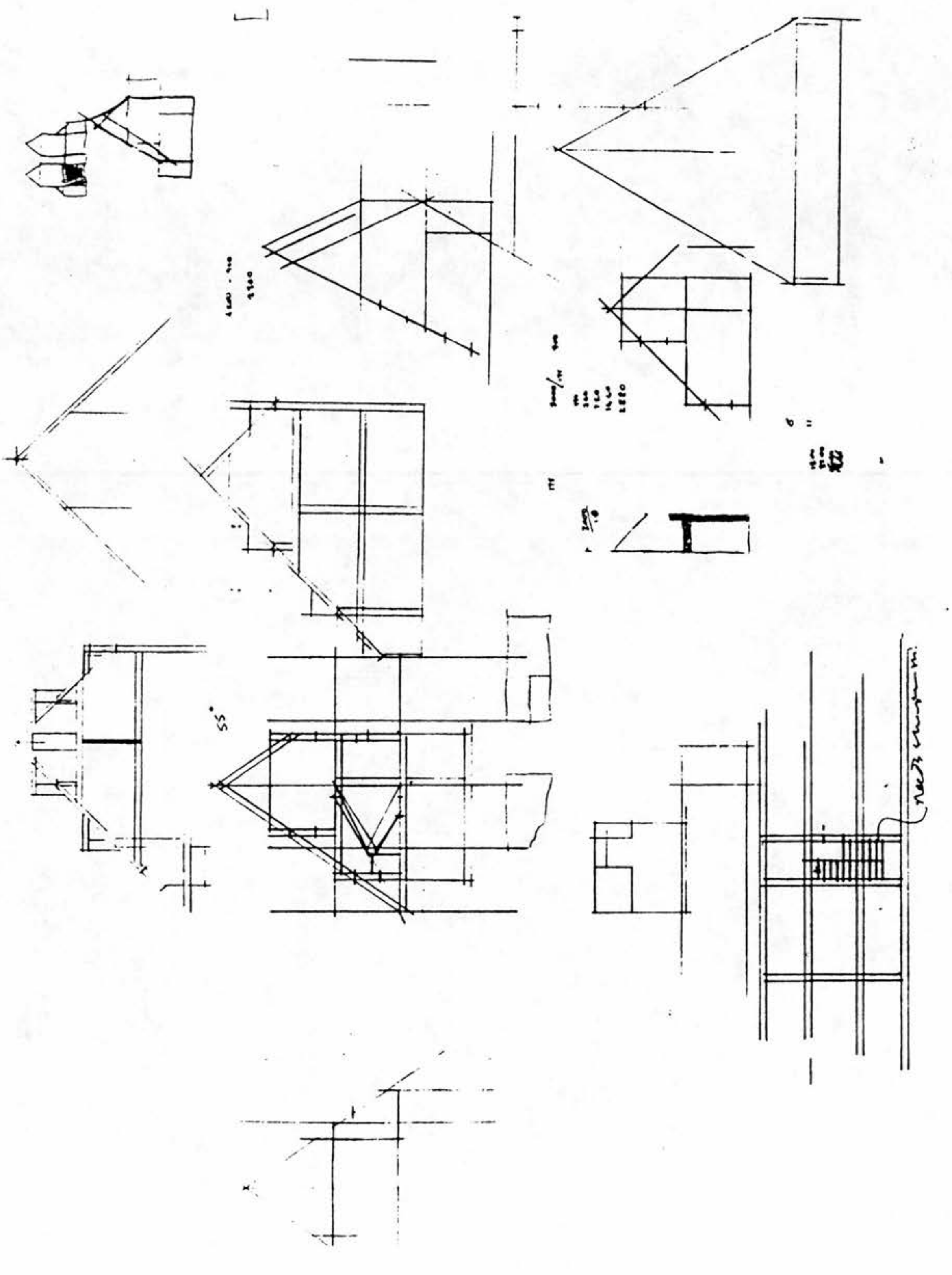
Student A; Instance 022



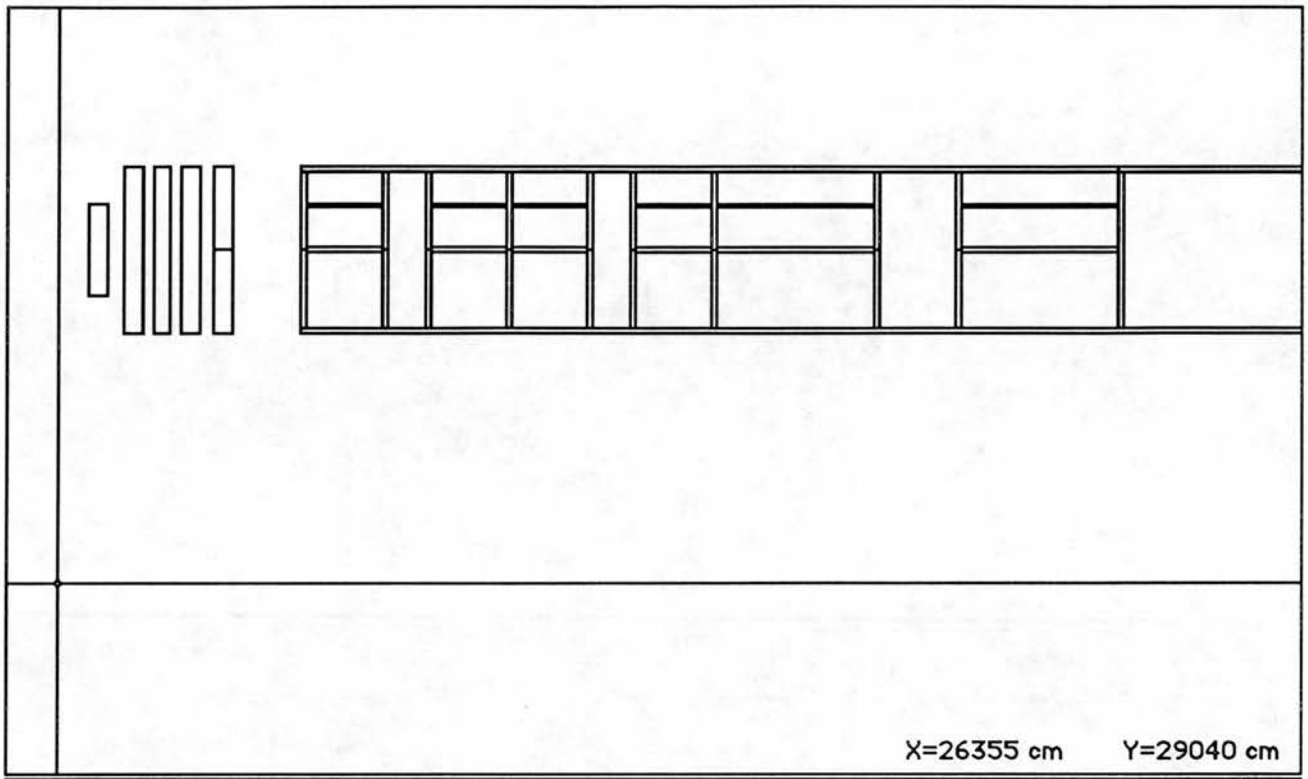
Student A; Instance 026

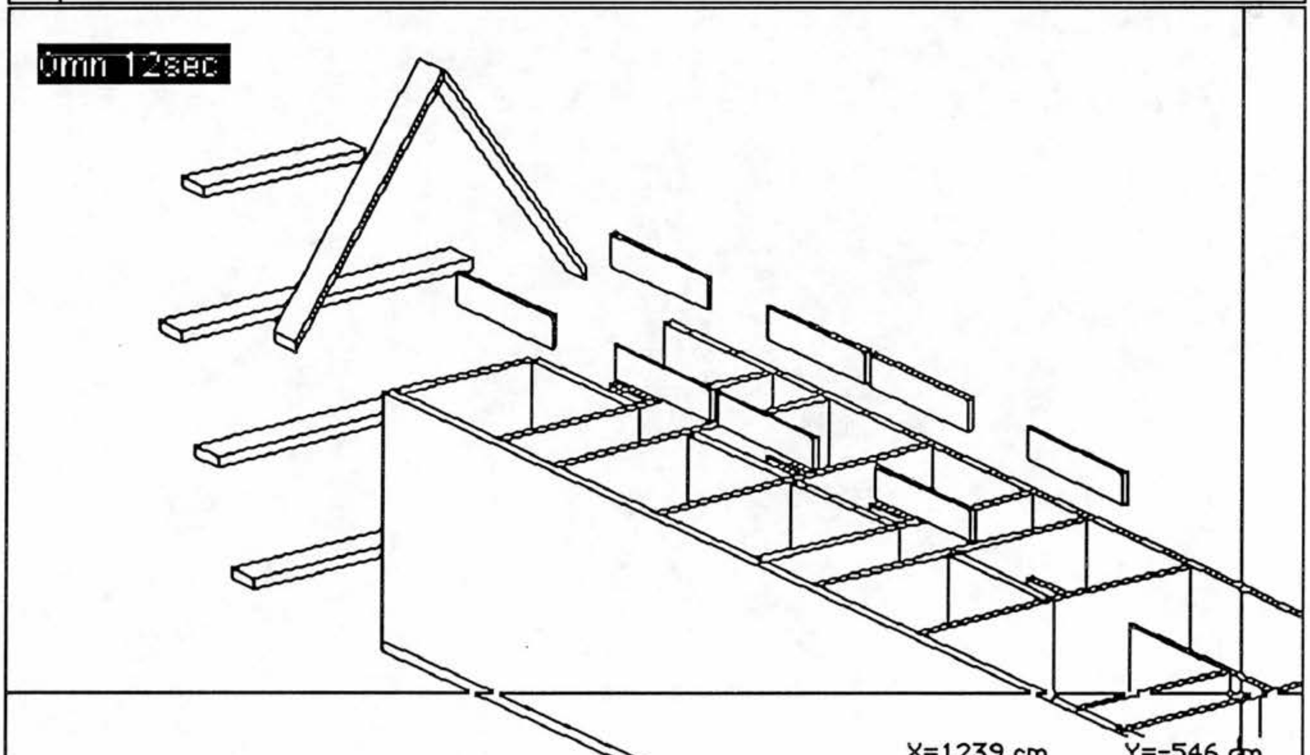


Student A; Instance 030

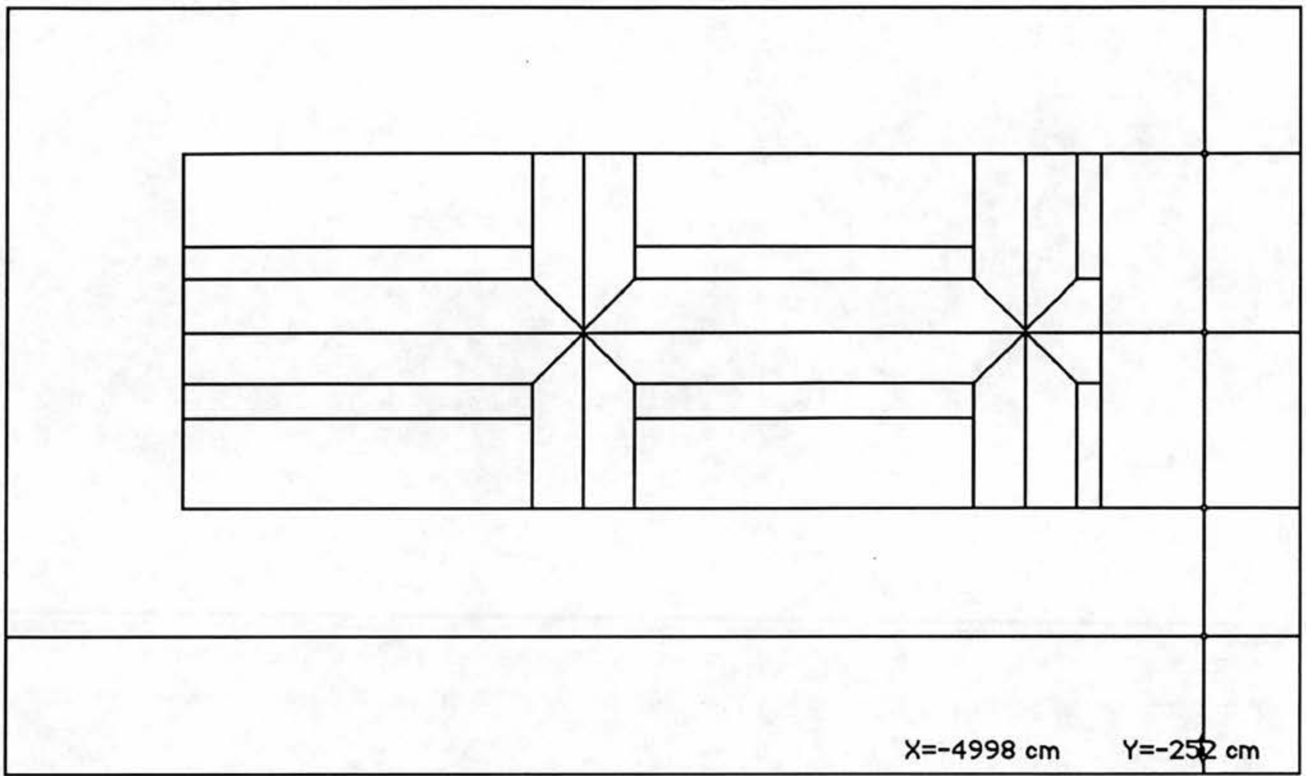


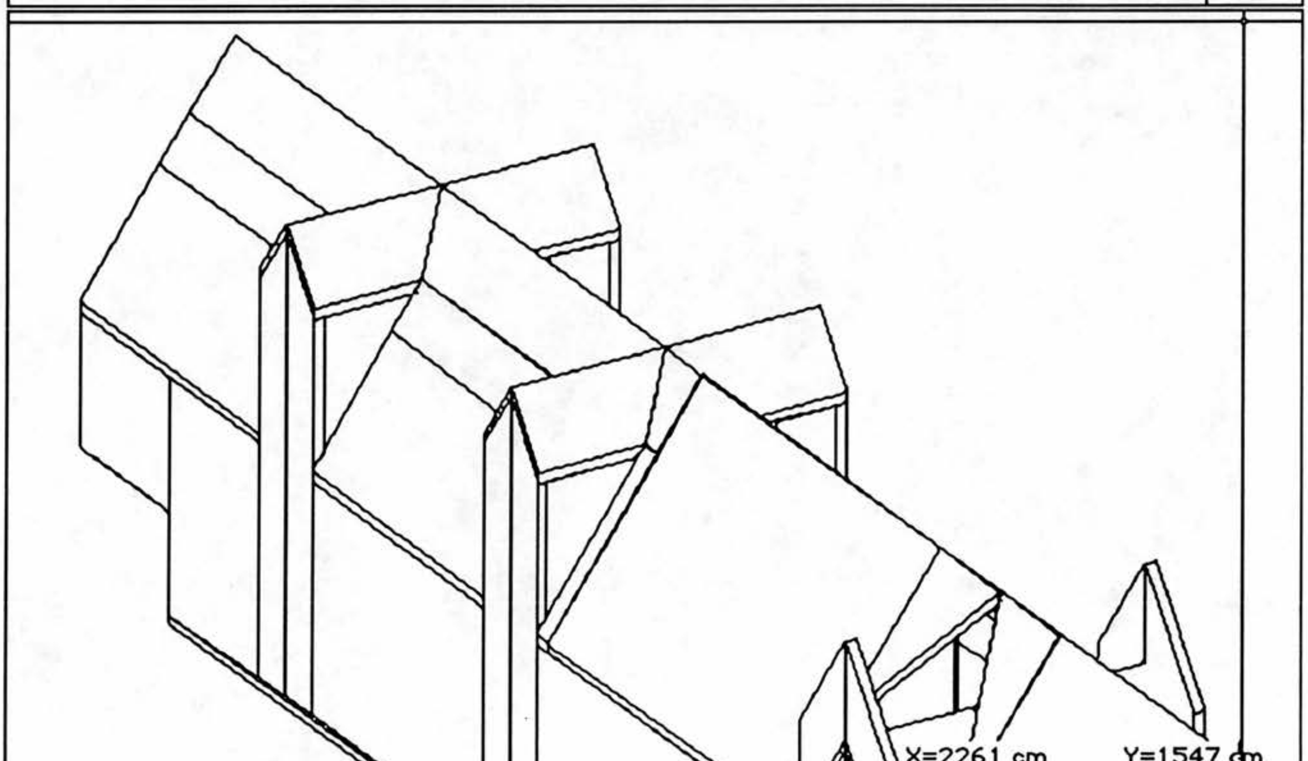
Student A; Instance 032



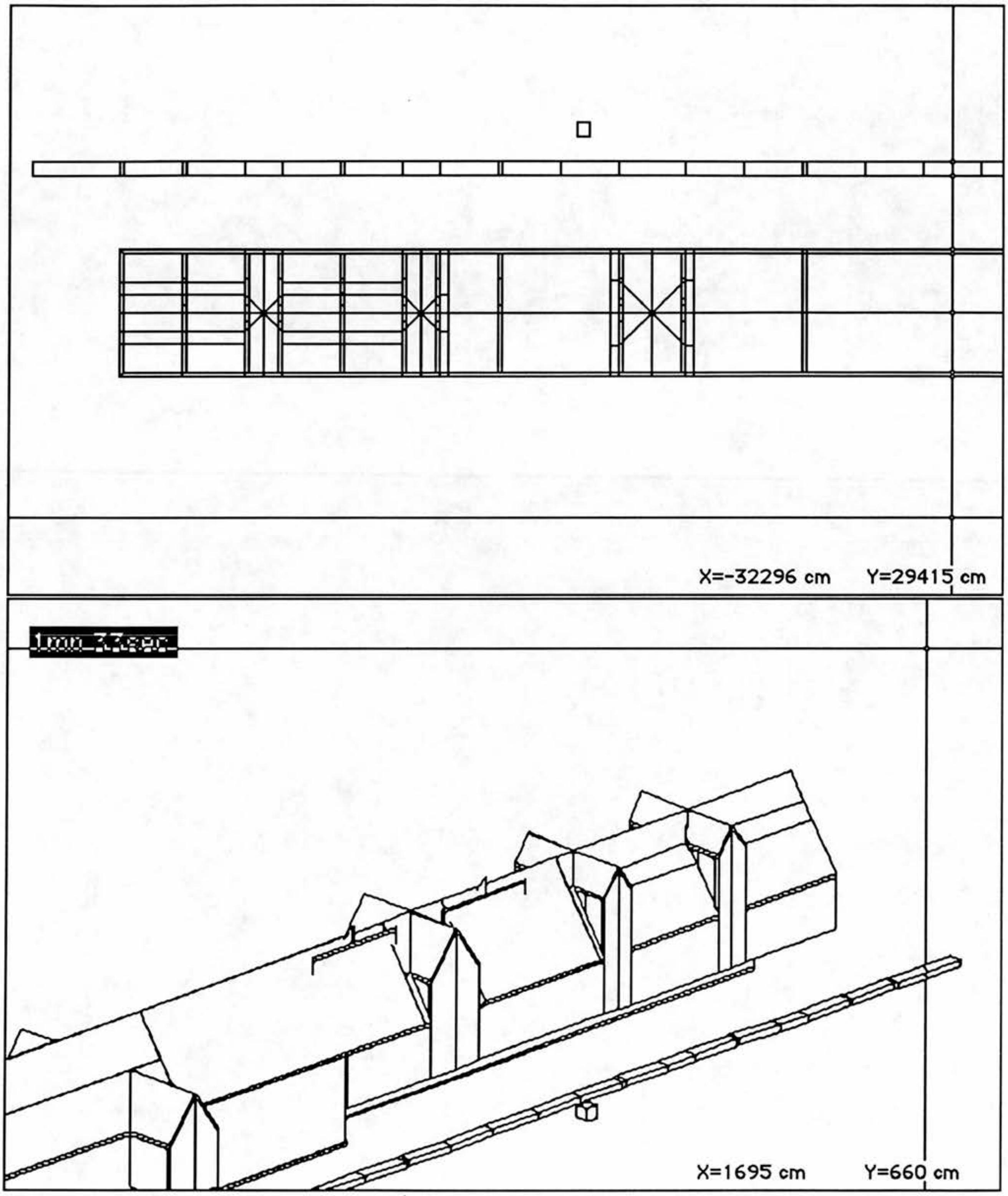


Student A; Instance 038

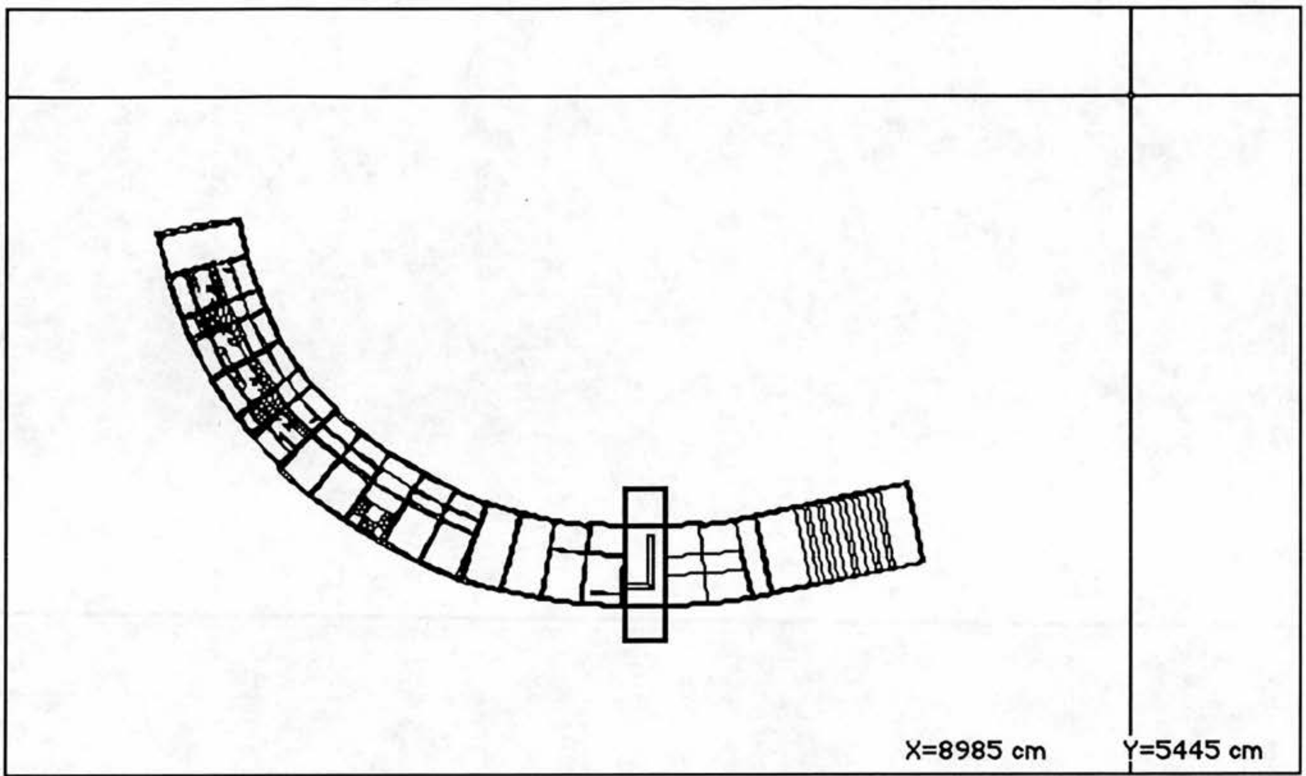


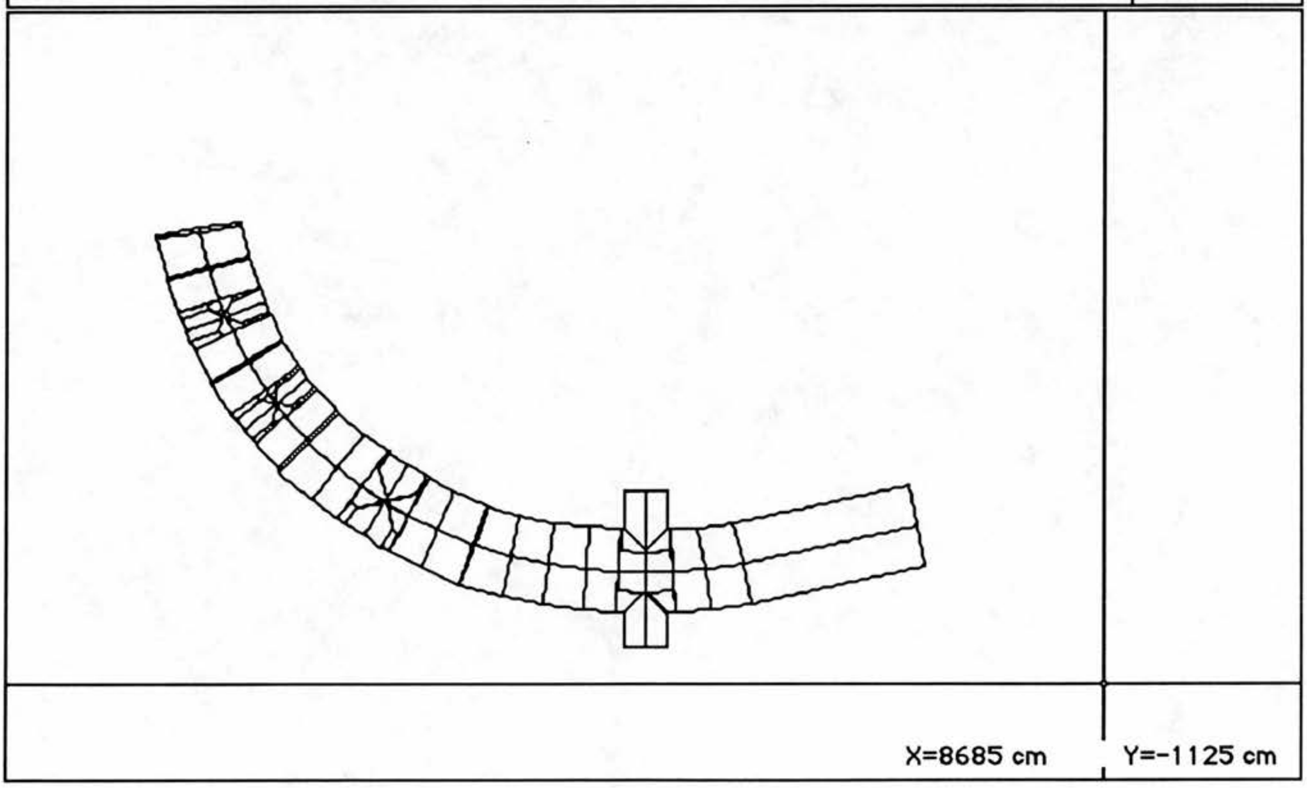


Student A; Instance 041

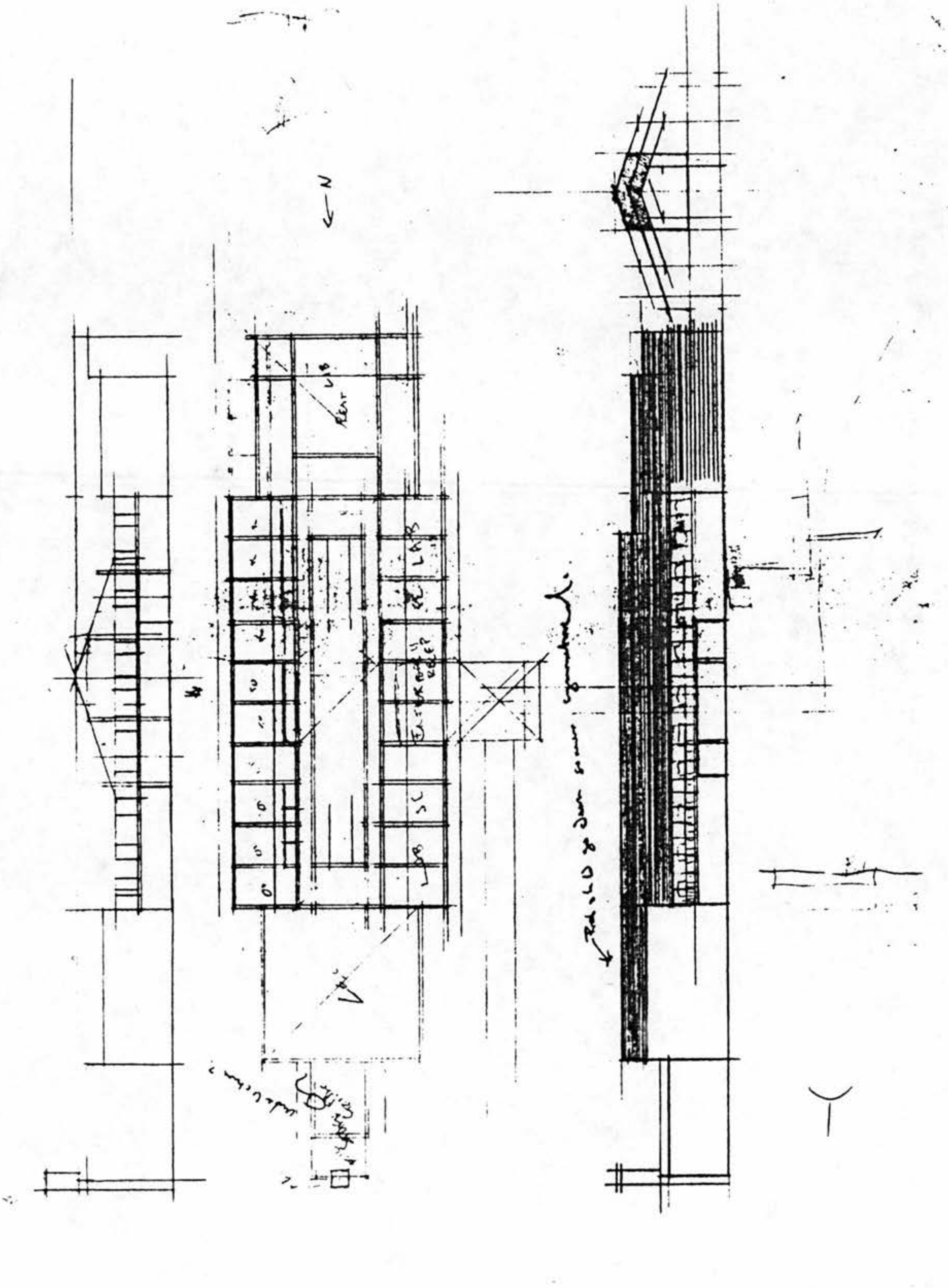


Student A; Instance 044

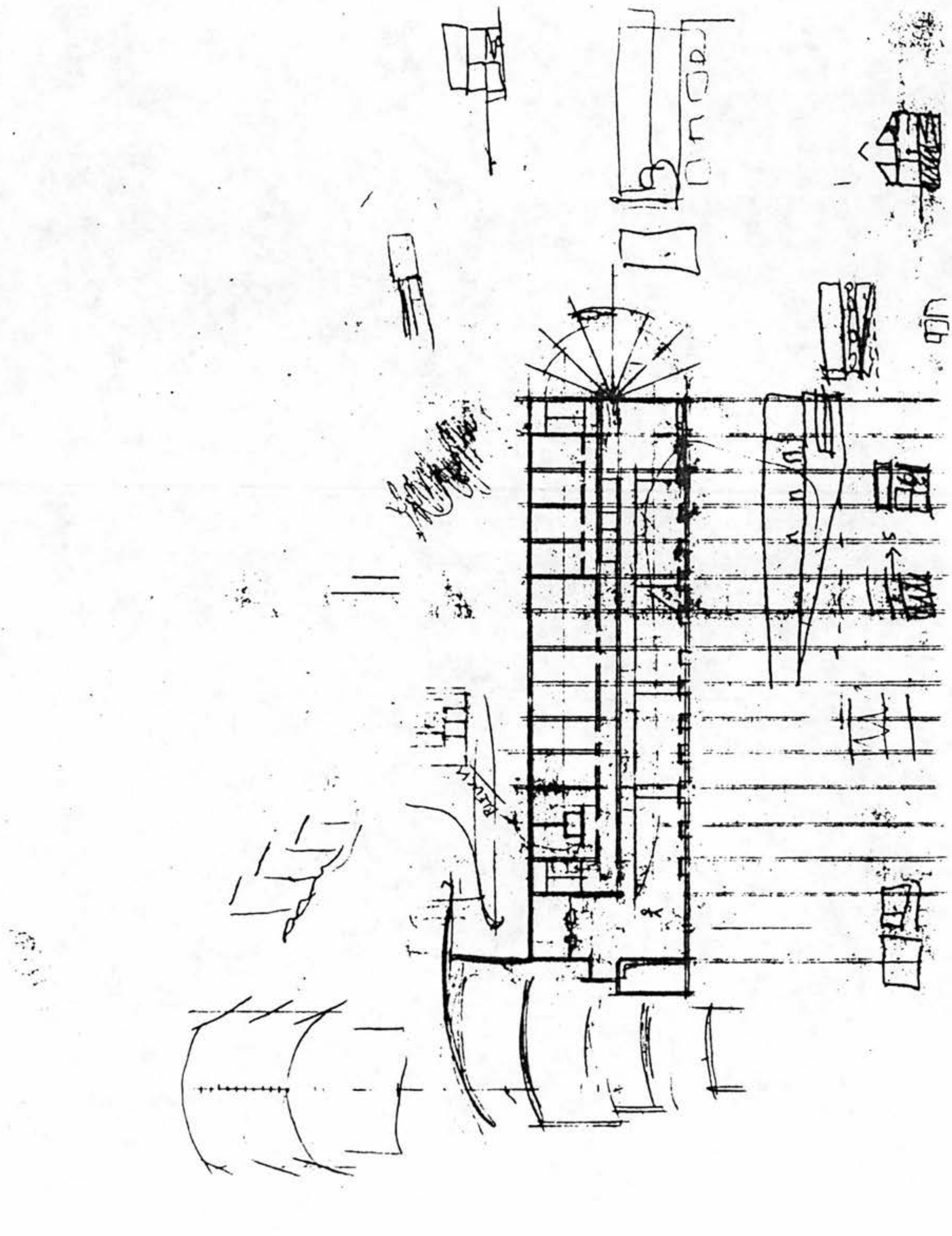




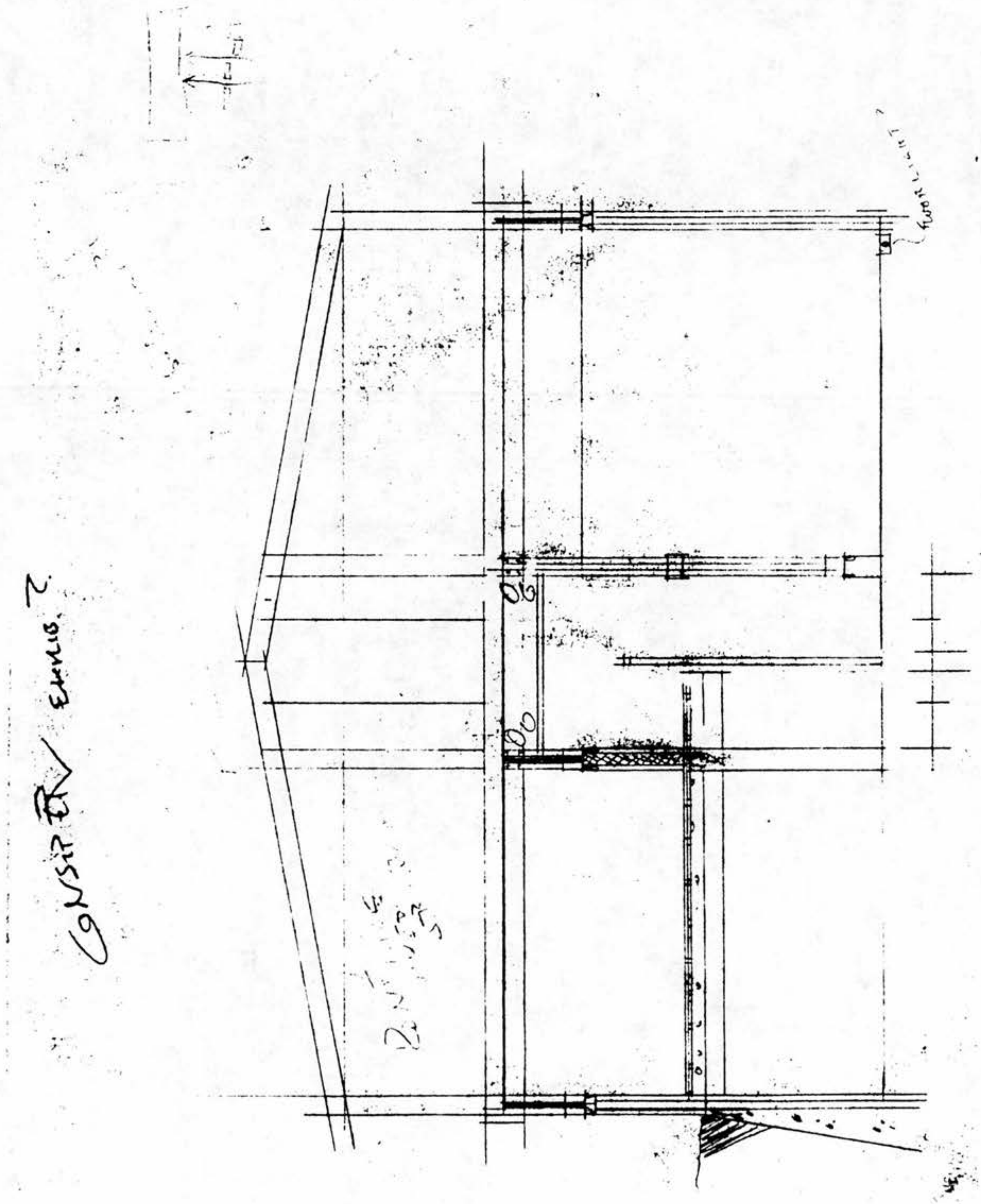
Student A; Instance 046



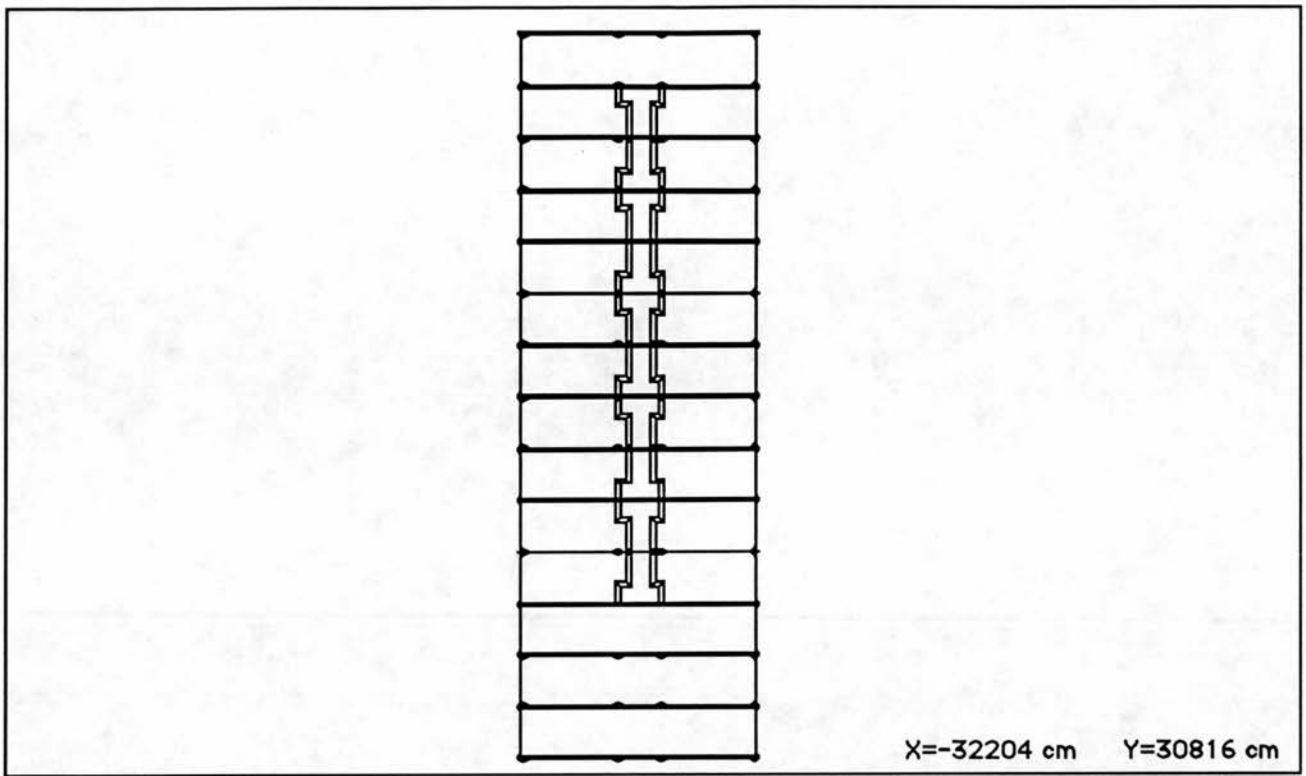
Student A; Instance 075

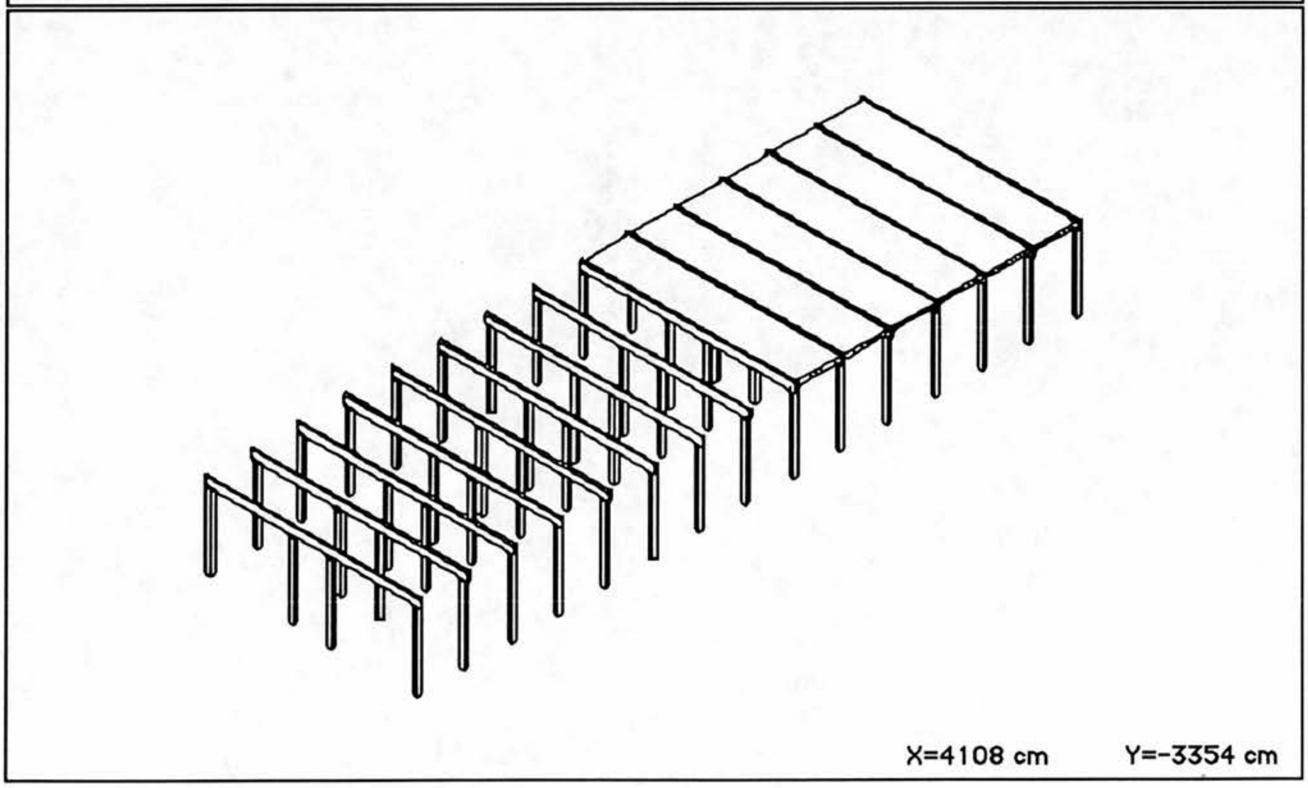


Student A; Instance 081

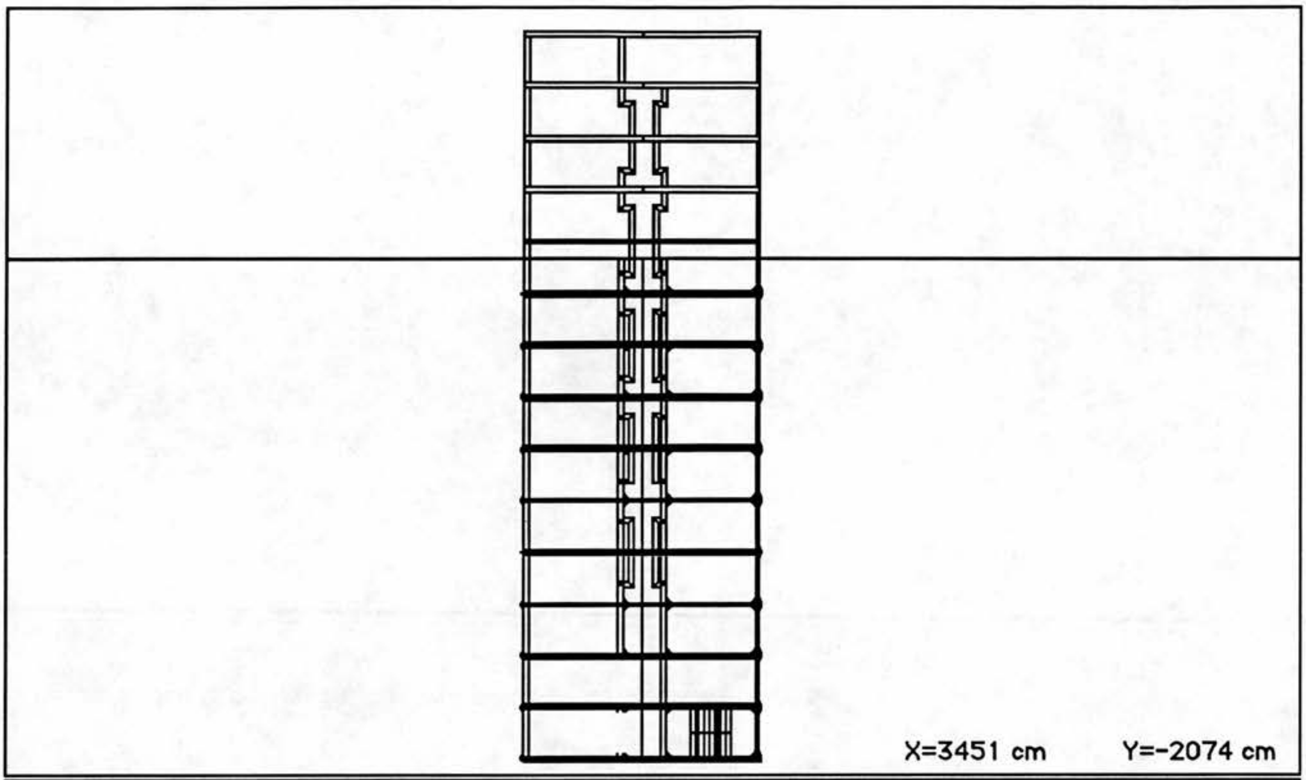


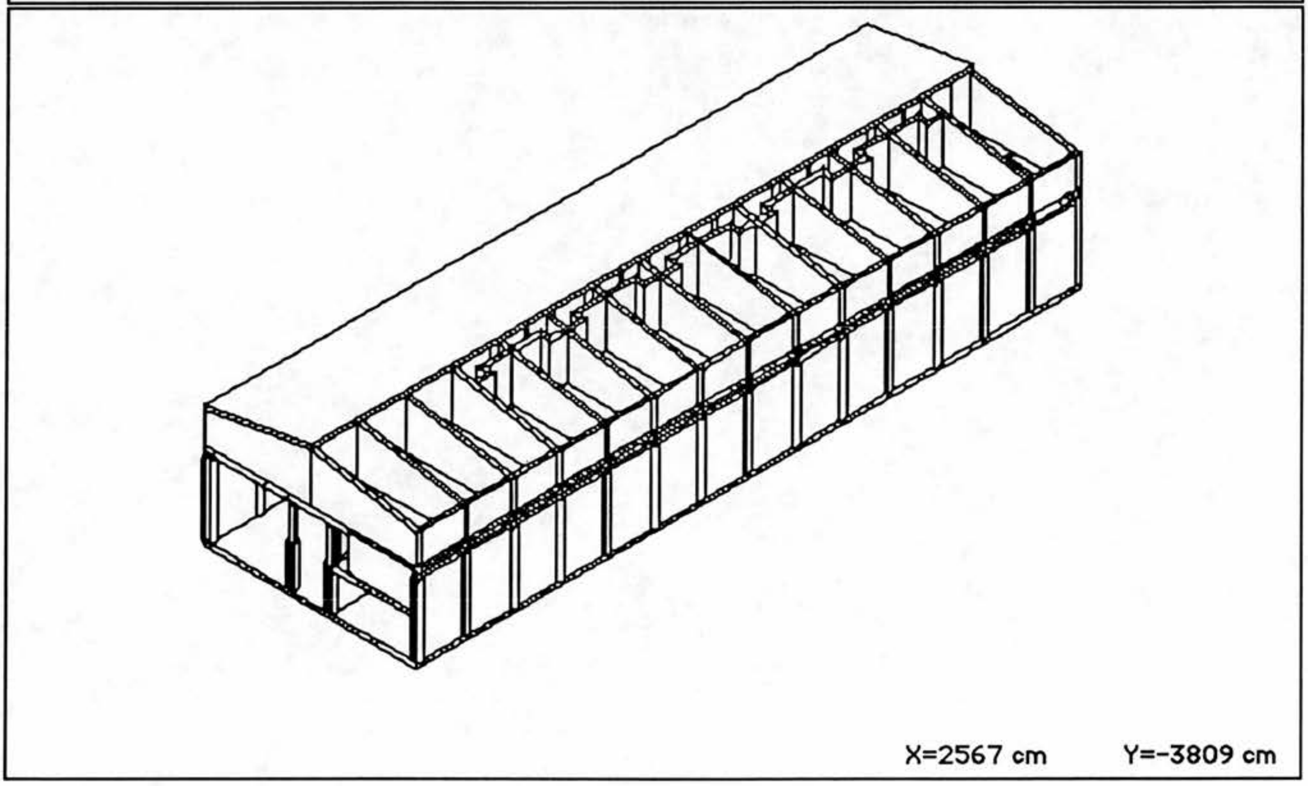
Student A; Instance 087



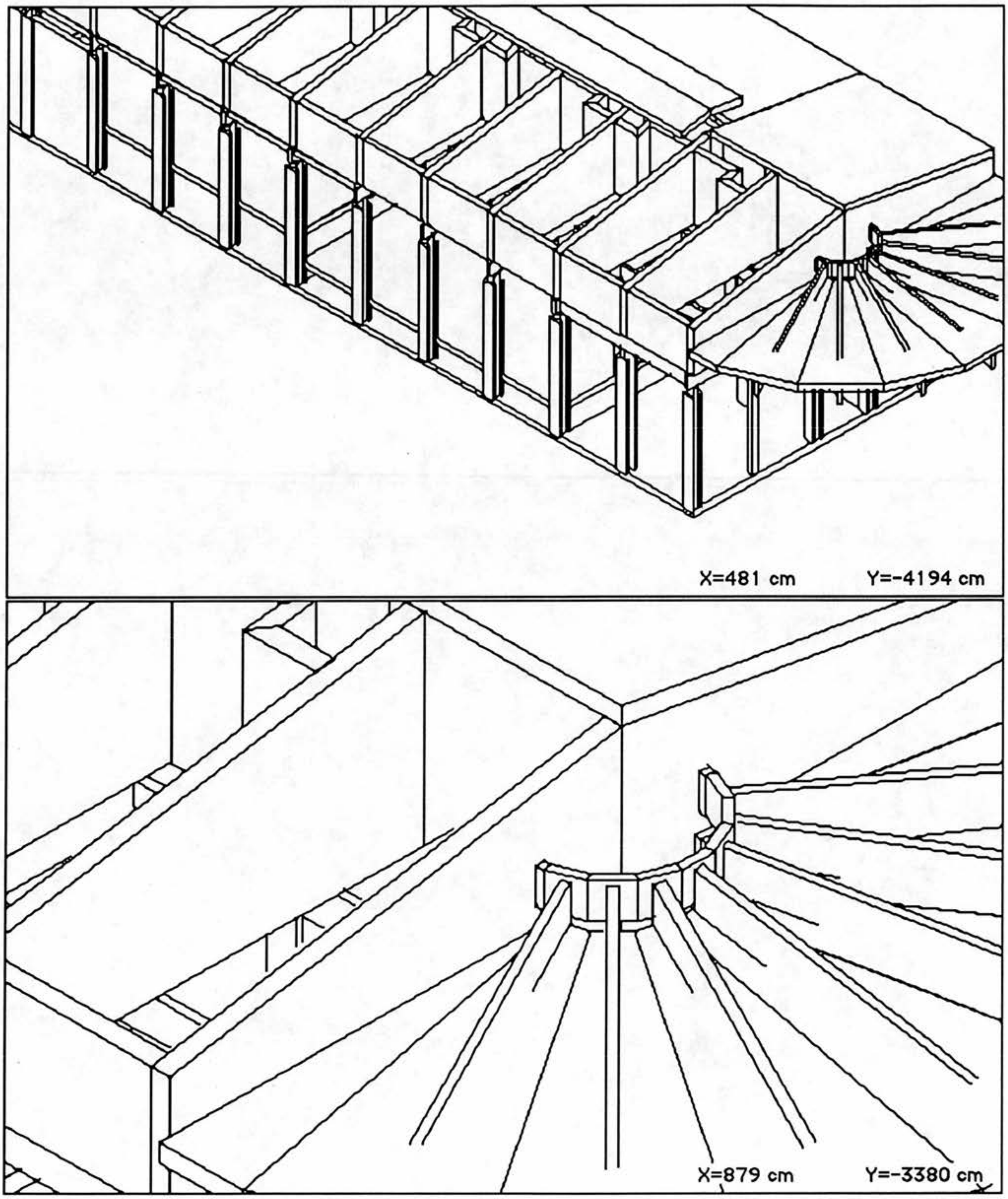


Student A; Instance 088

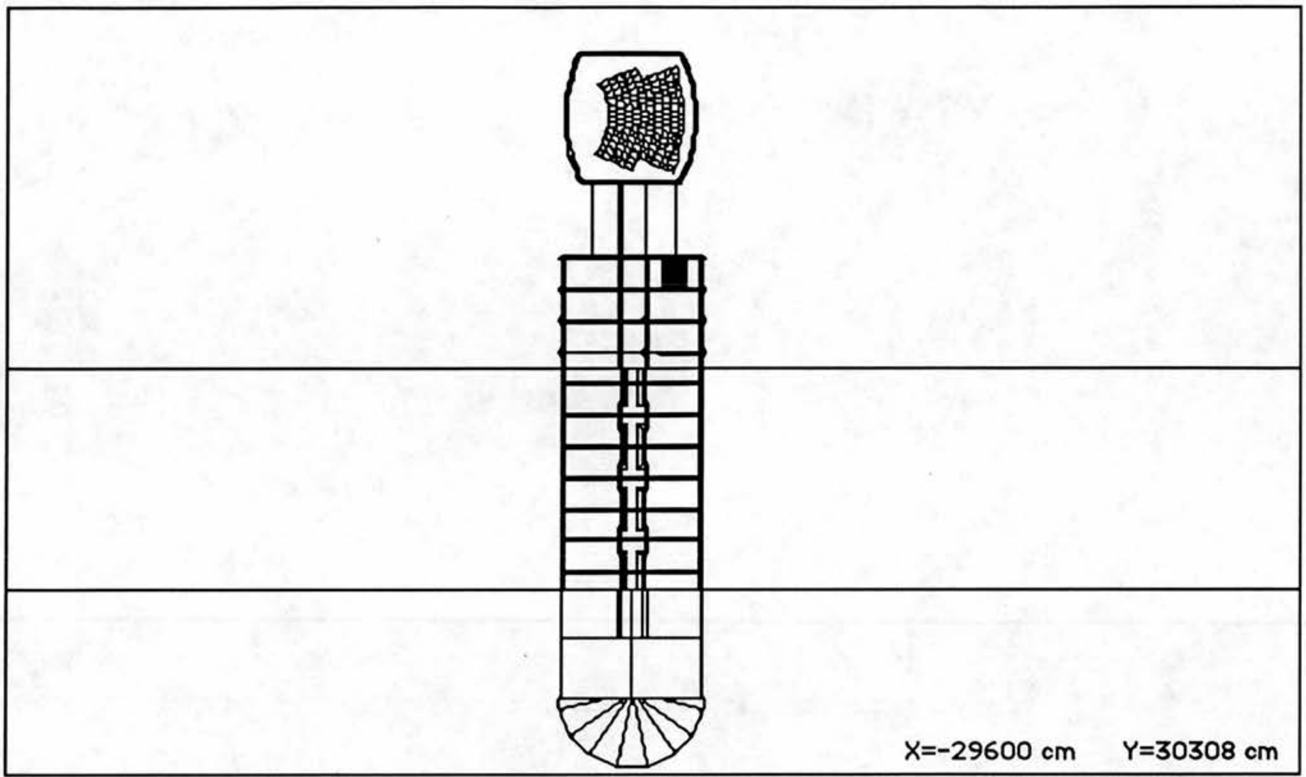


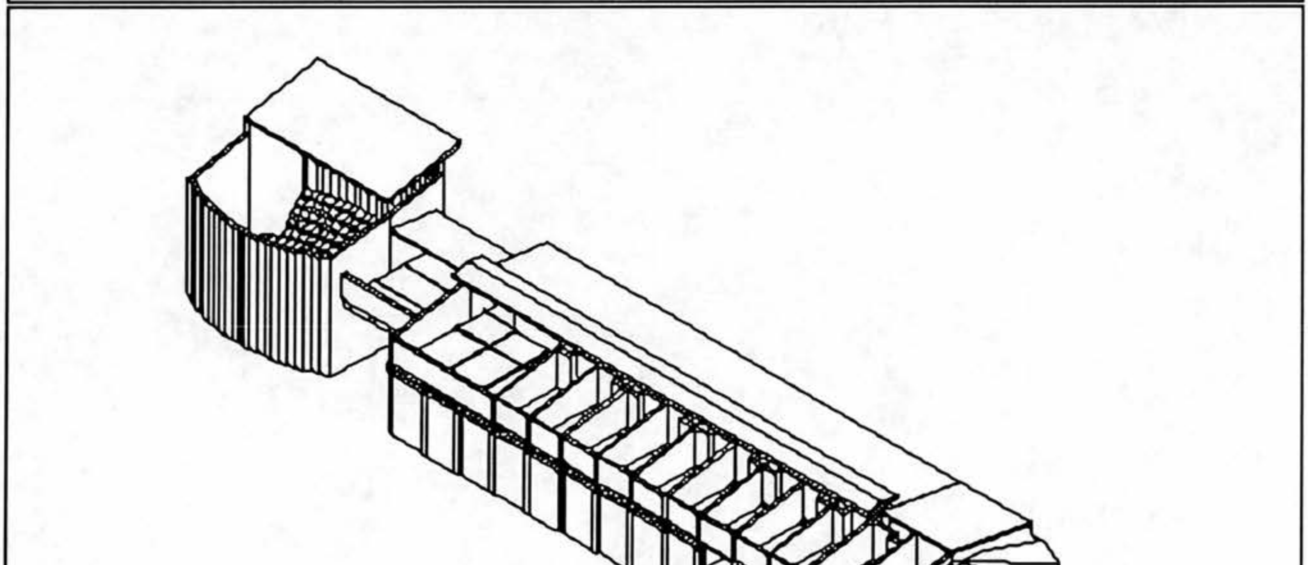


Student A; Instance 094

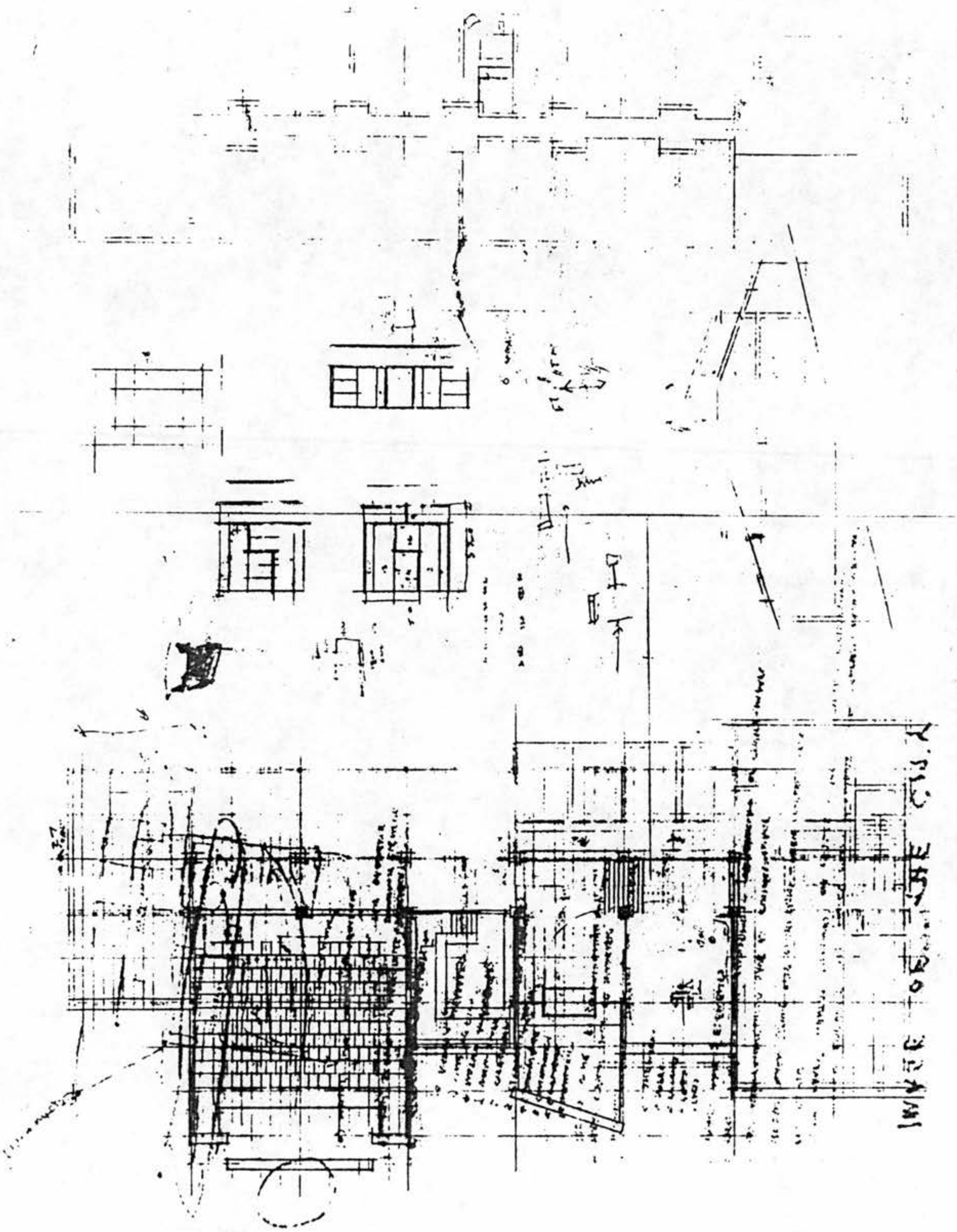


Student A; Instance 098

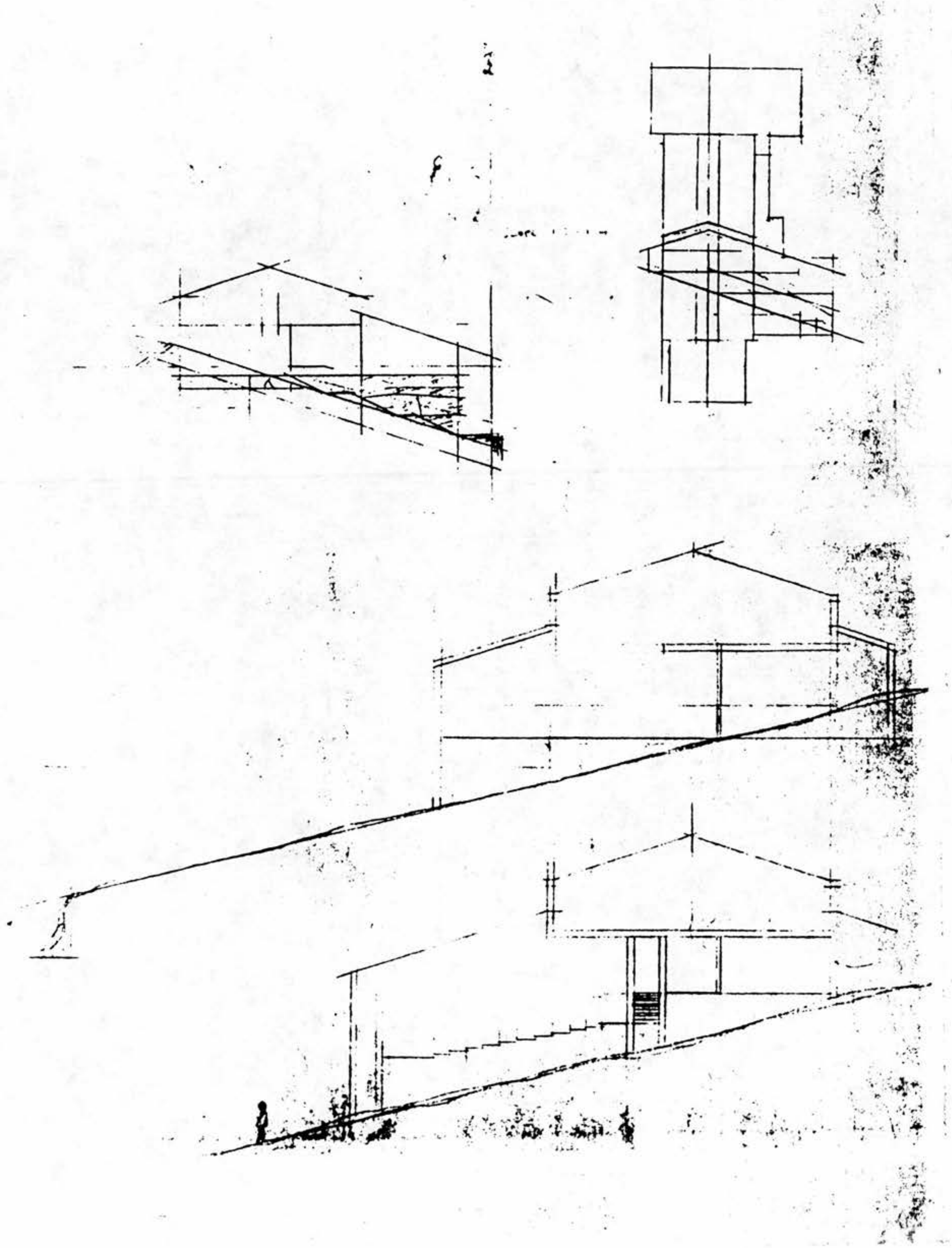




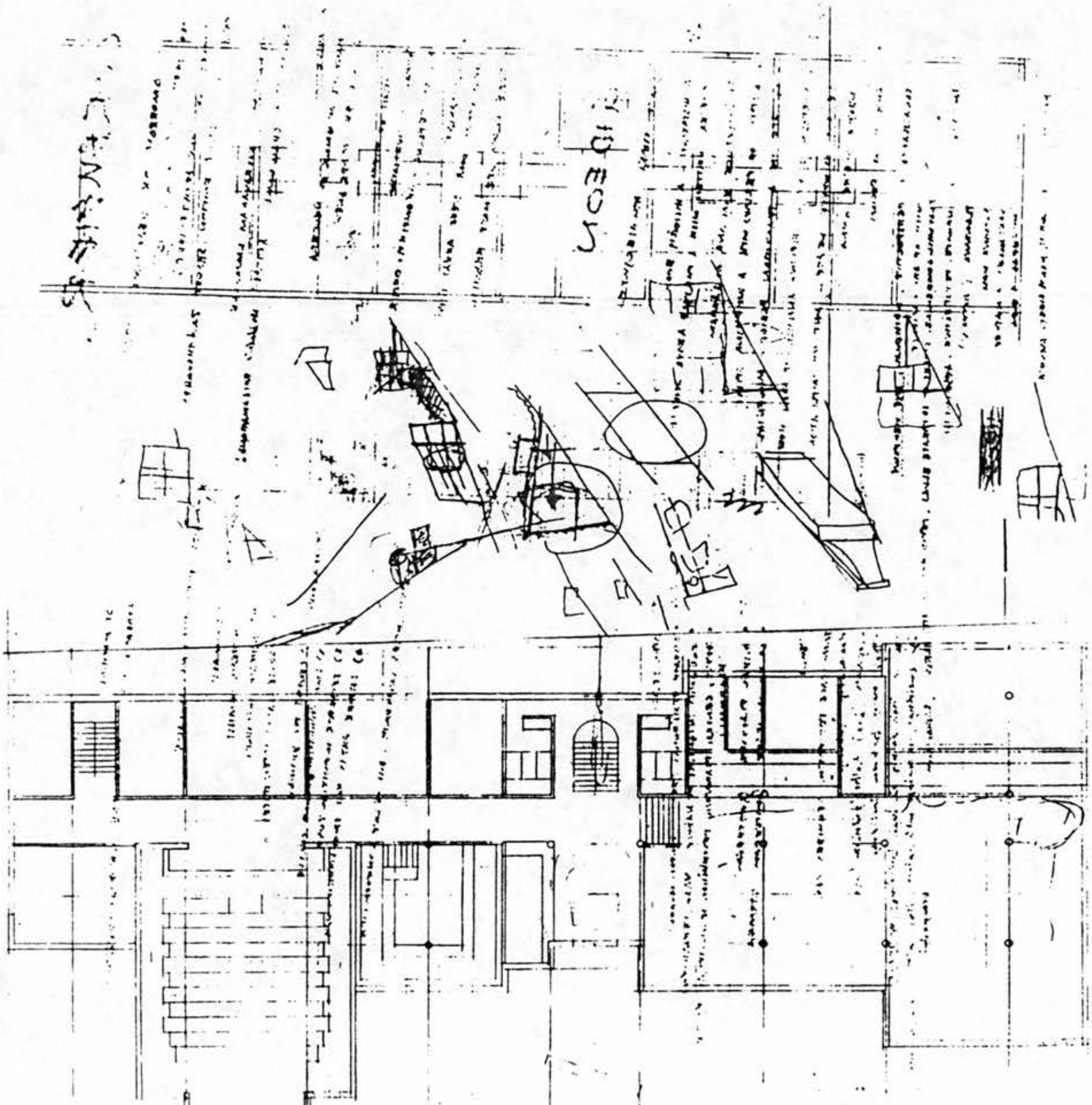
Student A; Instance 108



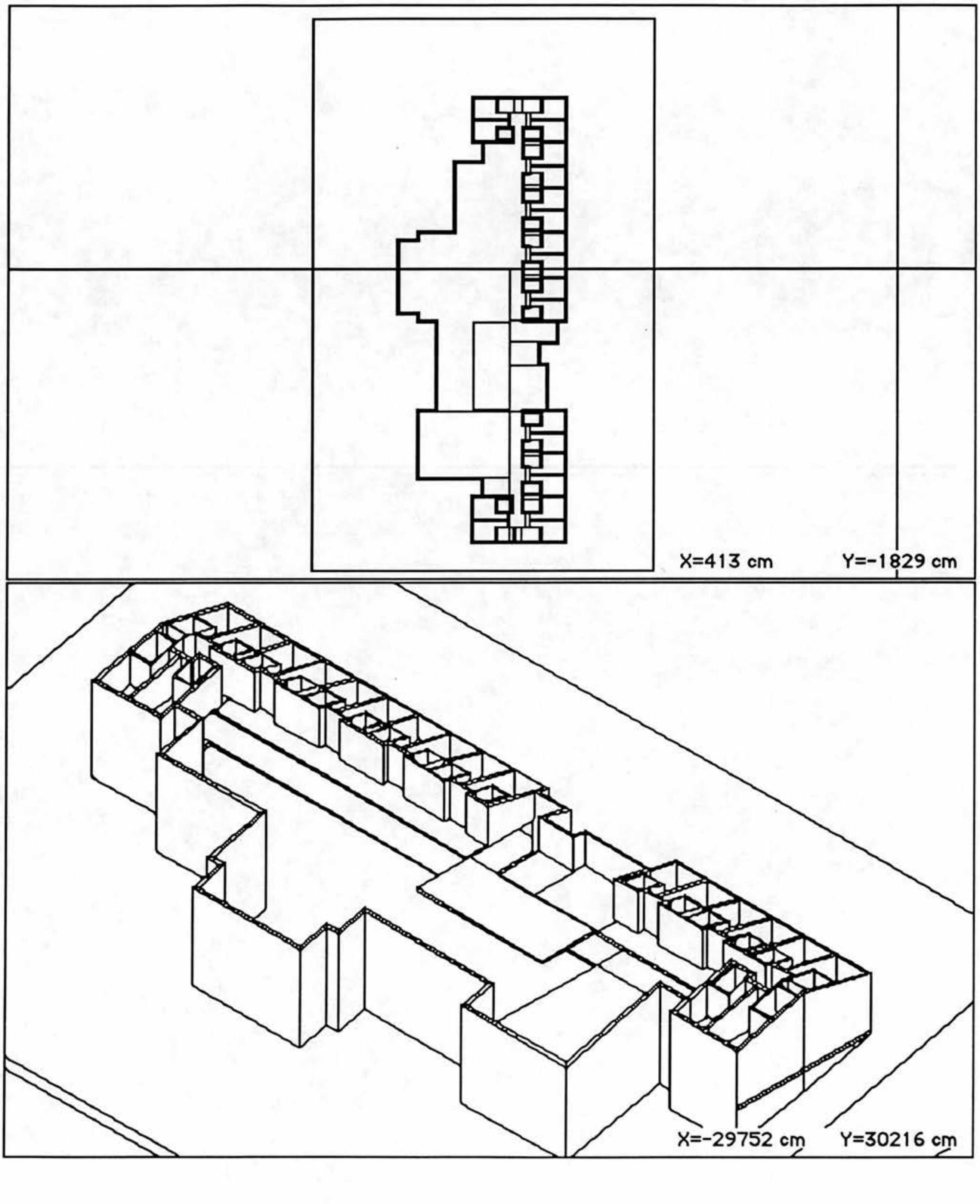
Student A; Instance 118



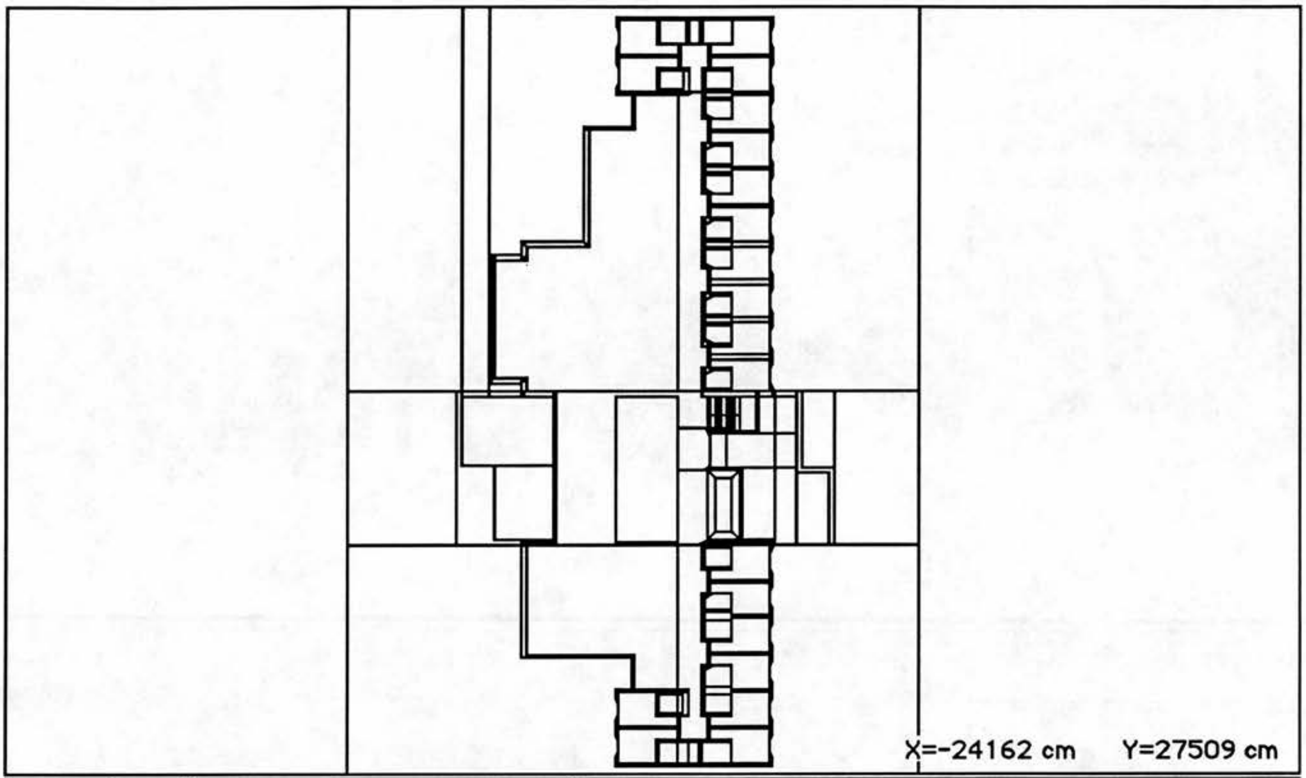
Student A; Instance 119

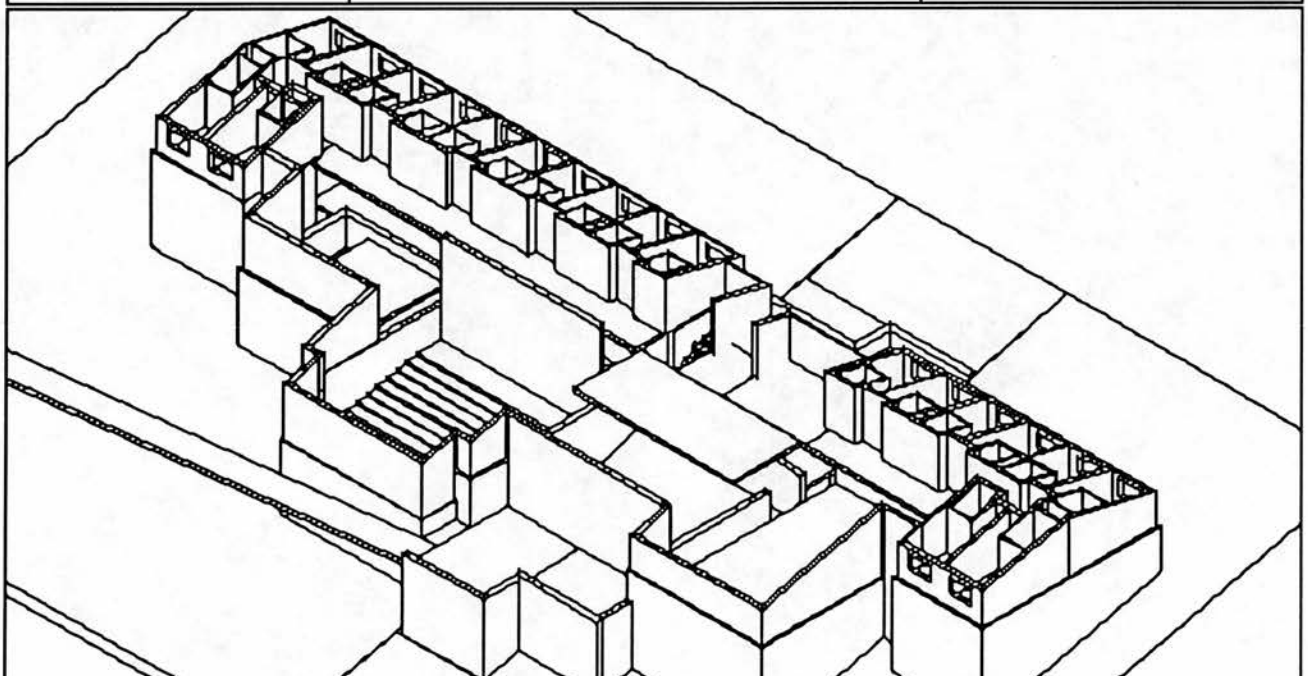


Student A; Instance 121

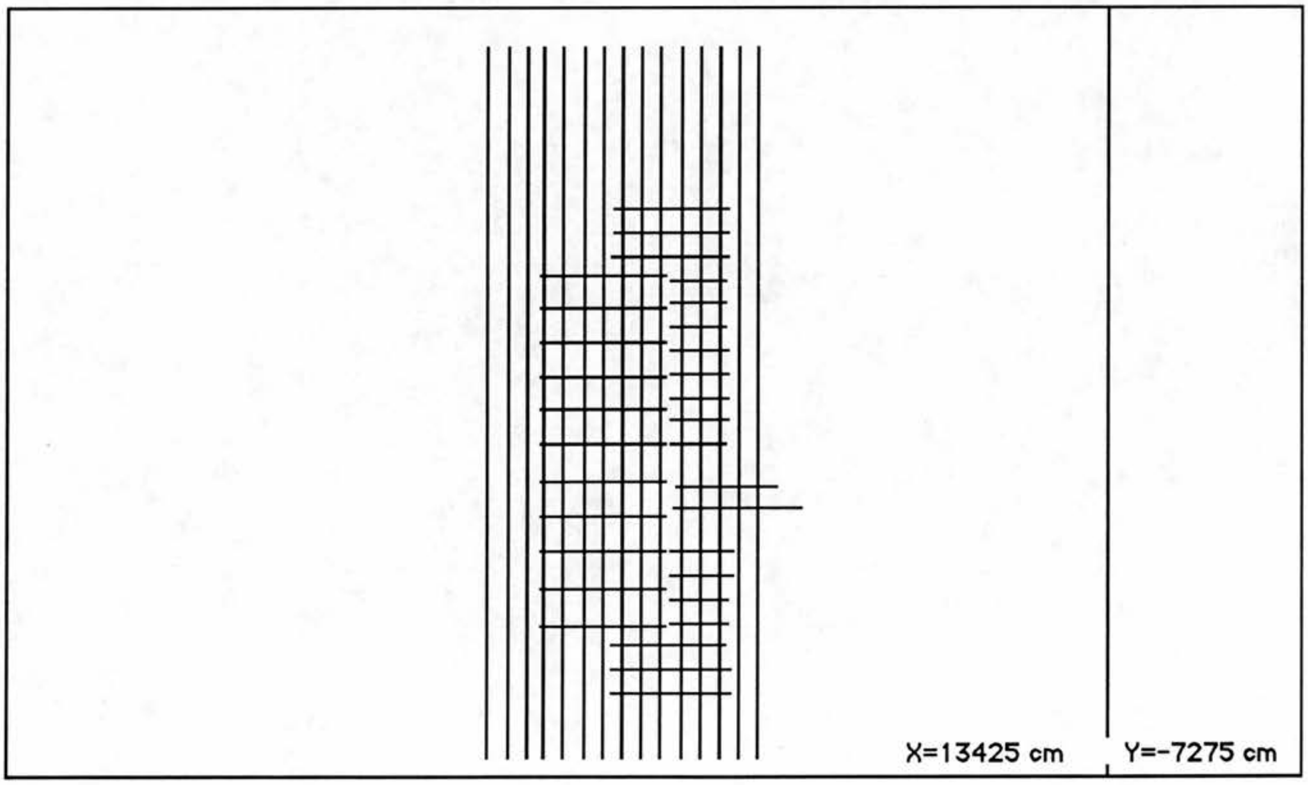


Student A; Instance 124

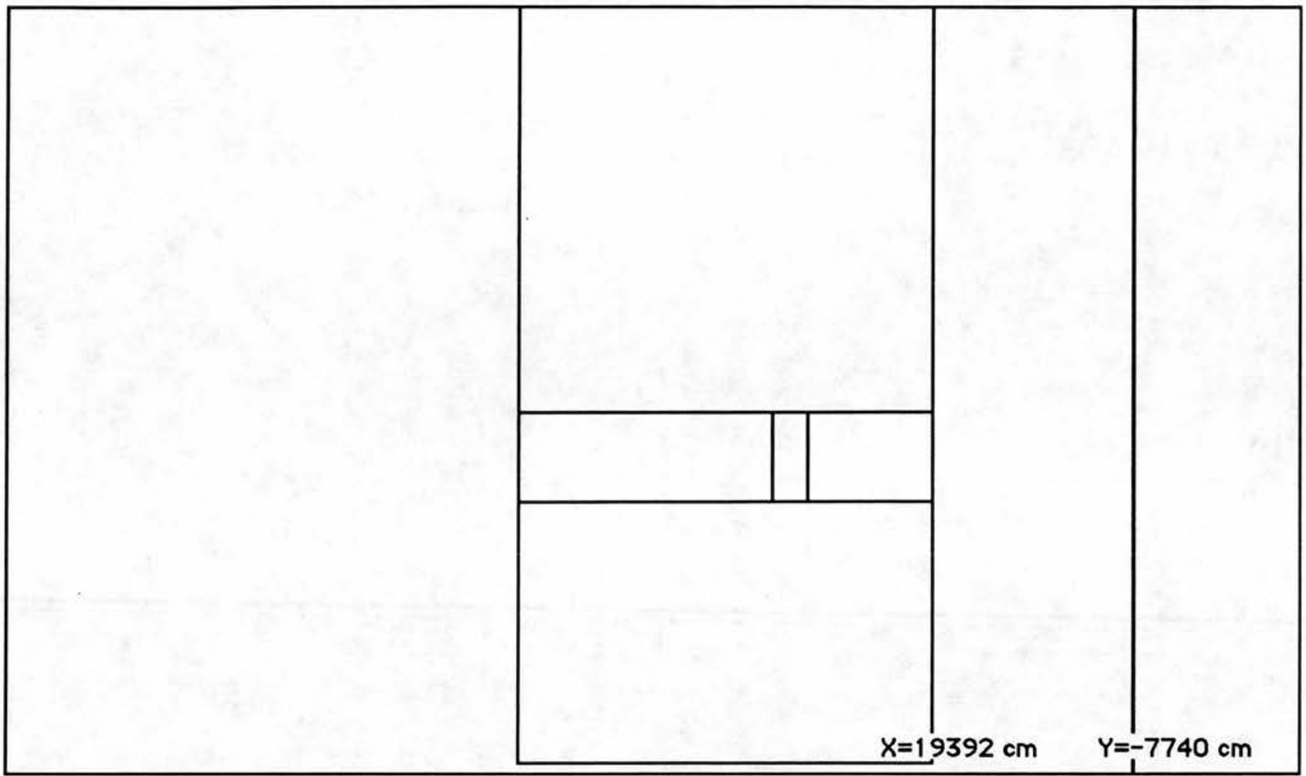


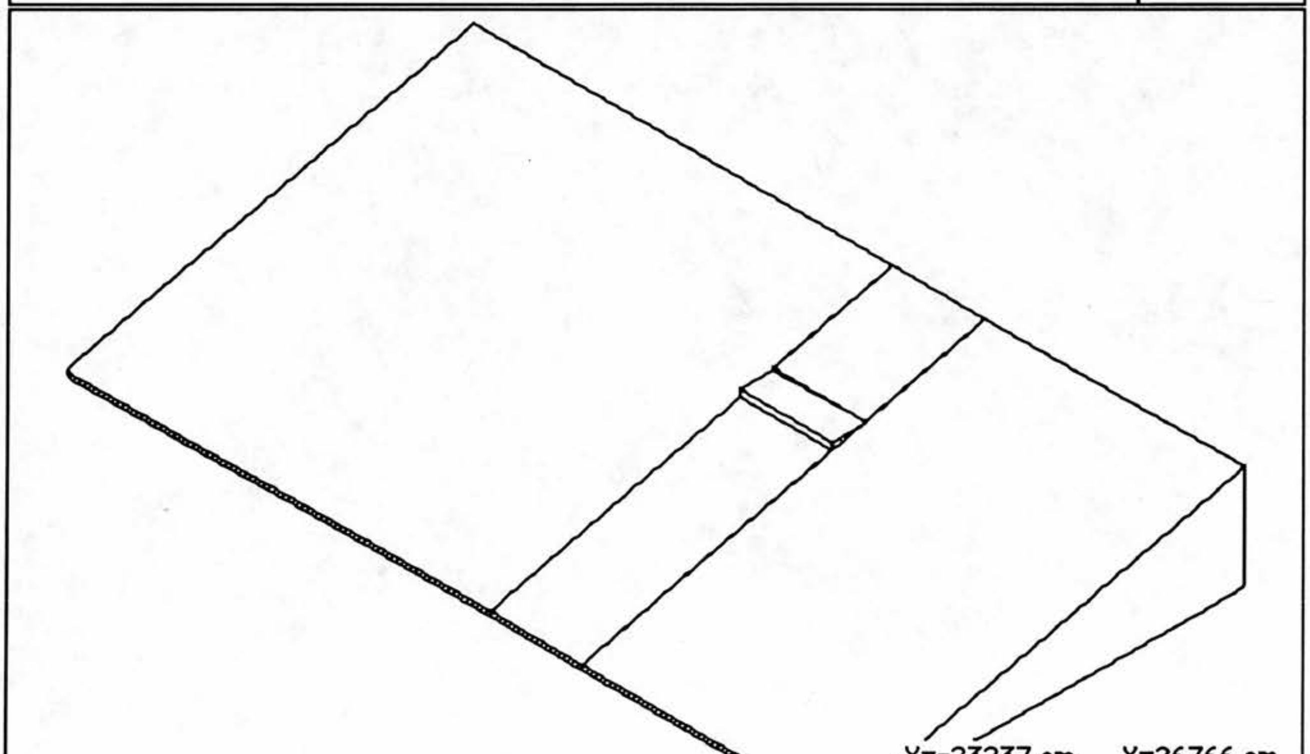


Student A; Instance 131

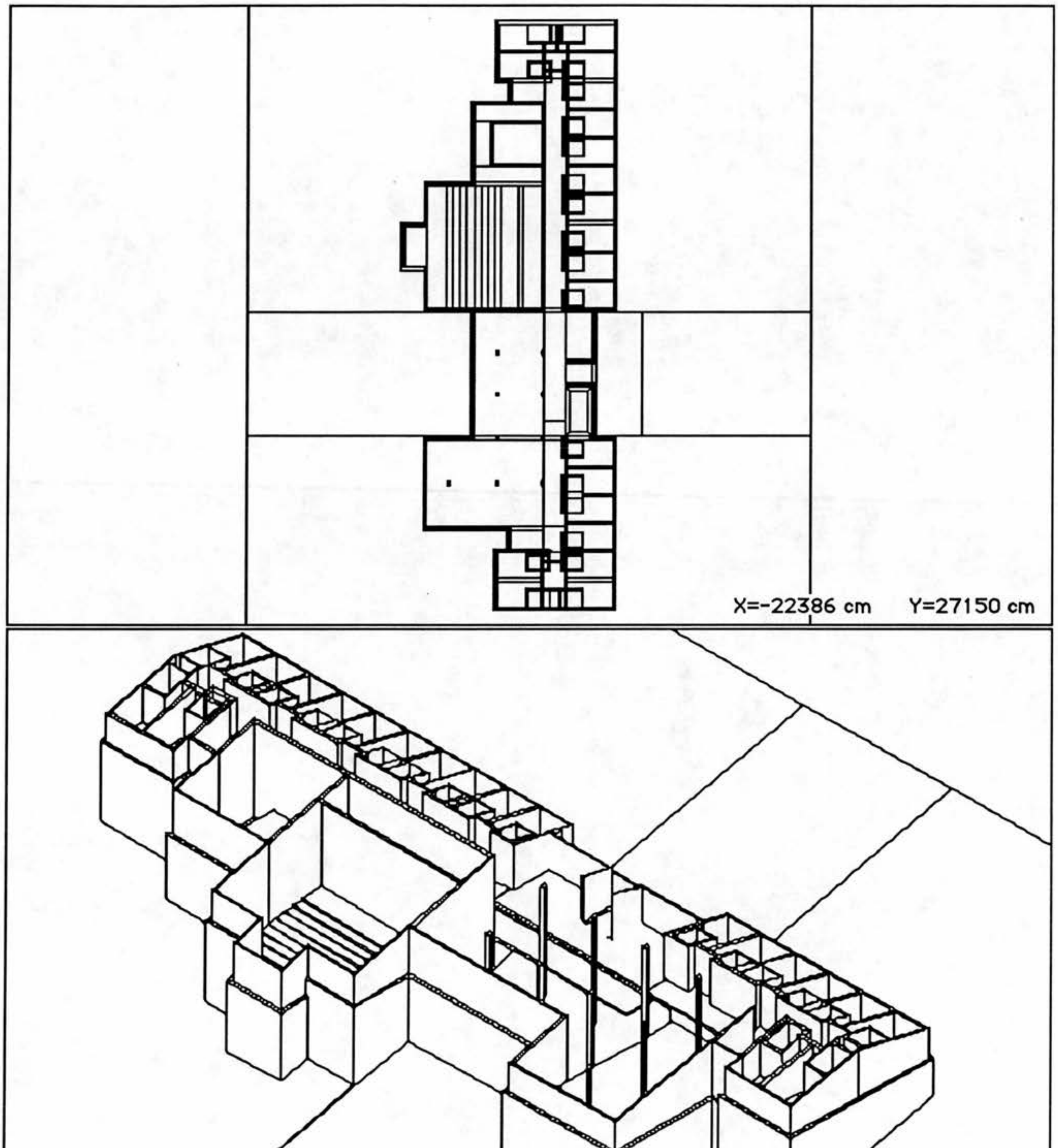


Student A; Instance 132

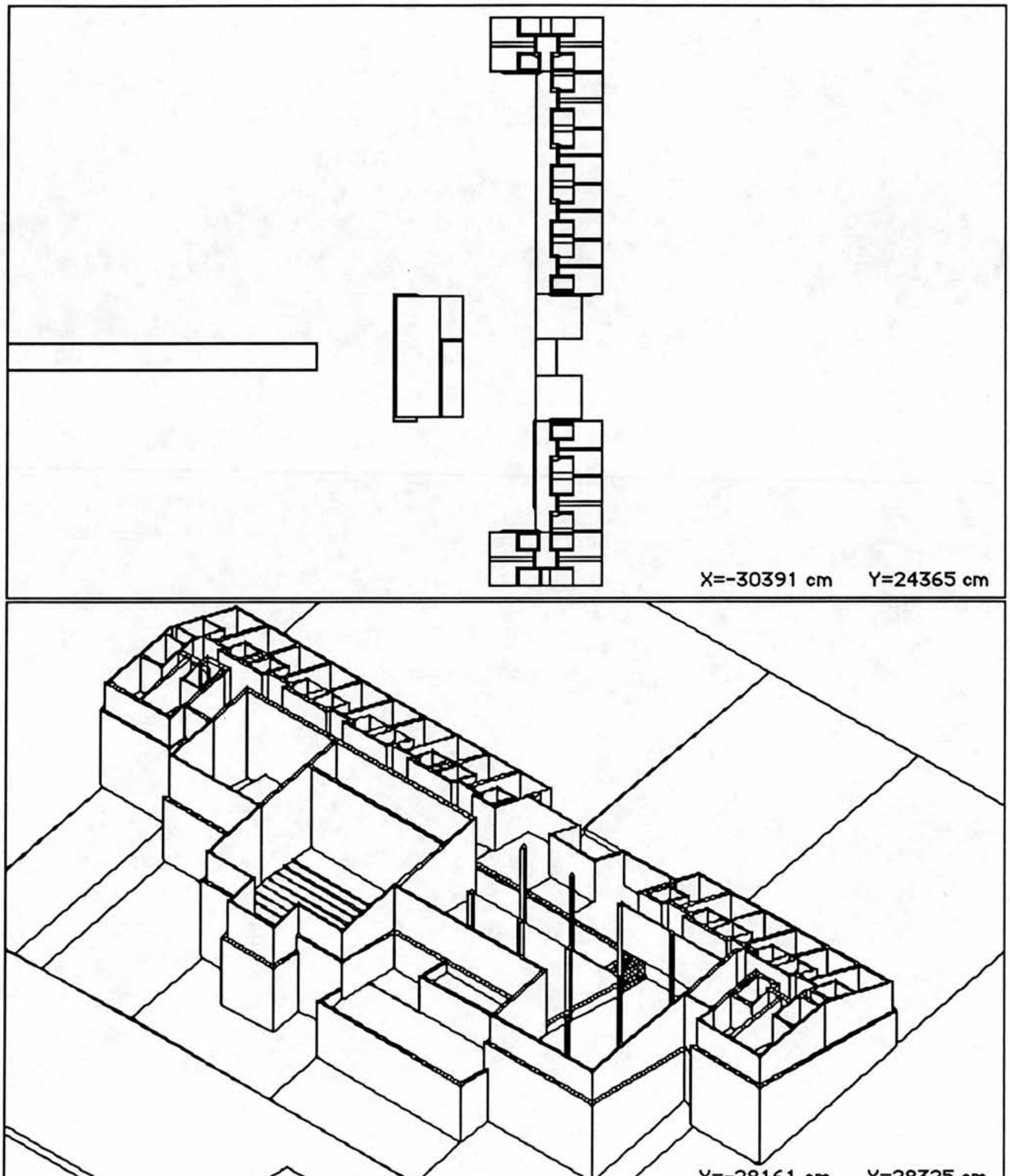




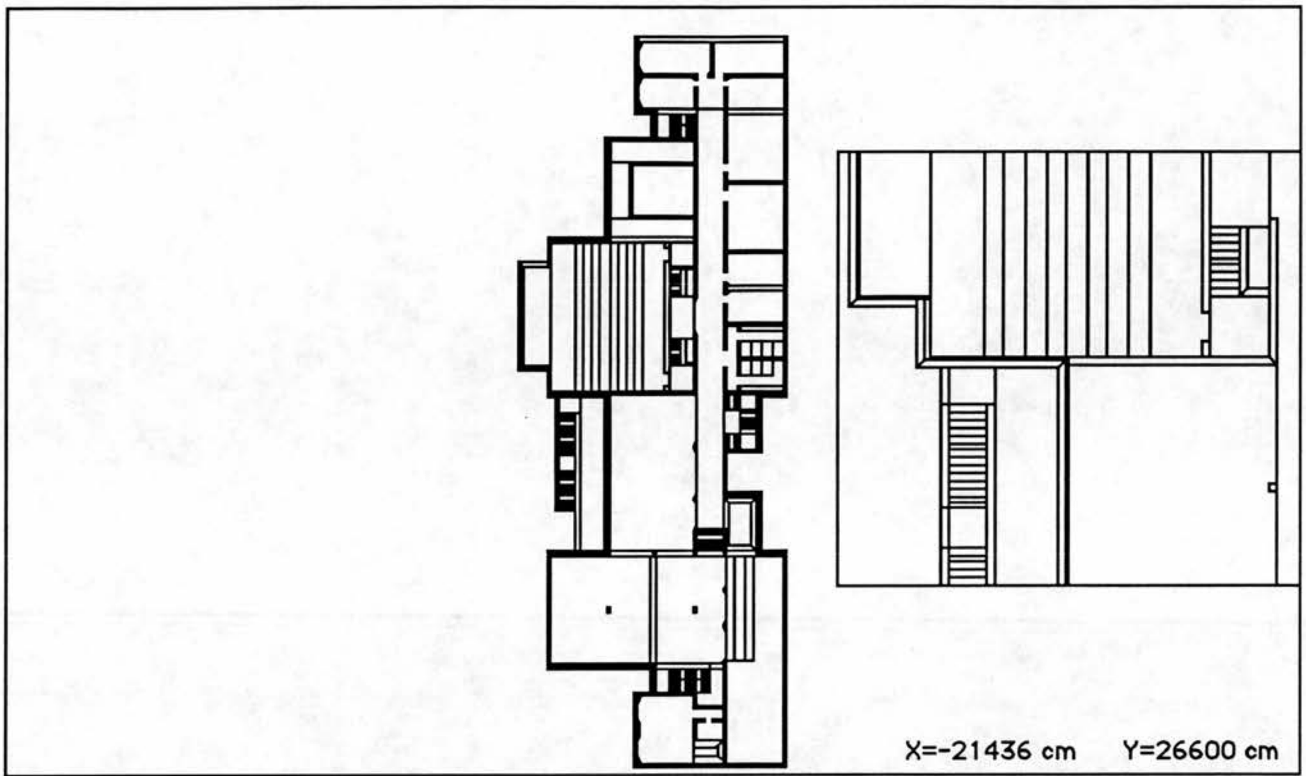
Student A; Instance 133

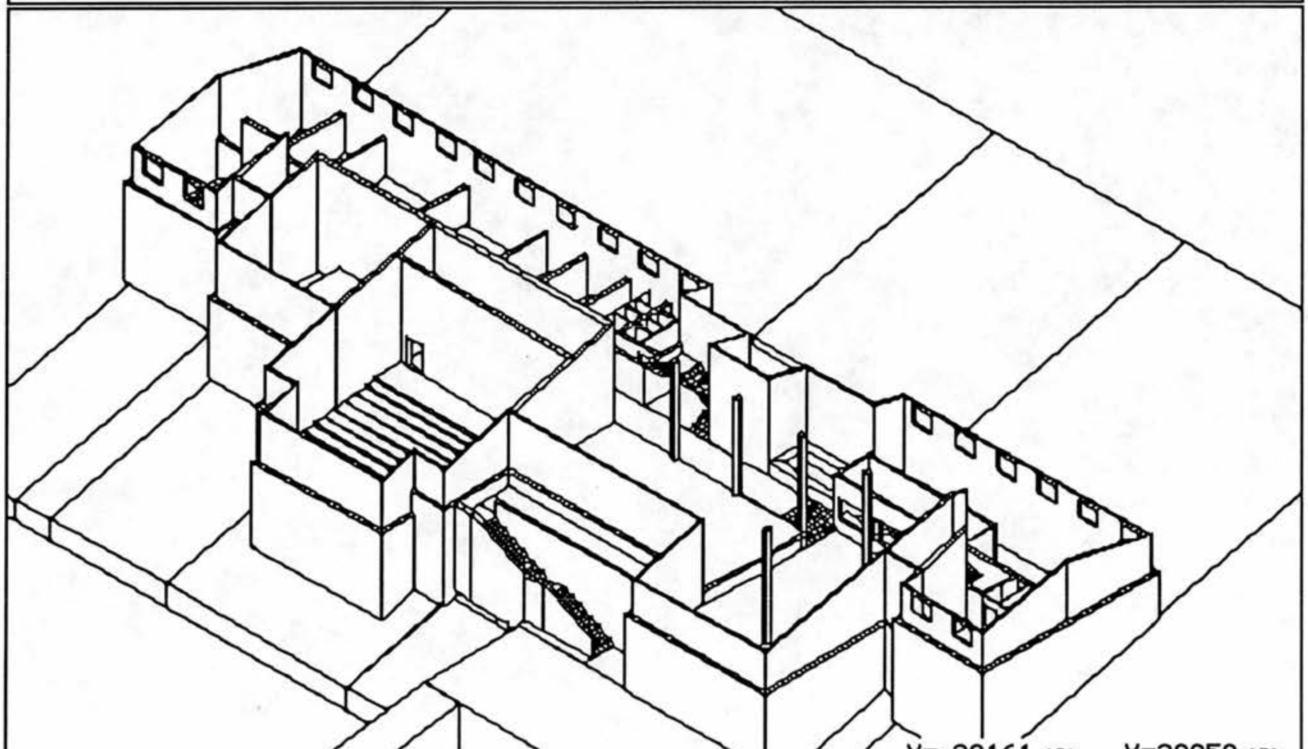


Student A; Instance 136

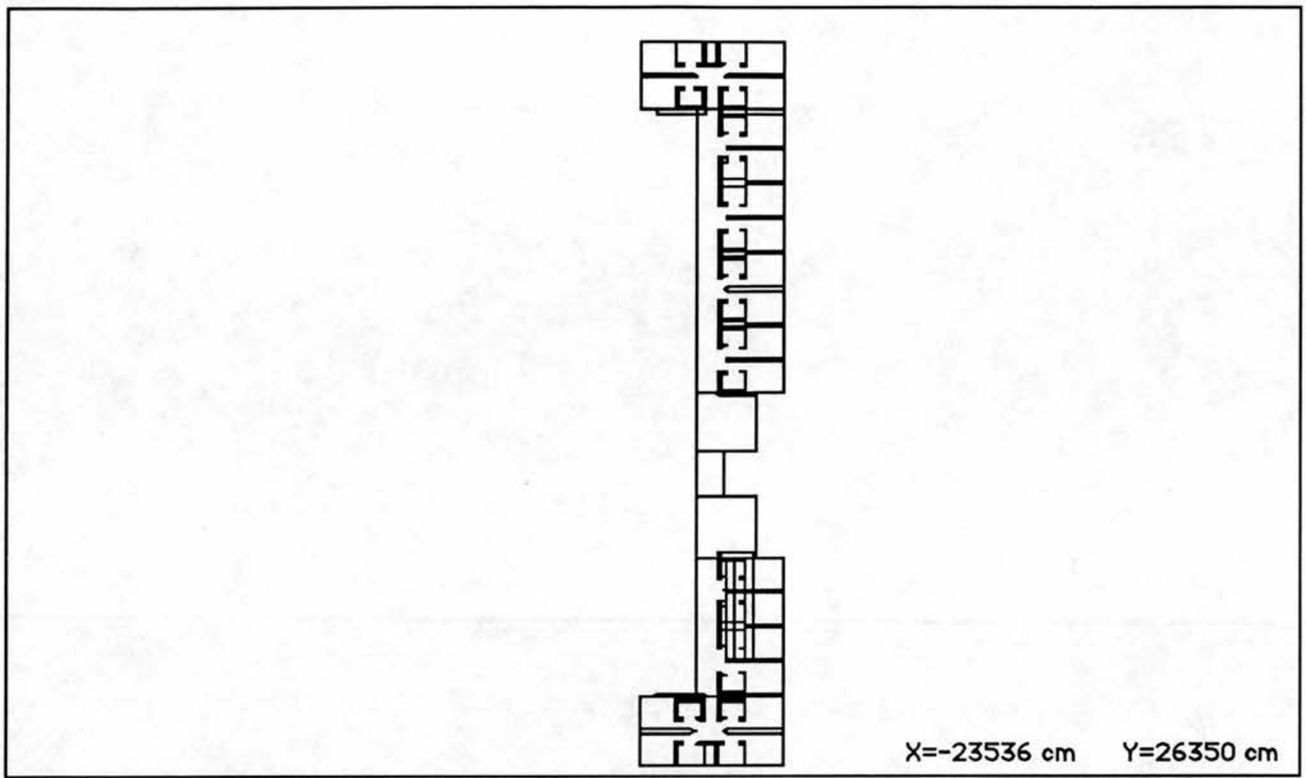


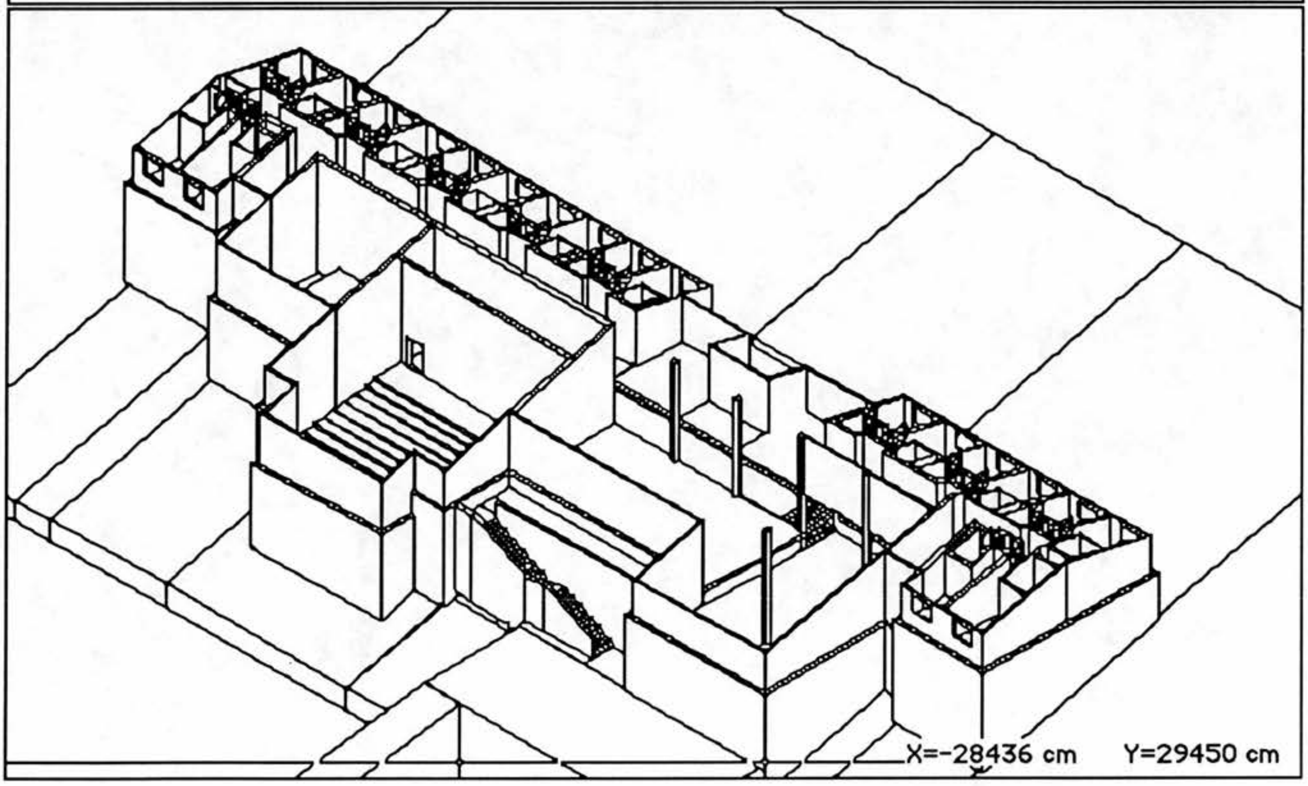
Student A; Instance 148



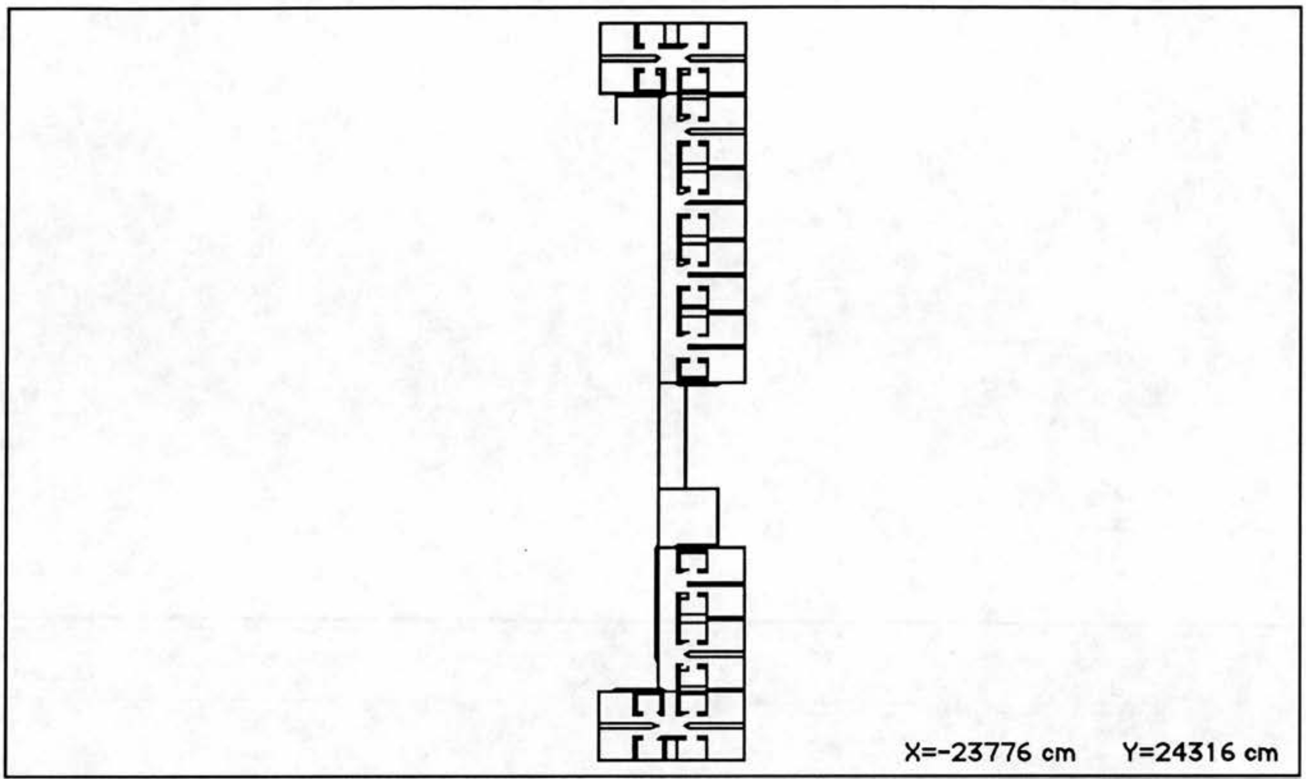


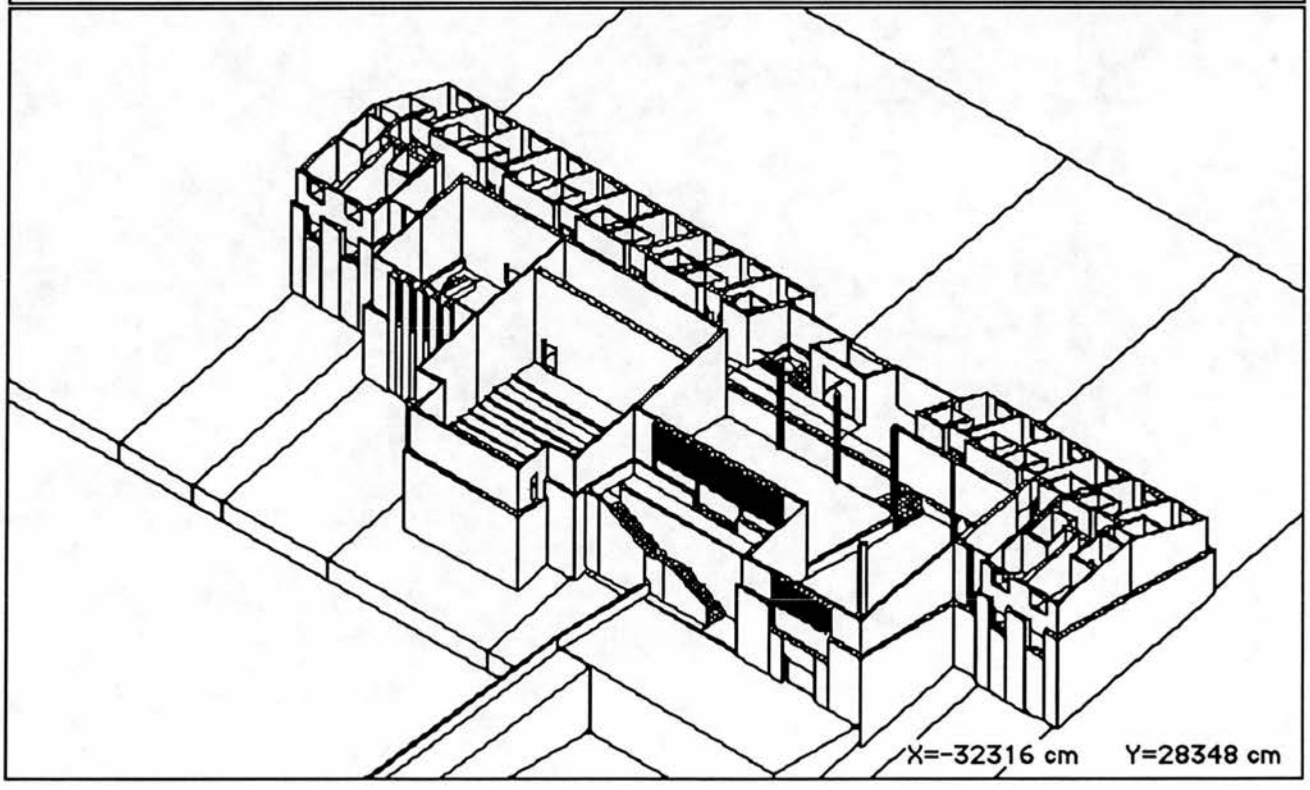
Student A; Instance 152.a



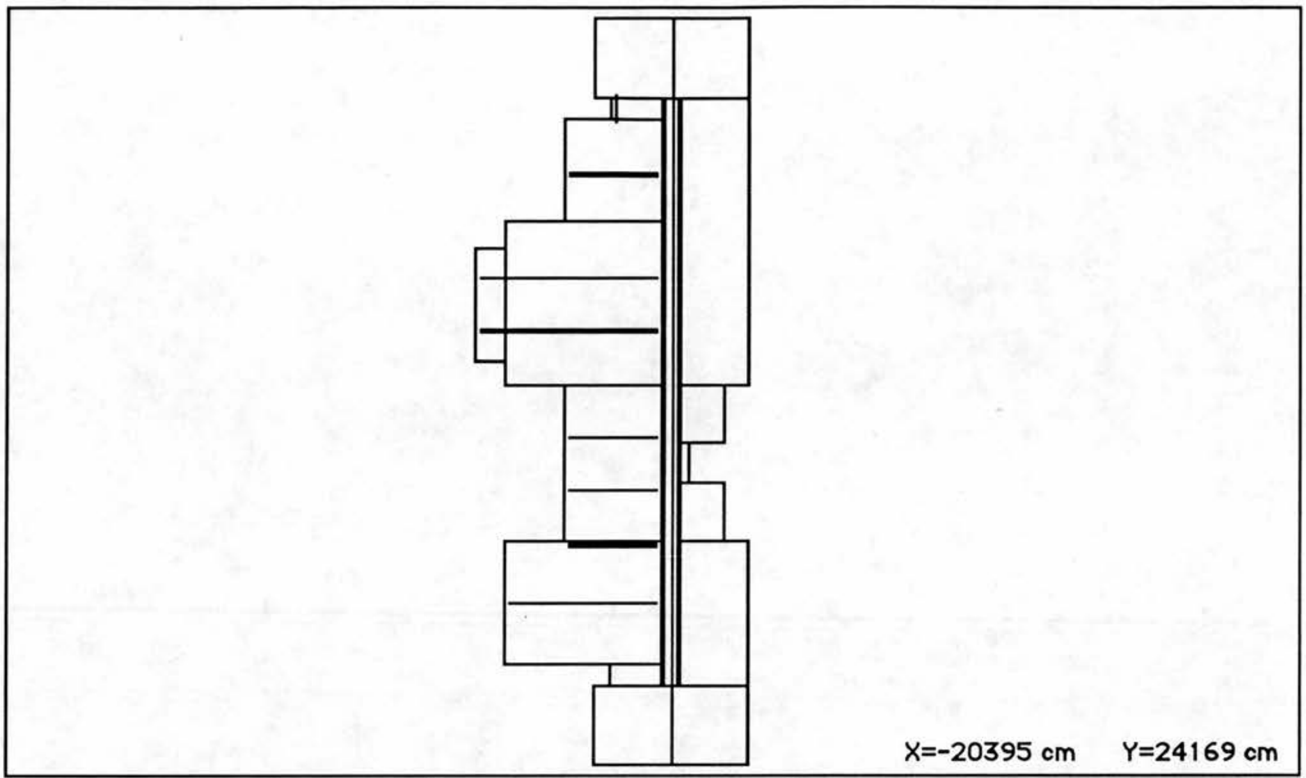


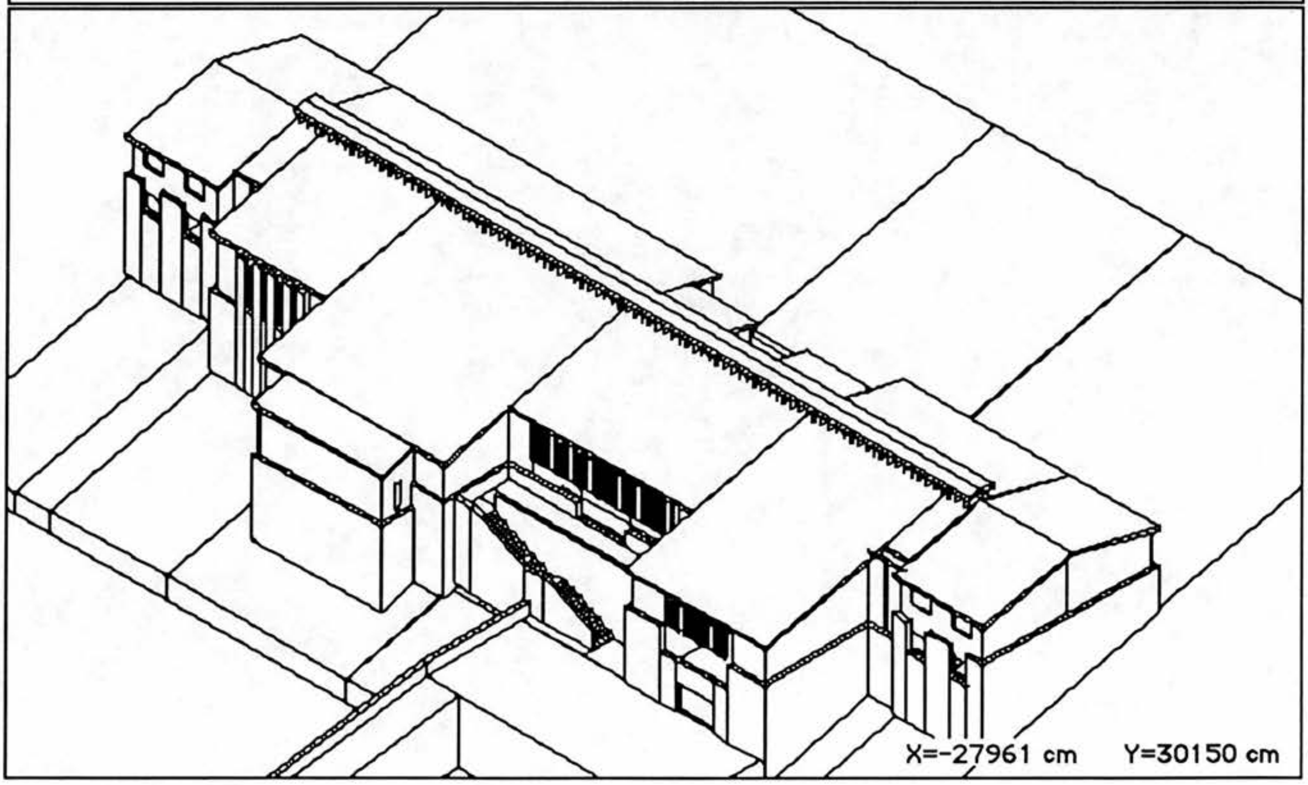
Student A; Instance 152.b



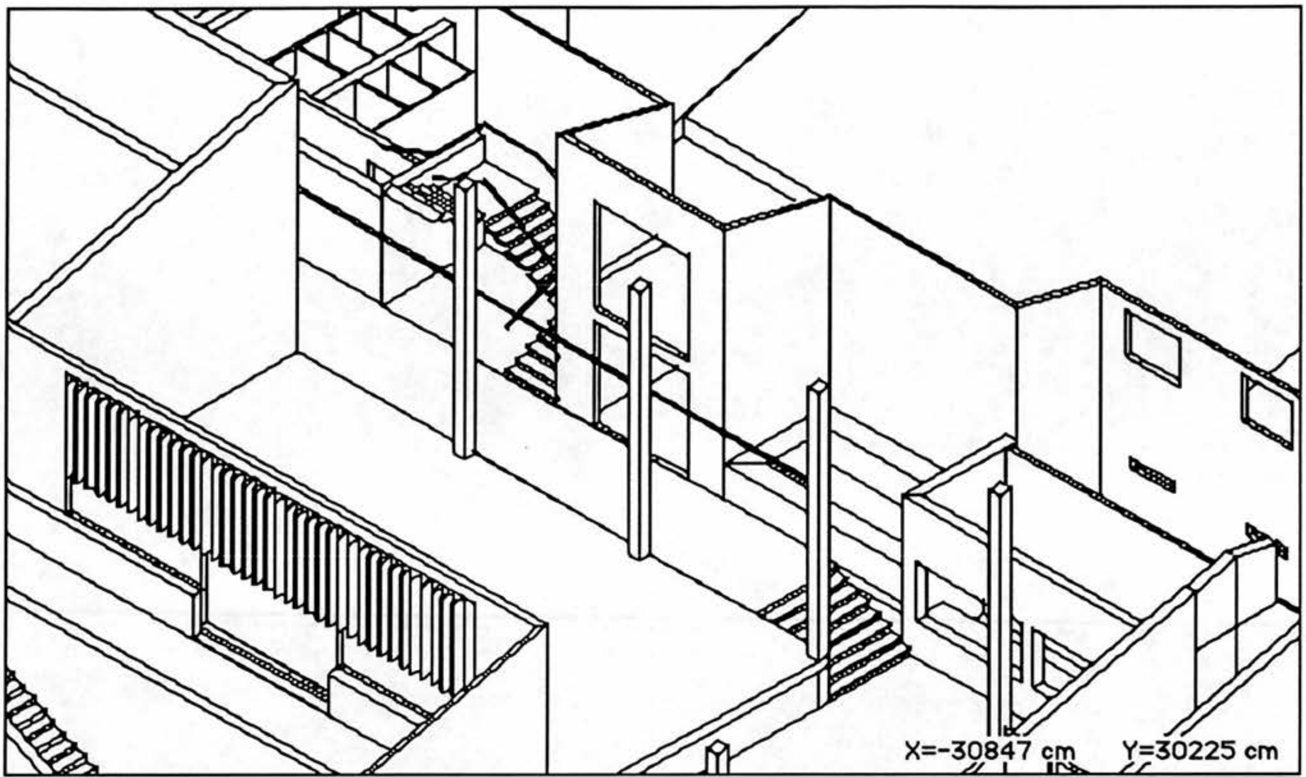


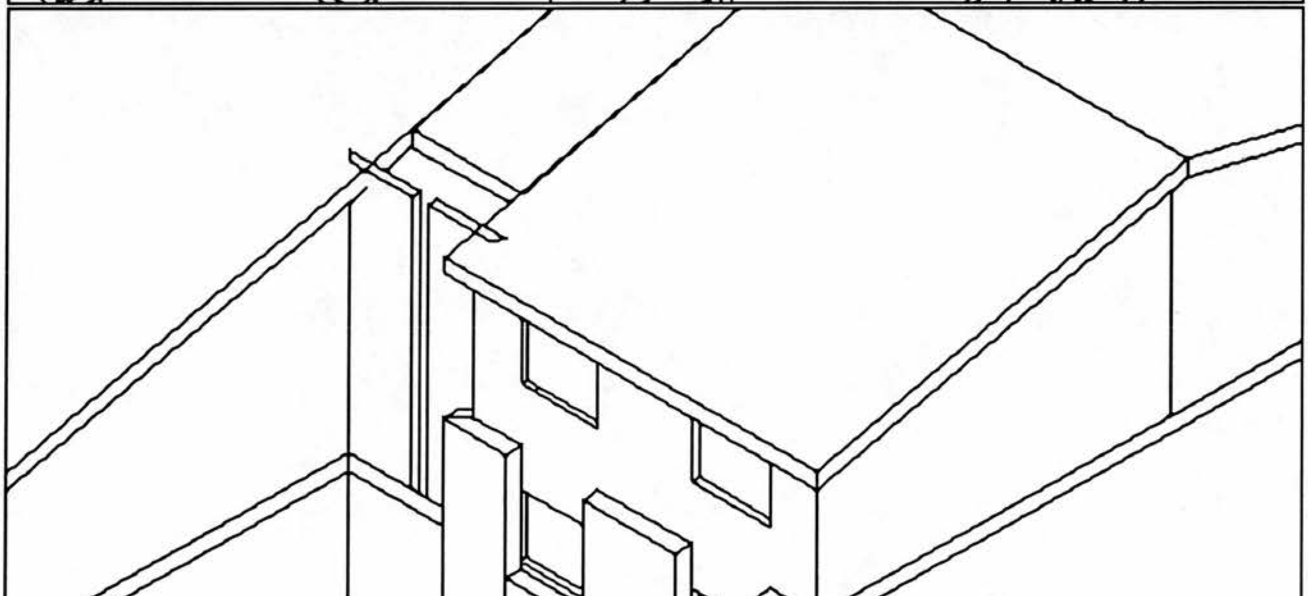
Student A; Instance 156.a



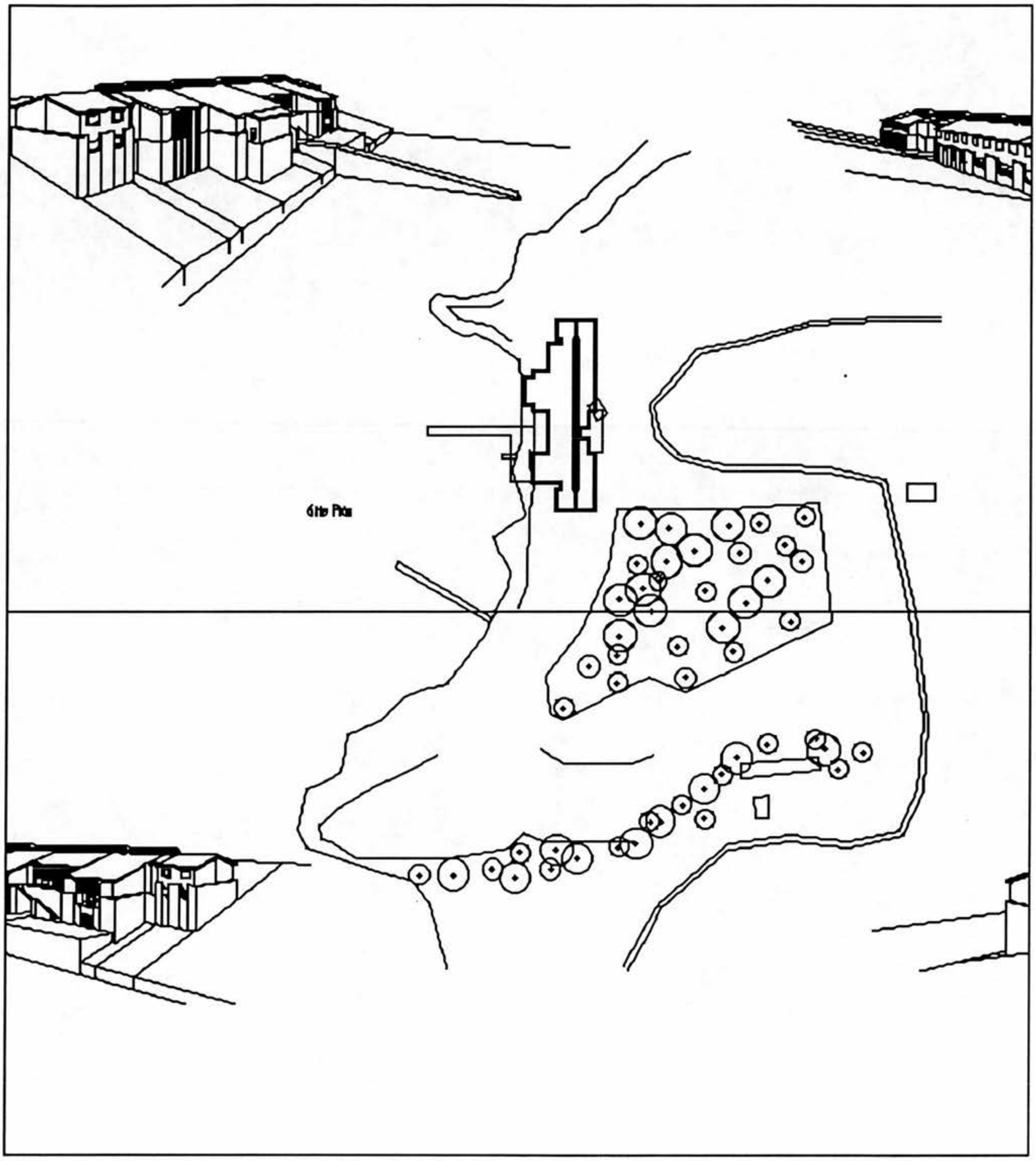


Student A; Instance 156.b



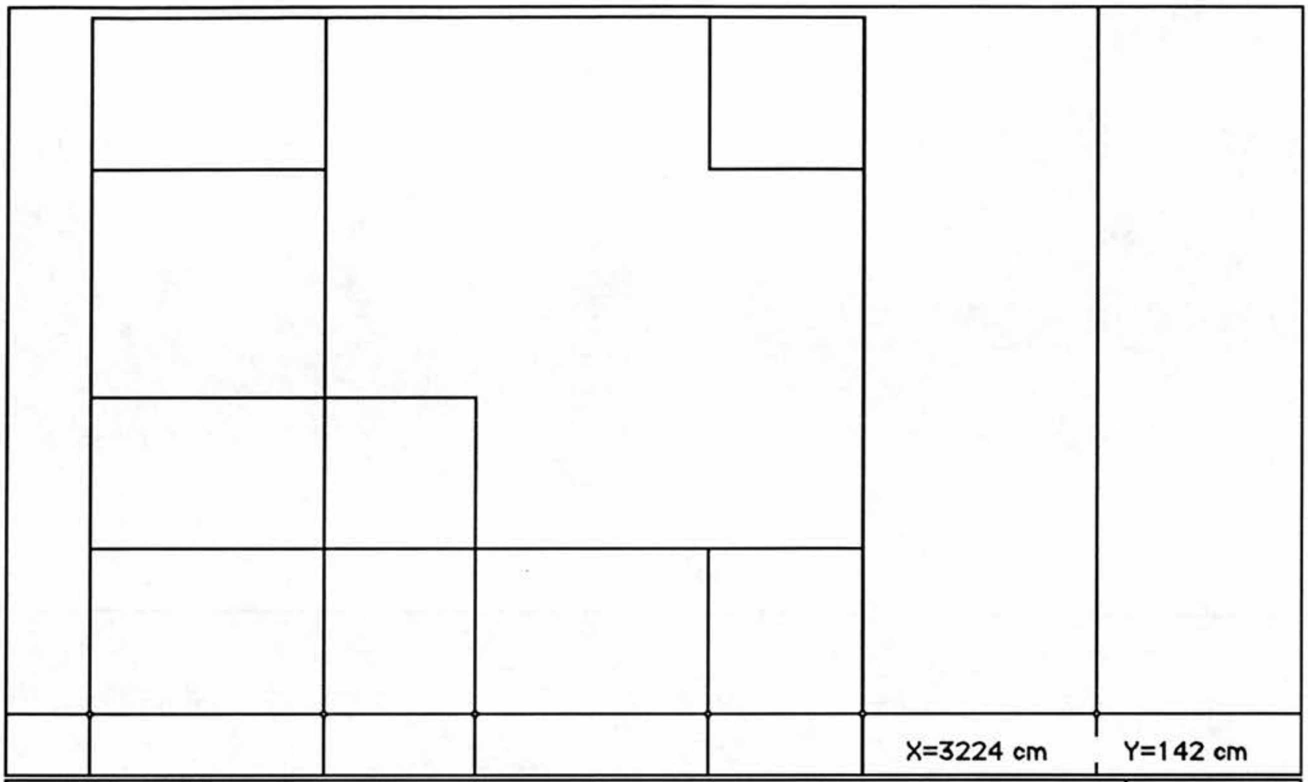


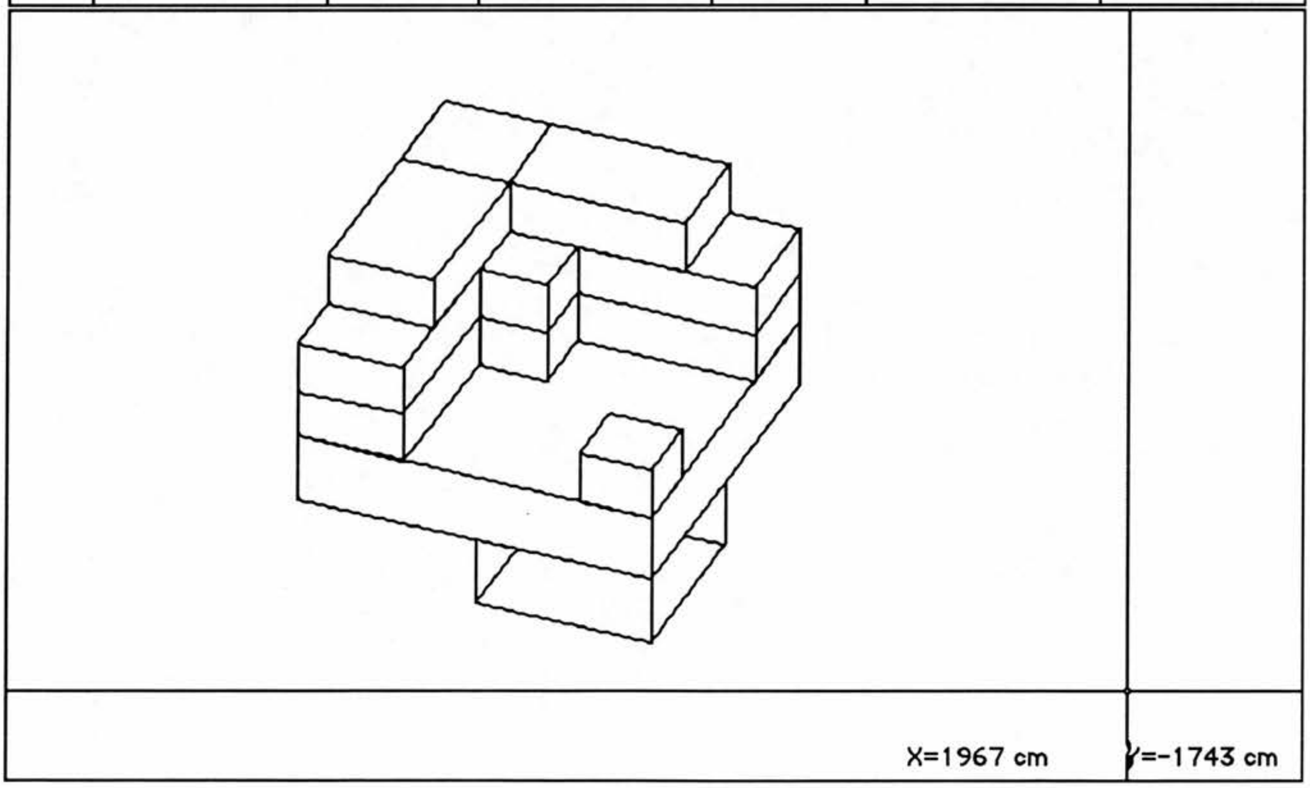
Student A; Instance 156.c



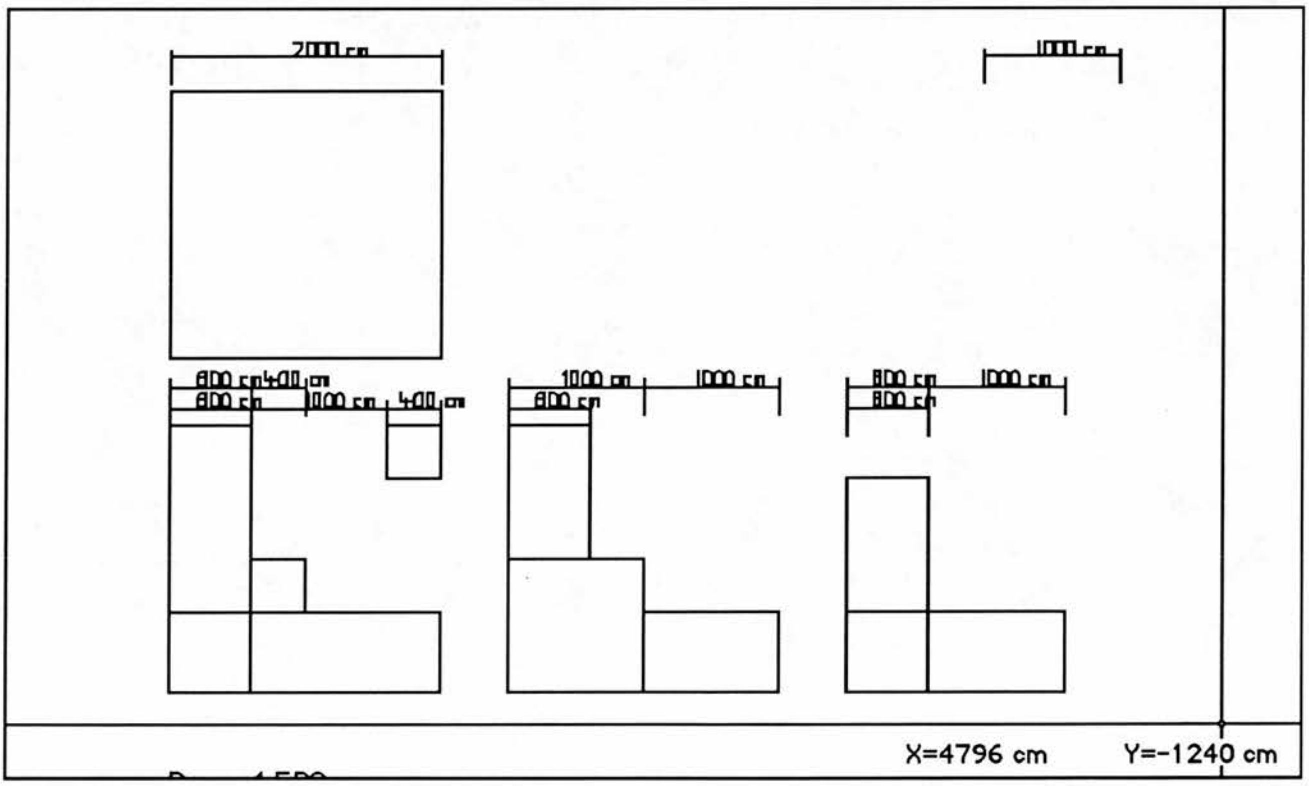
Student A; Instance 189

B.2. Student B

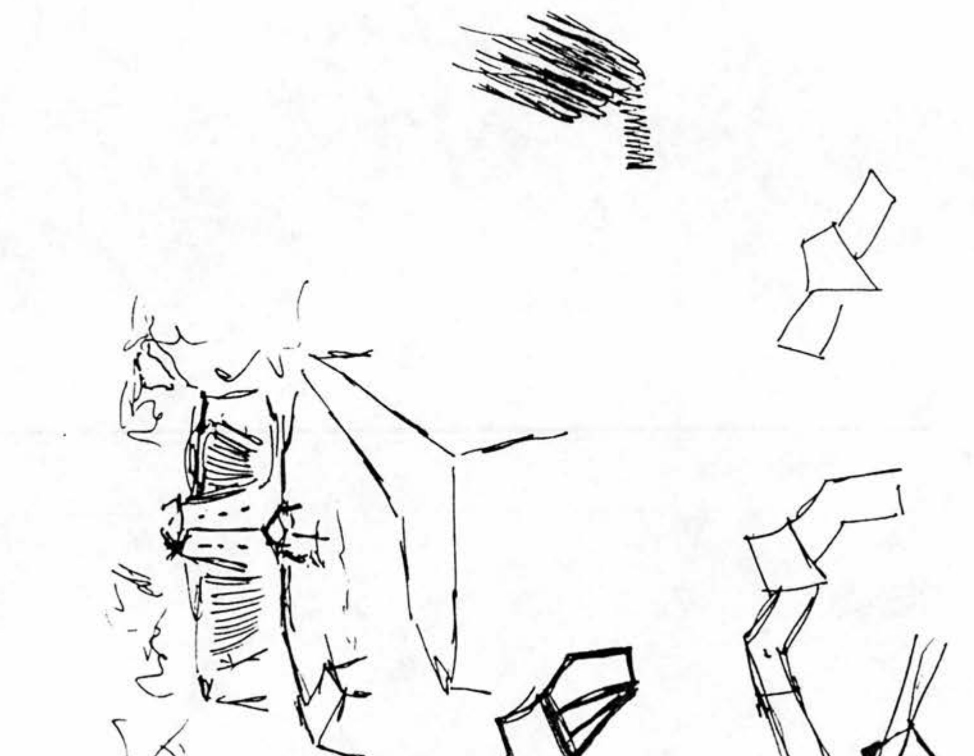




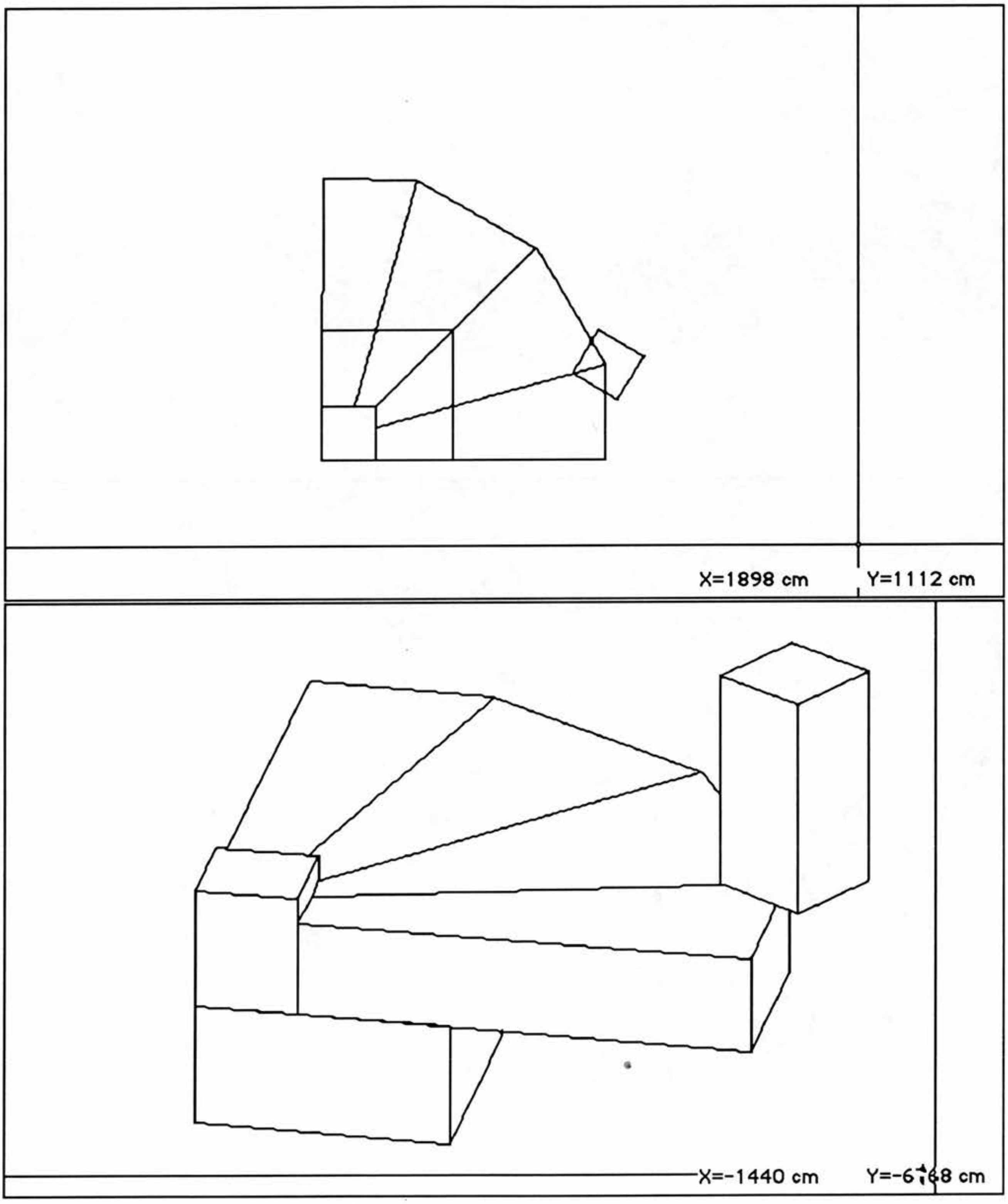
Student B; Instance 004



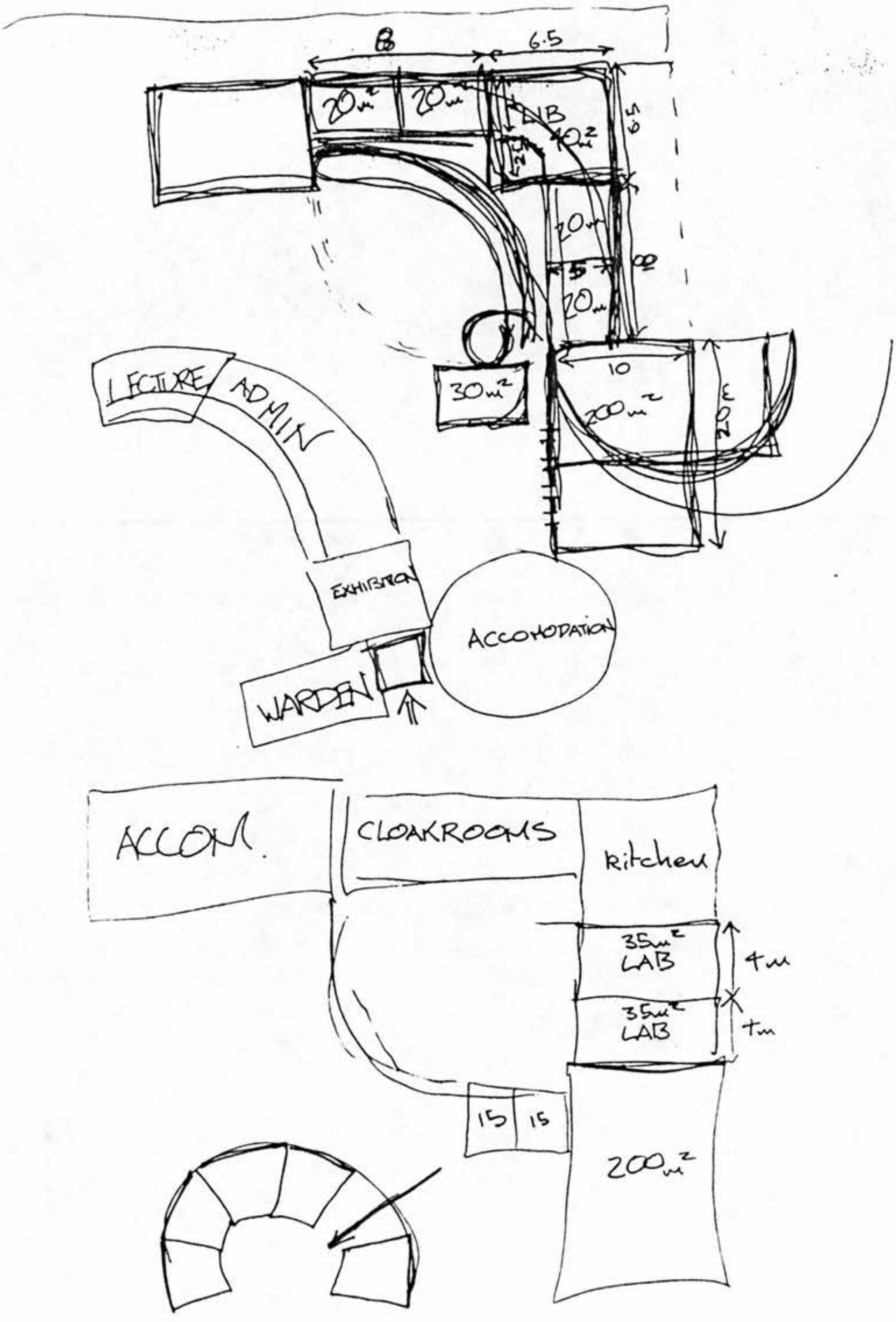
Student B; Instance 005



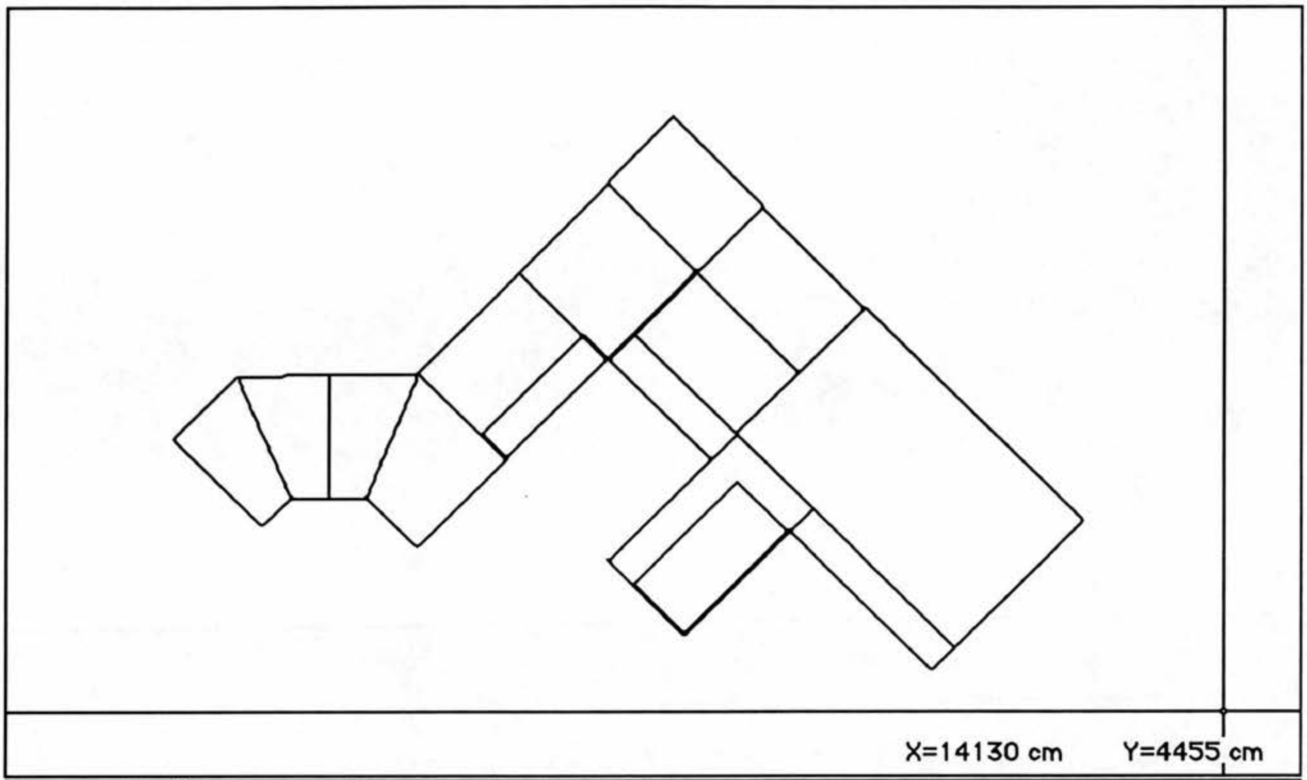
Student B; Instance 008

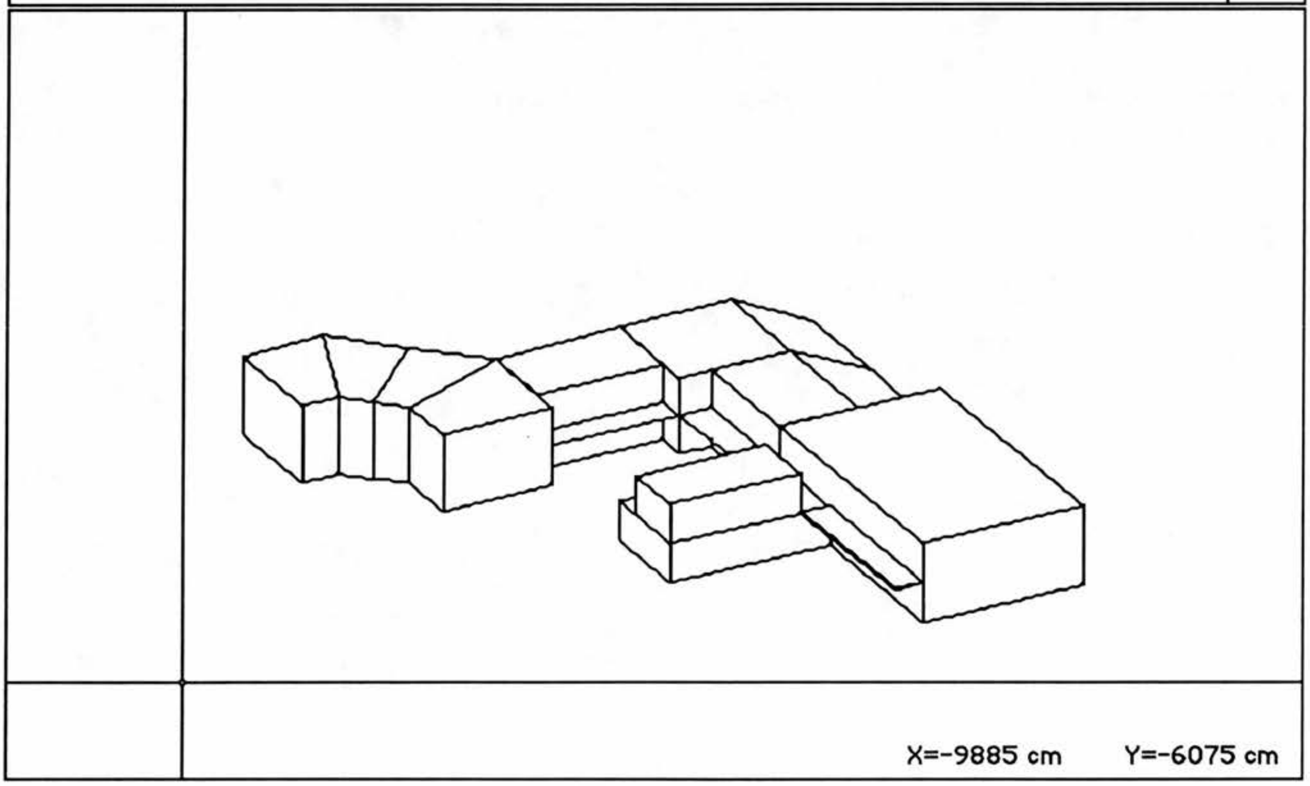


Student B; Instance 012

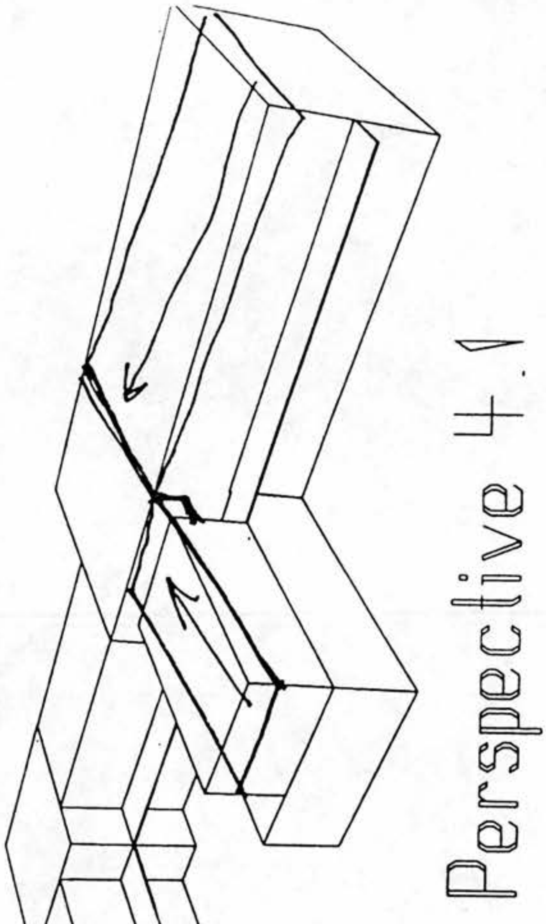


Student B; Instance 014

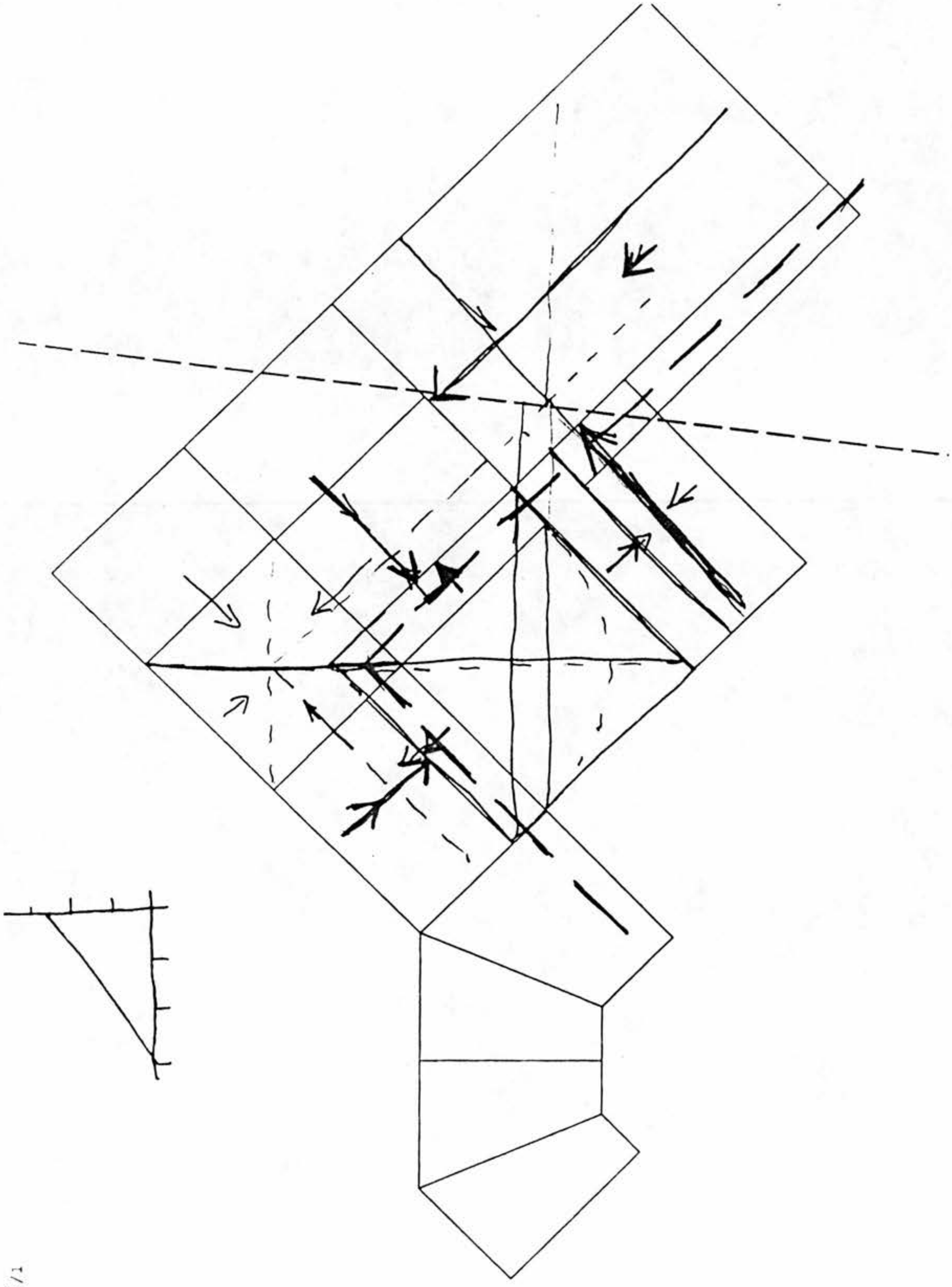




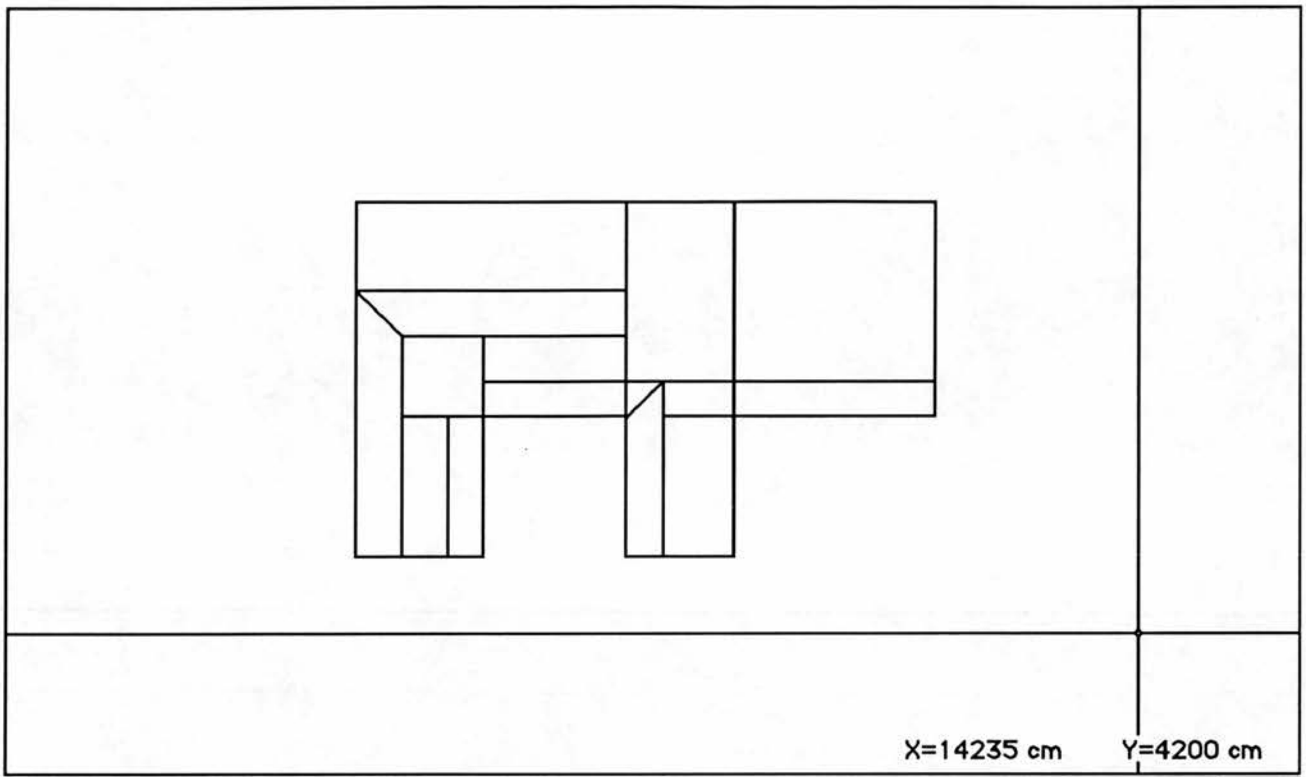
Student B; Instance 015

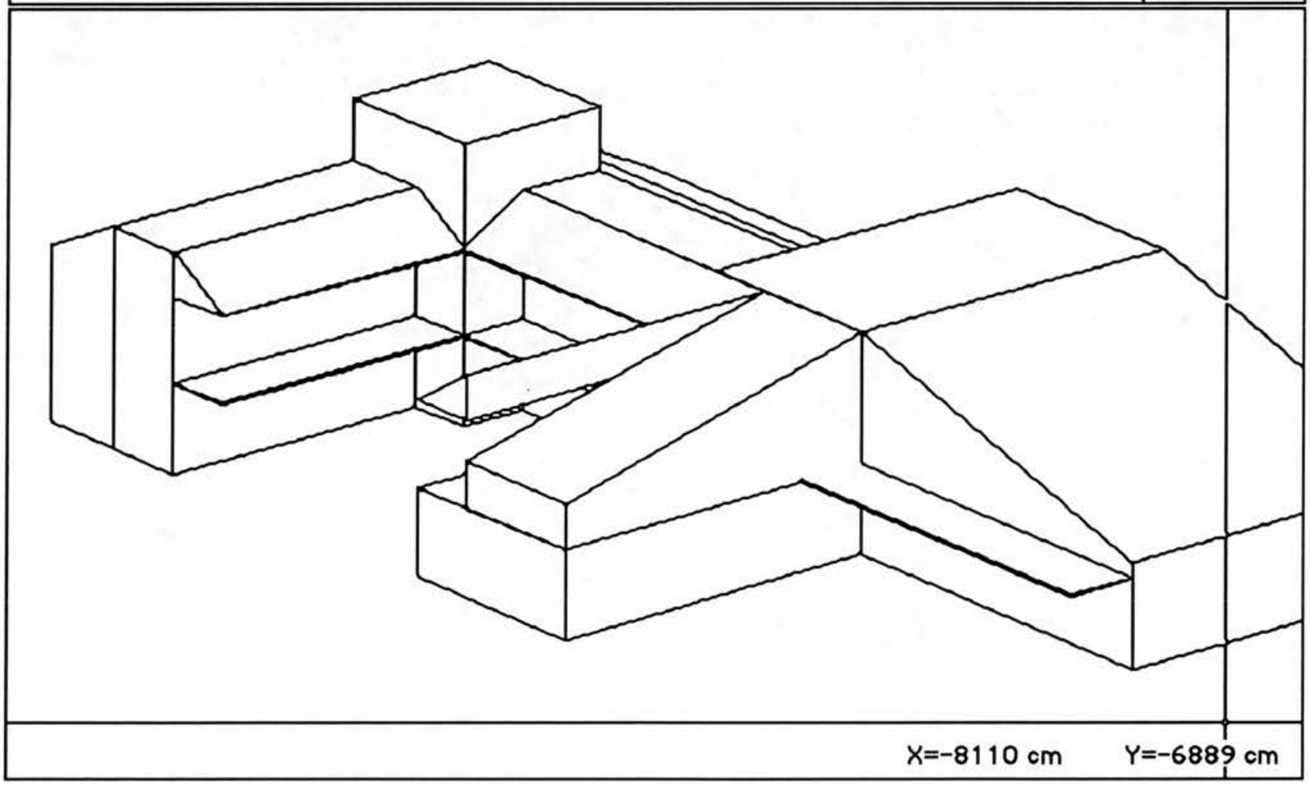


Student B; Instance 019

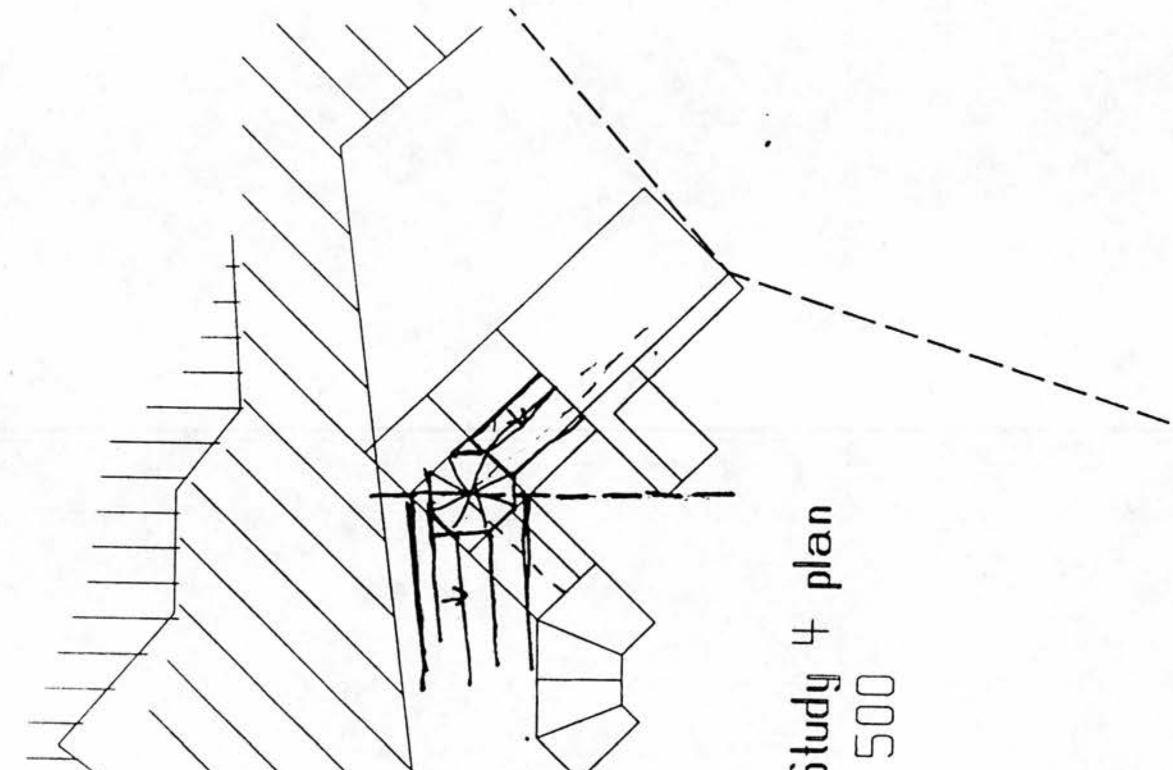


Student B; Instance 023

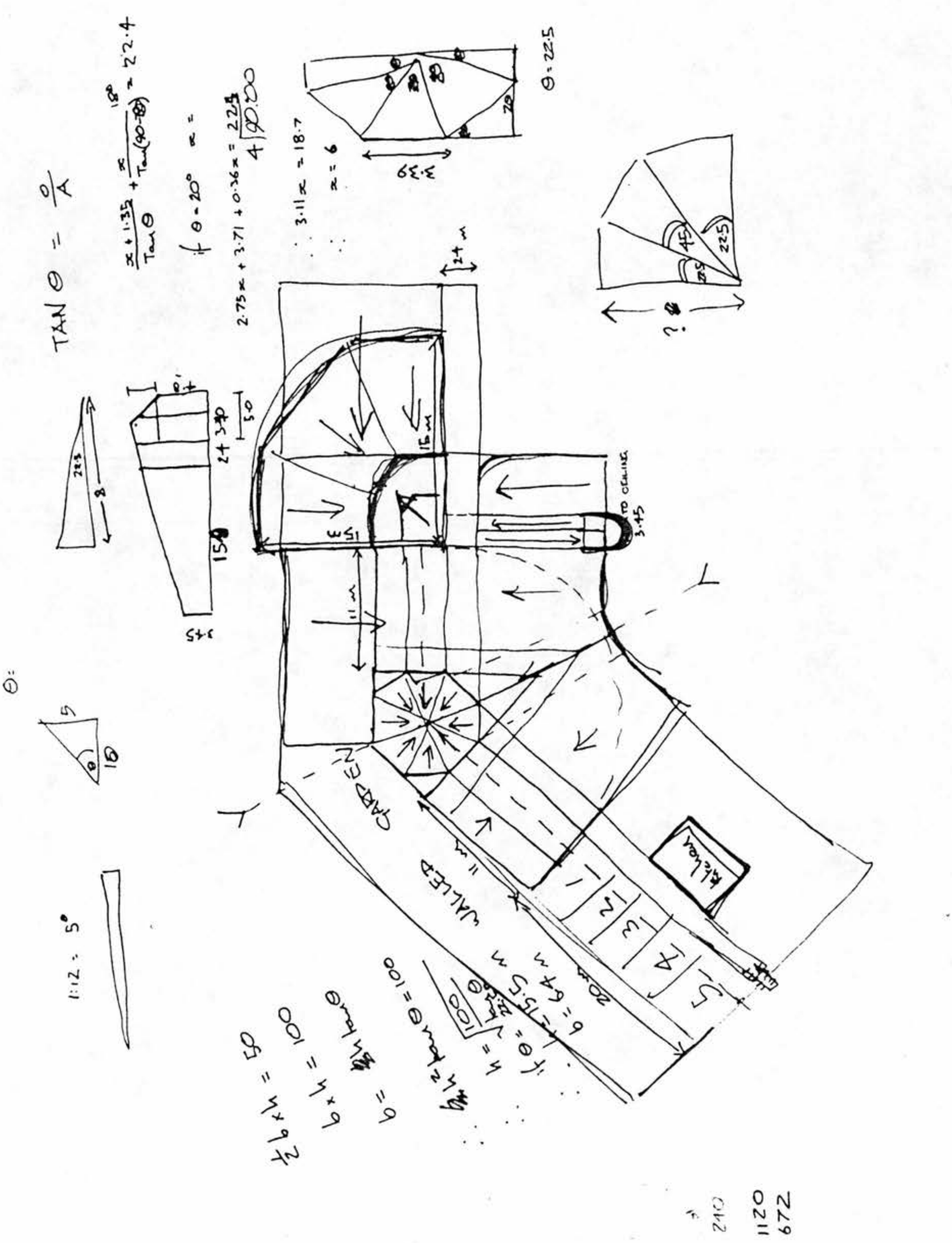




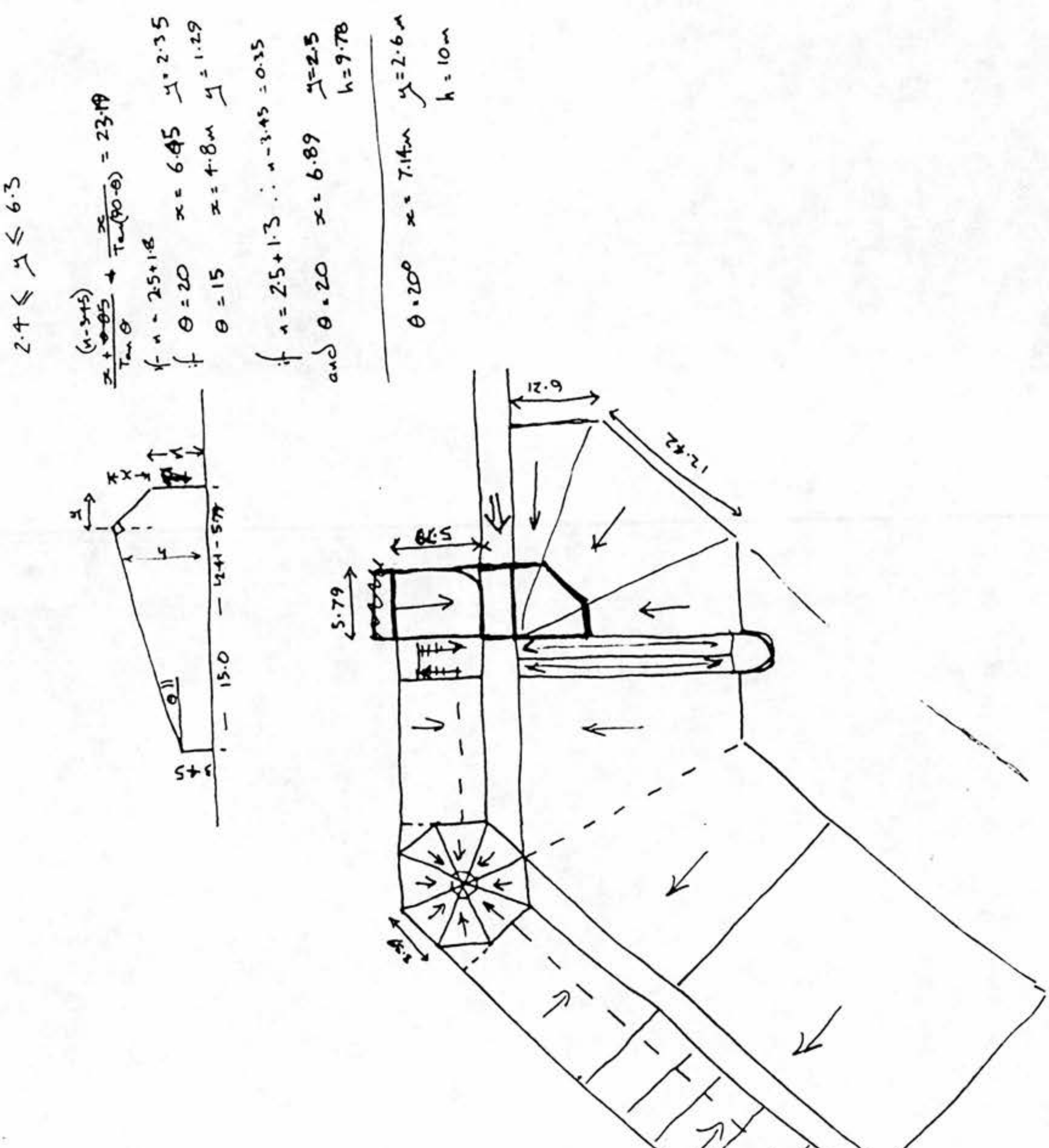
Student B; Instance 026



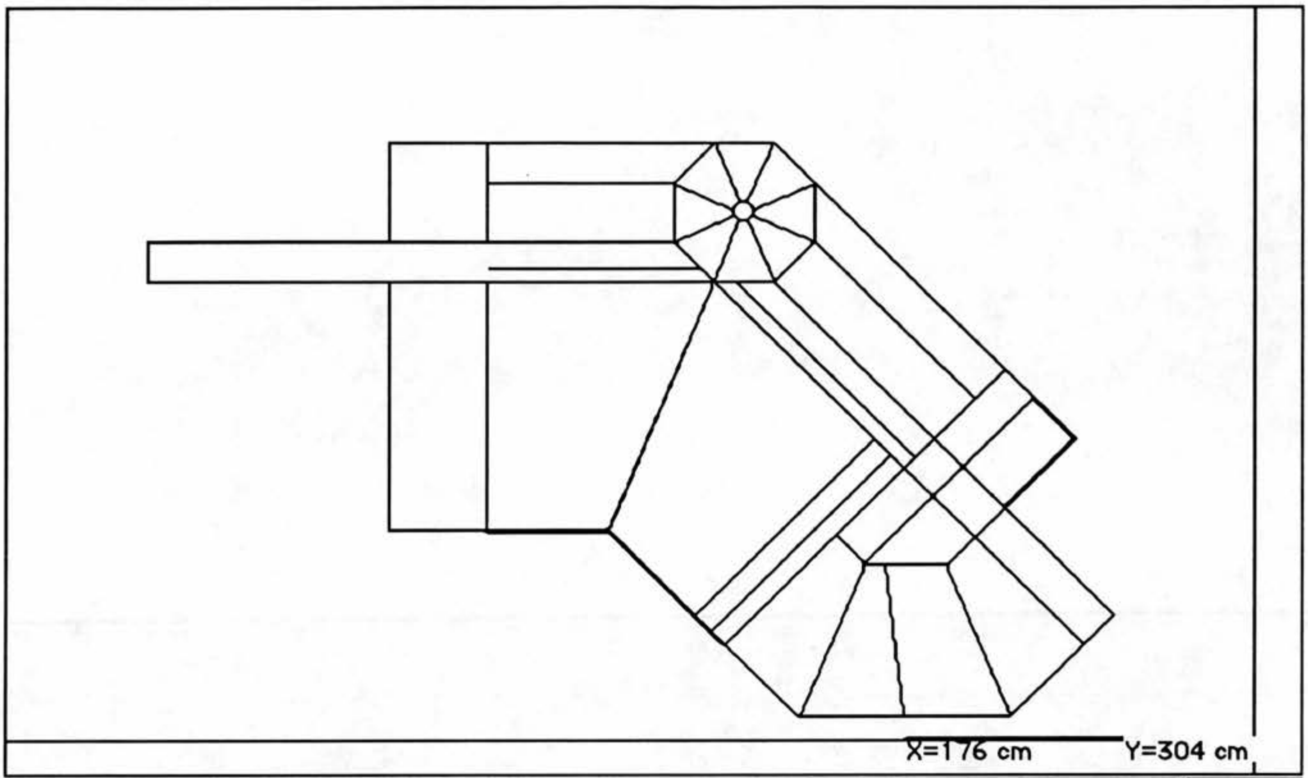
Student B; Instance 033

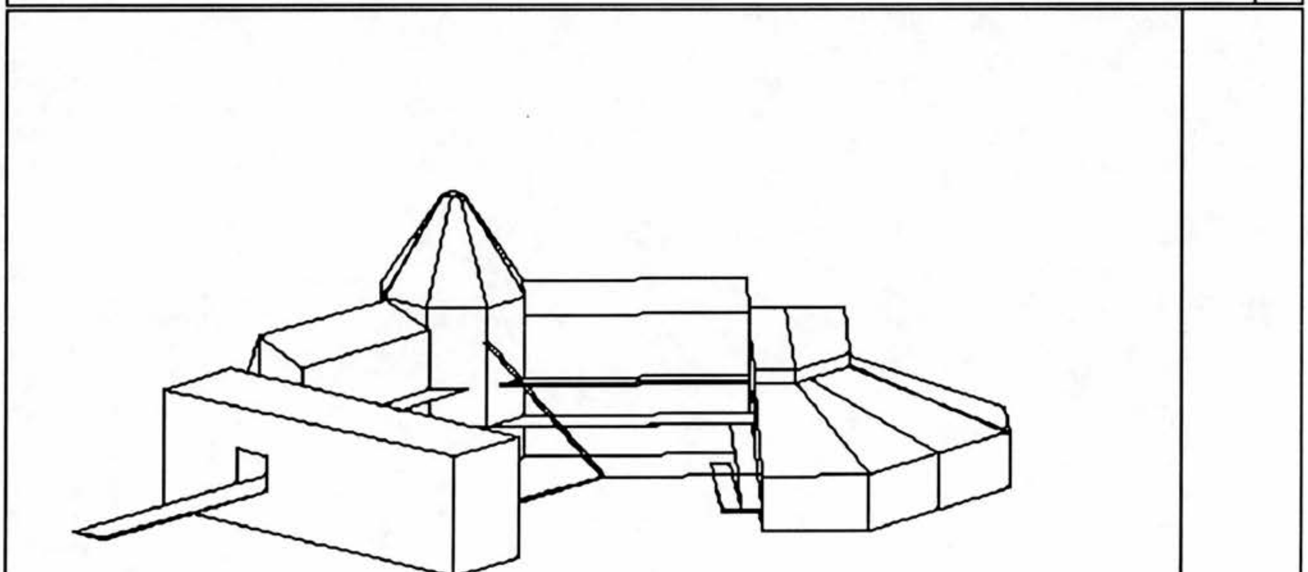


Student B; Instance 034

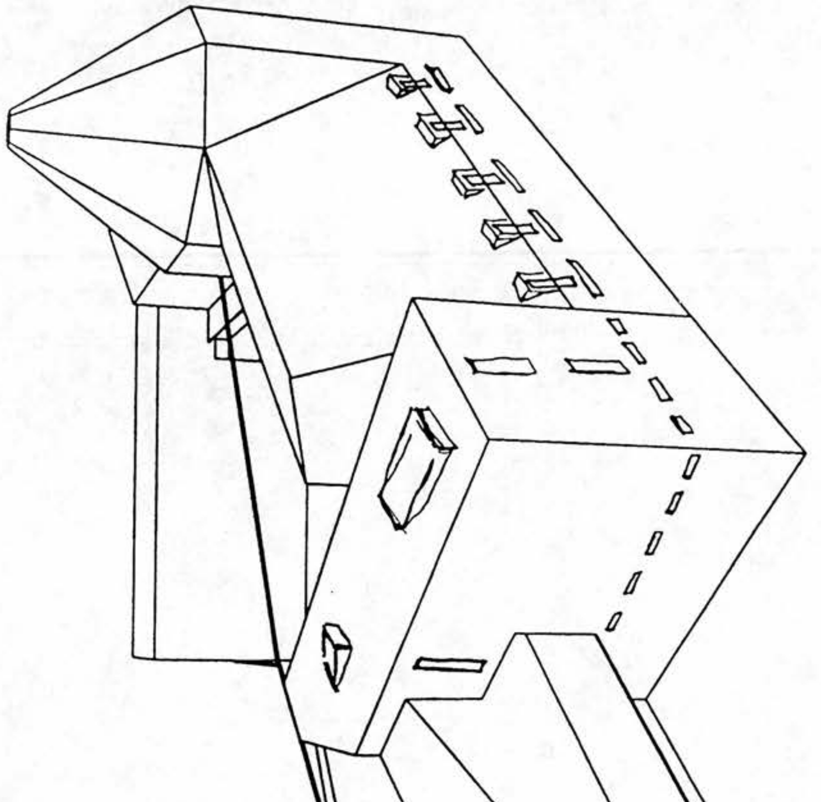


Student B; Instance 035





Student B; Instance 043



Student B; Instance 047

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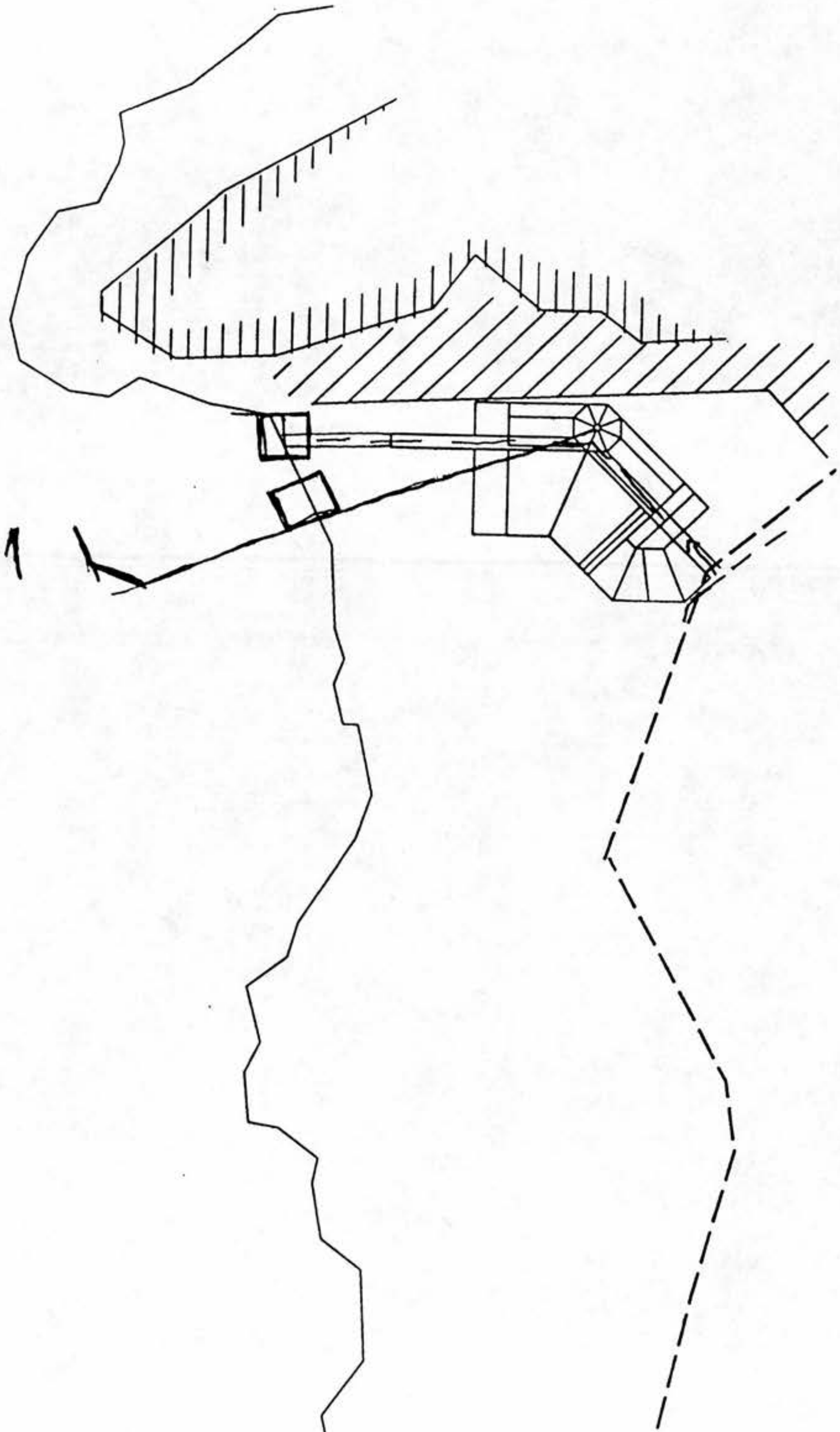
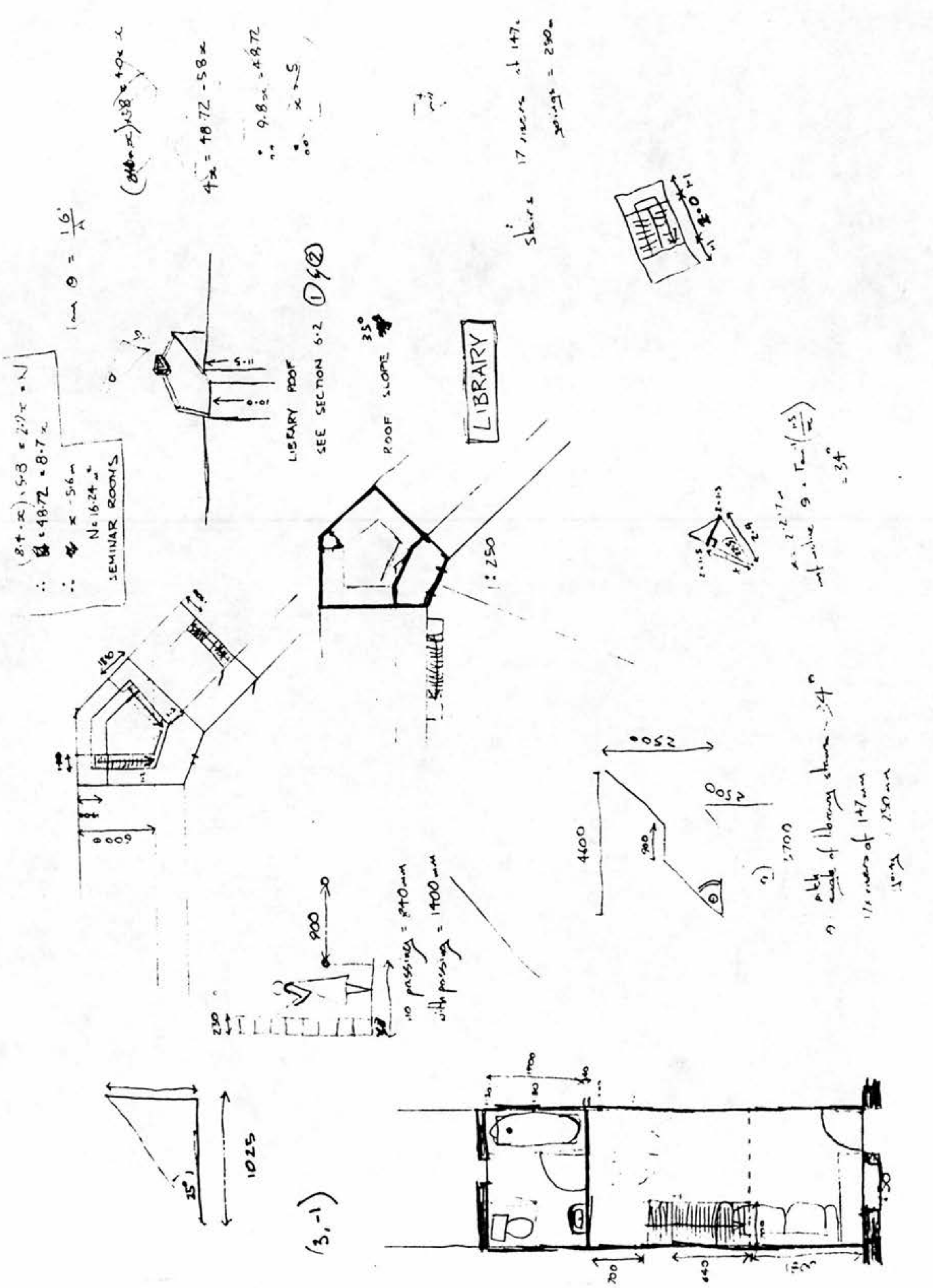
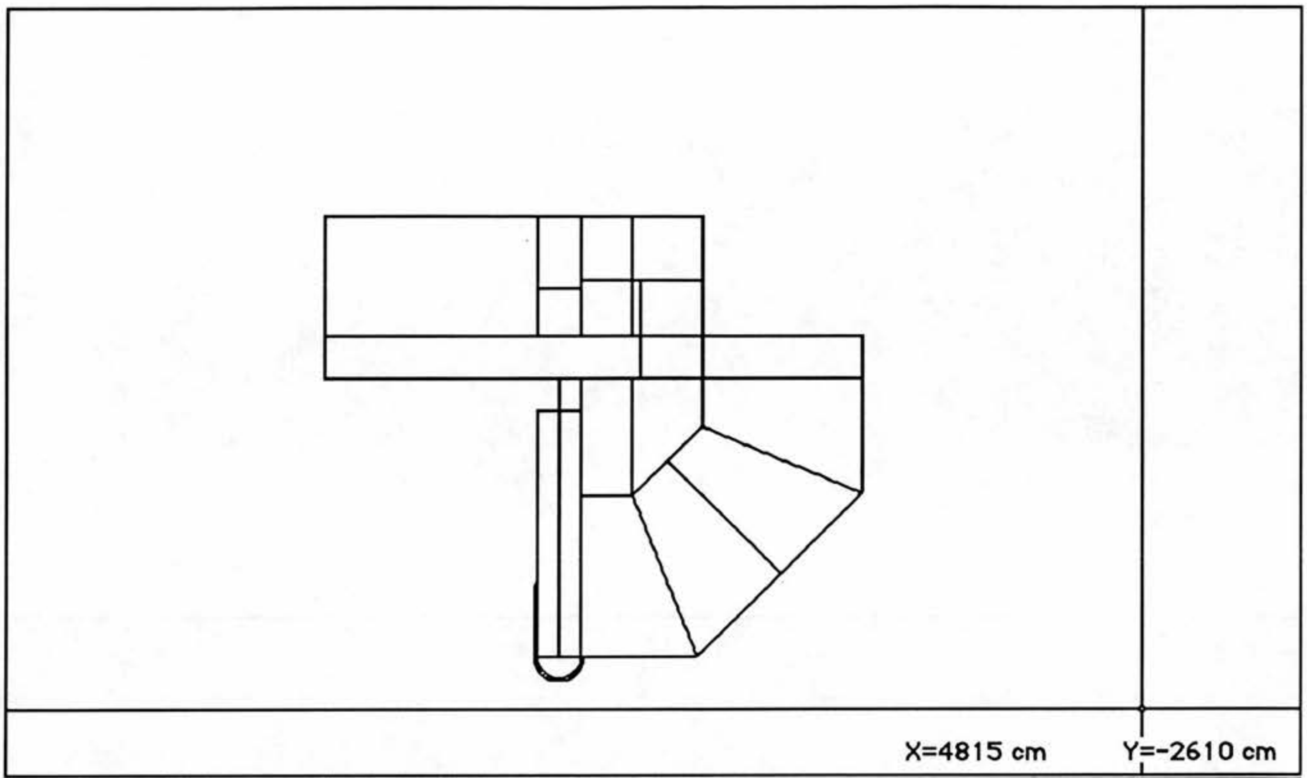


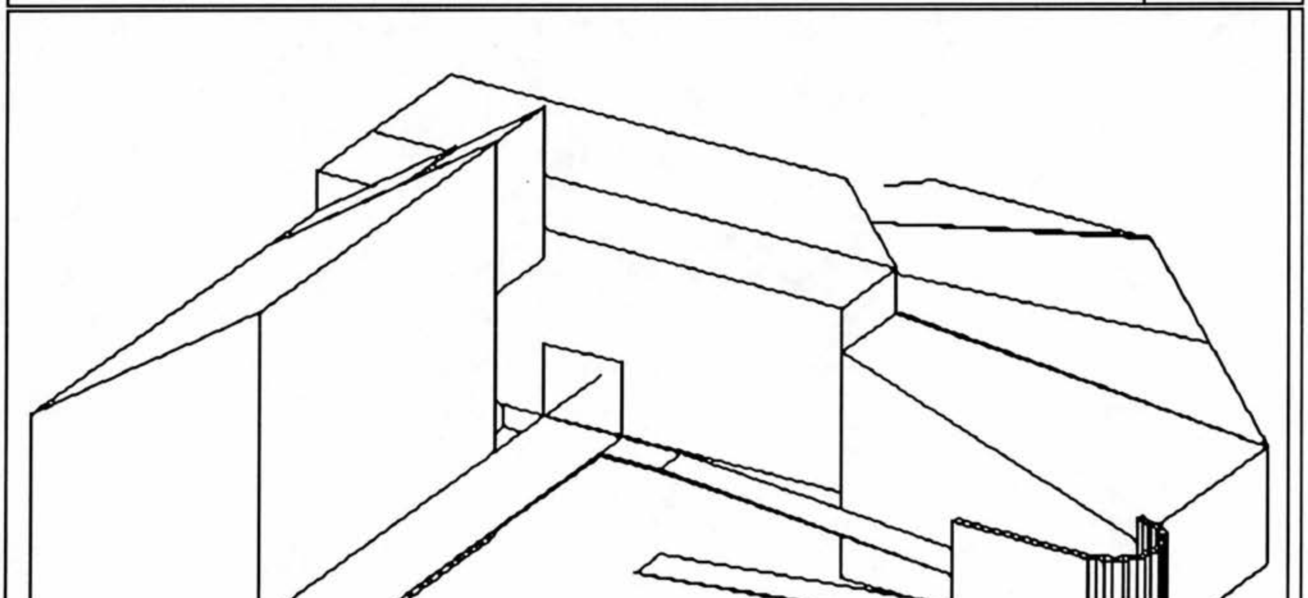
Mass Study
Scale 1 : 1000

Student B; Instance 051

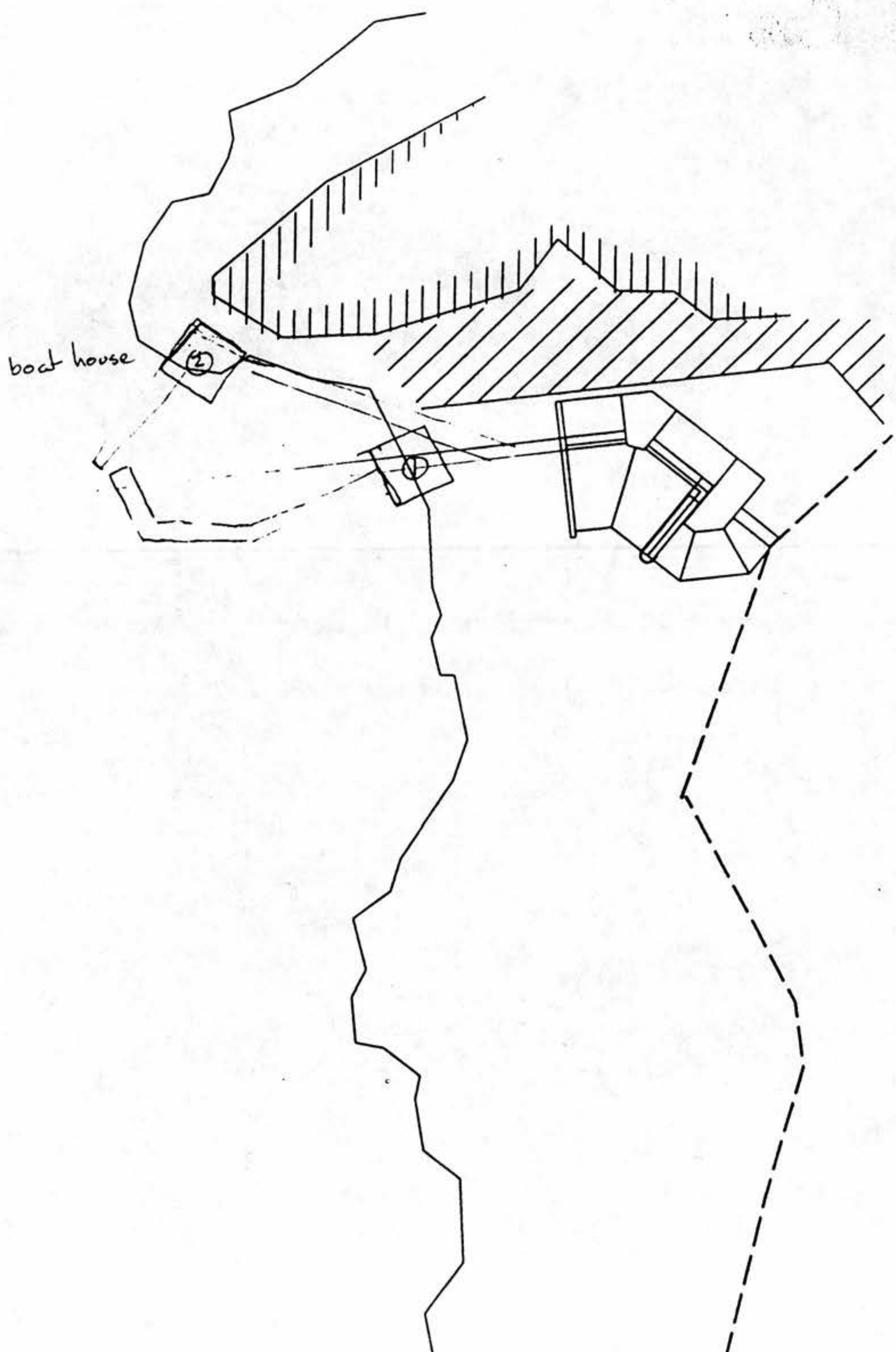


Student B; Instance 058

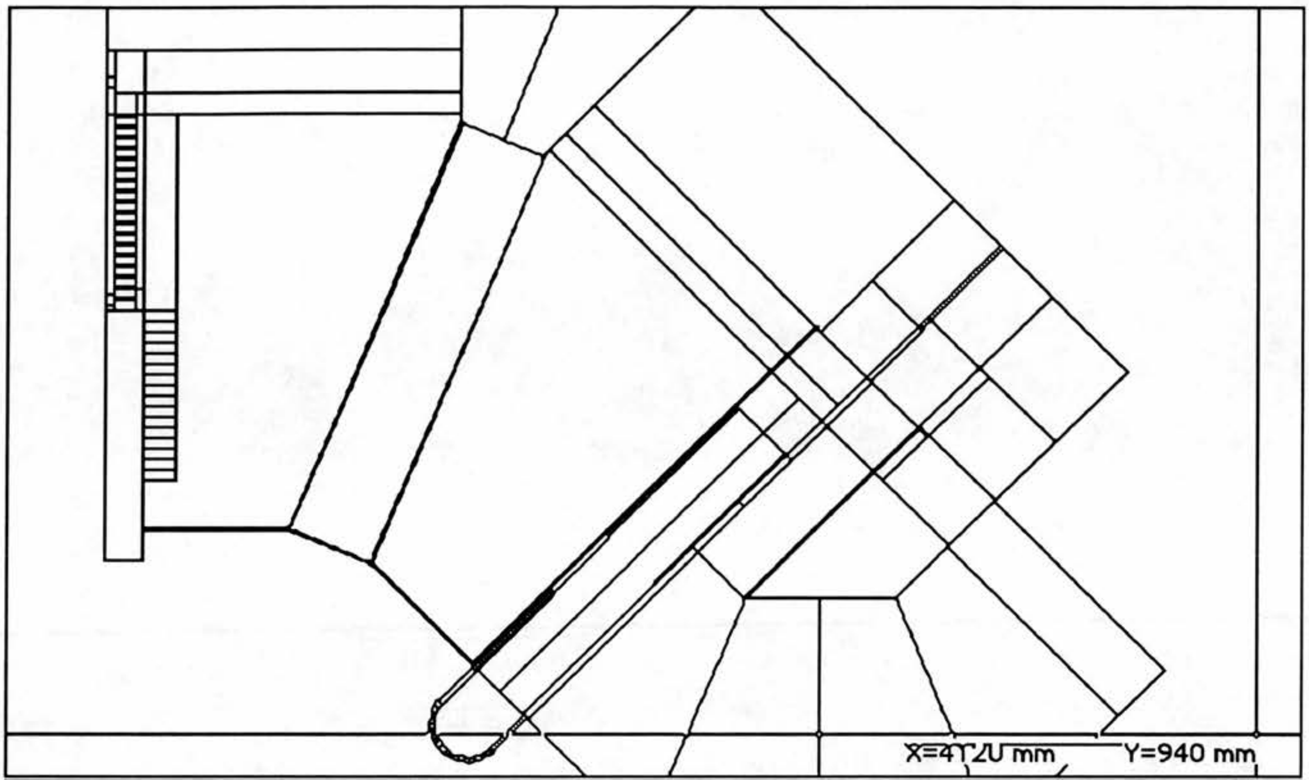


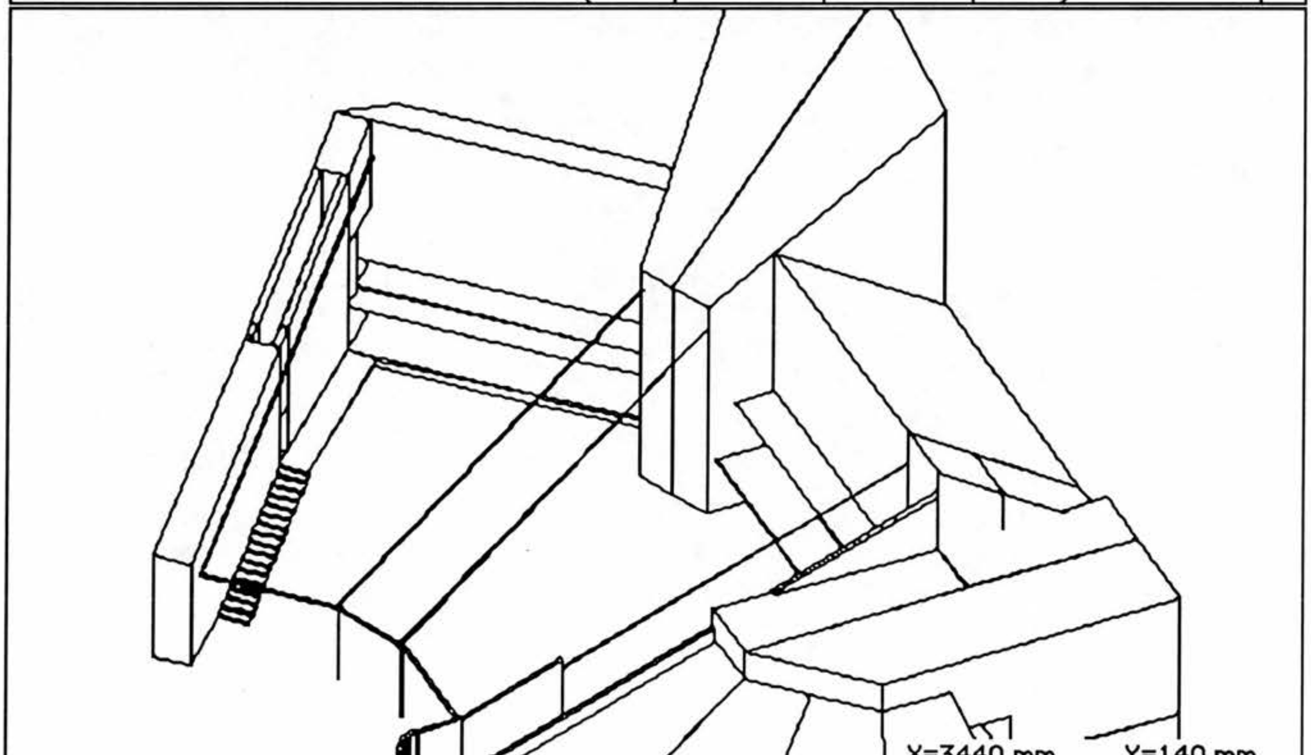


Student B; Instance 065

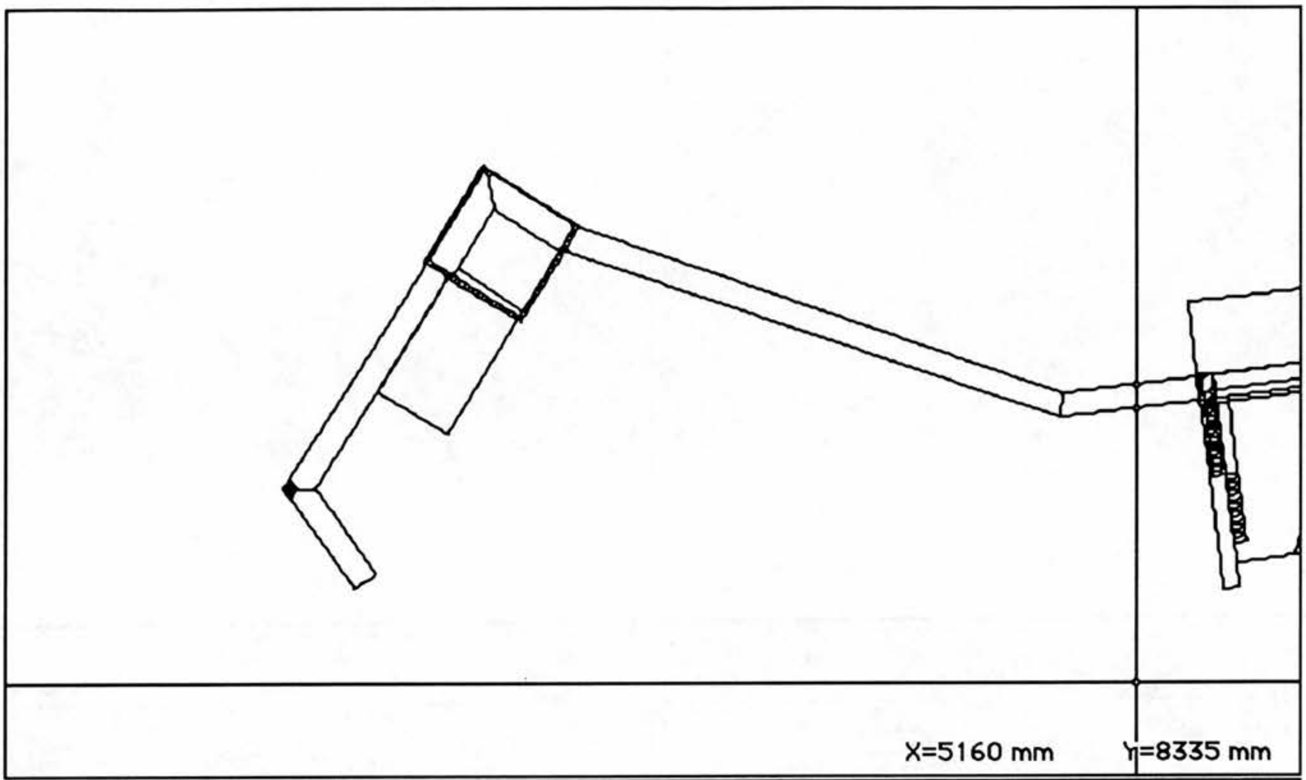


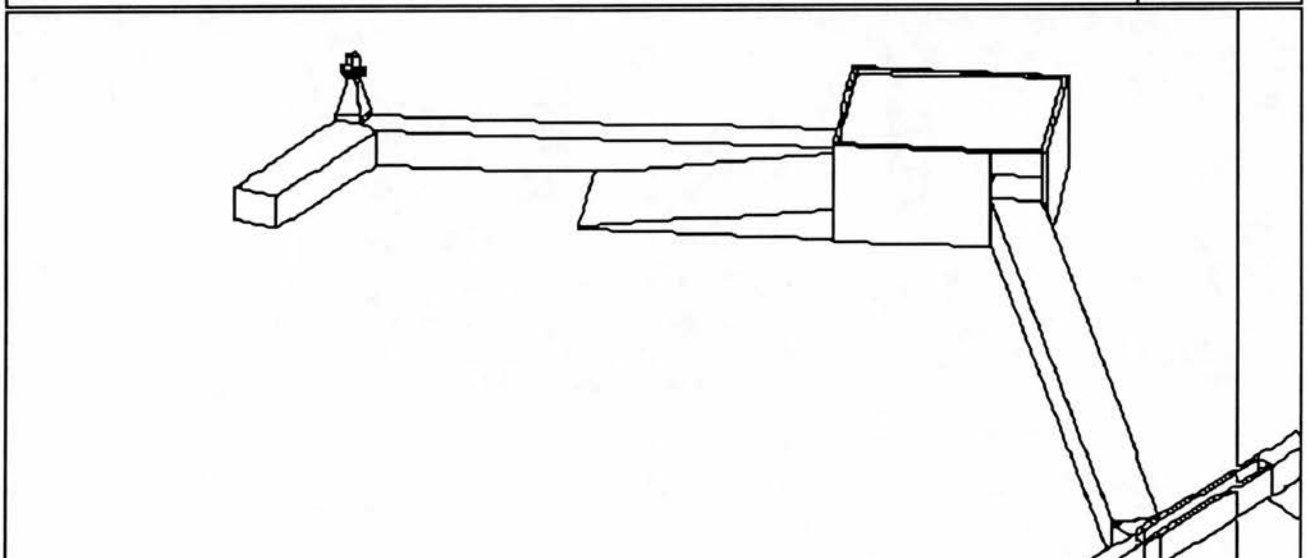
Student B; Instance 081



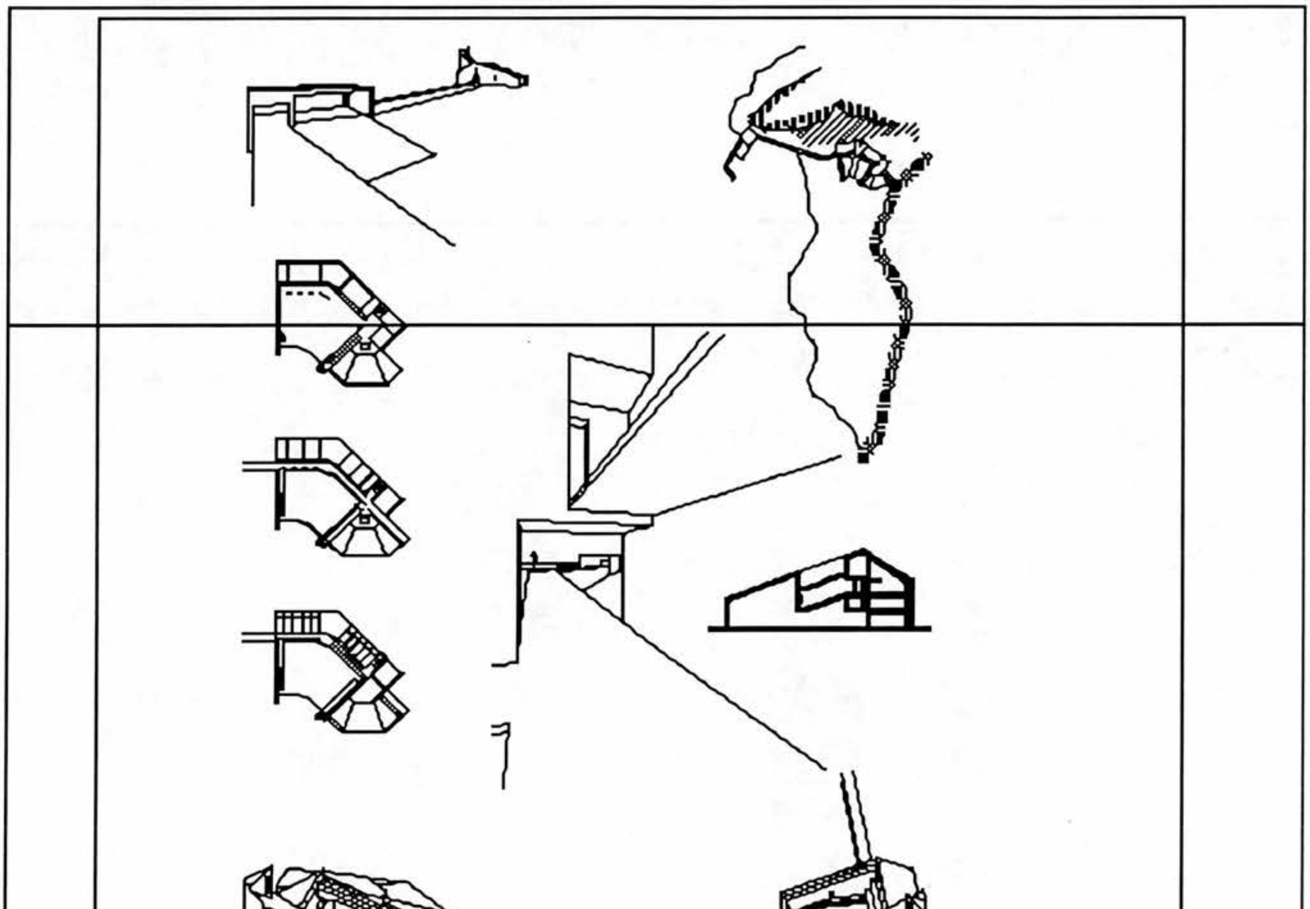


Student B; Instance 087

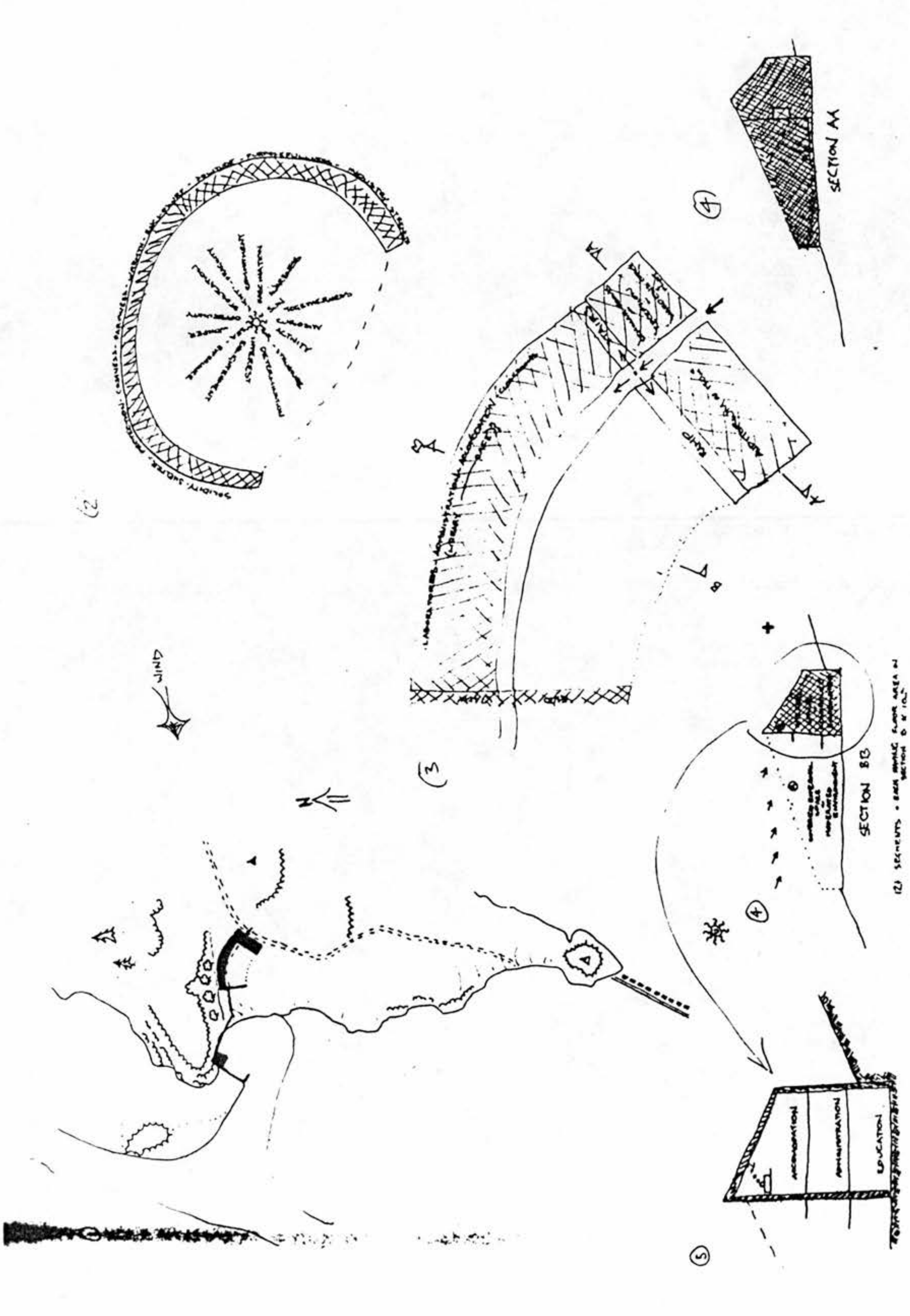




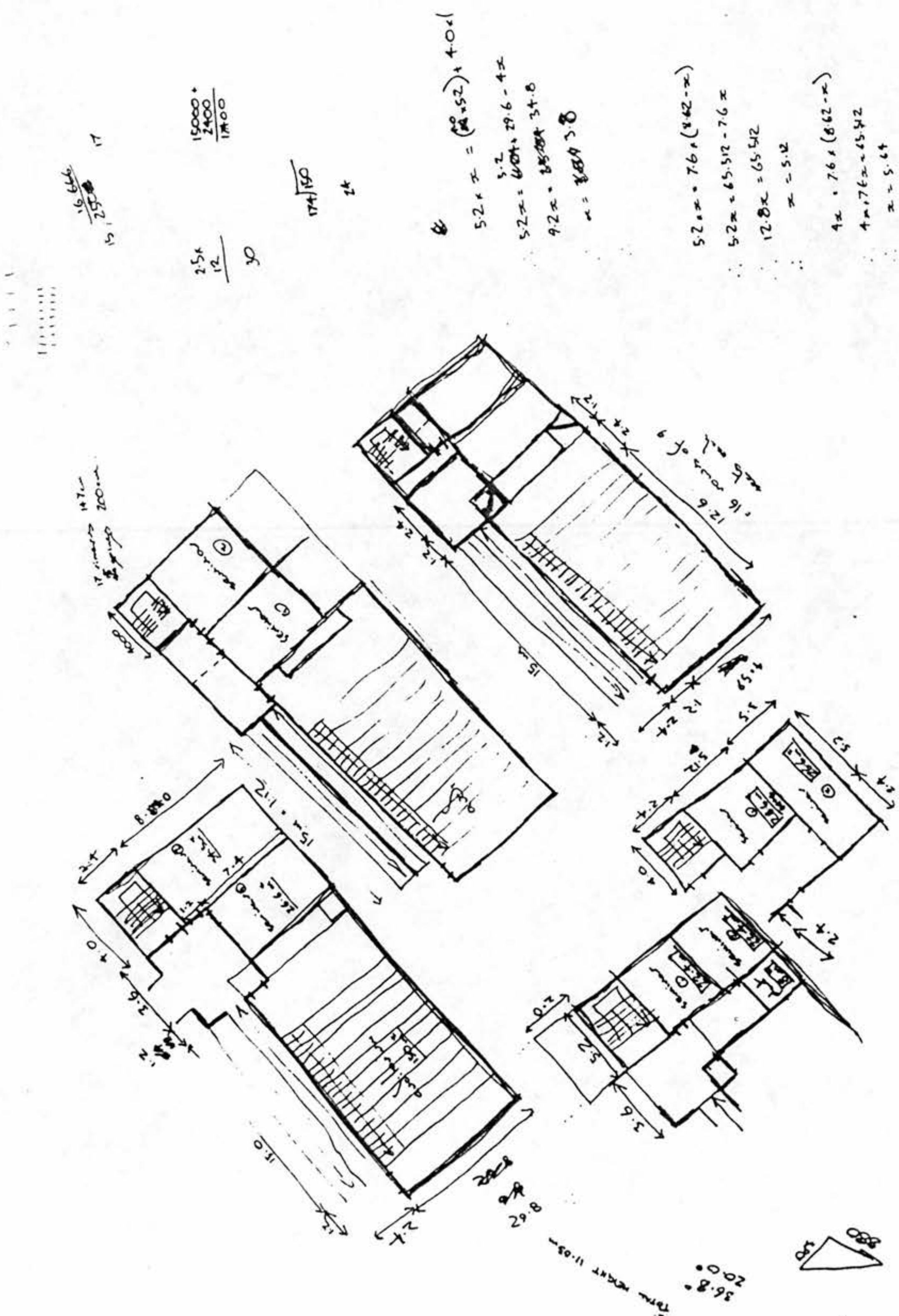
Student B; Instance 109



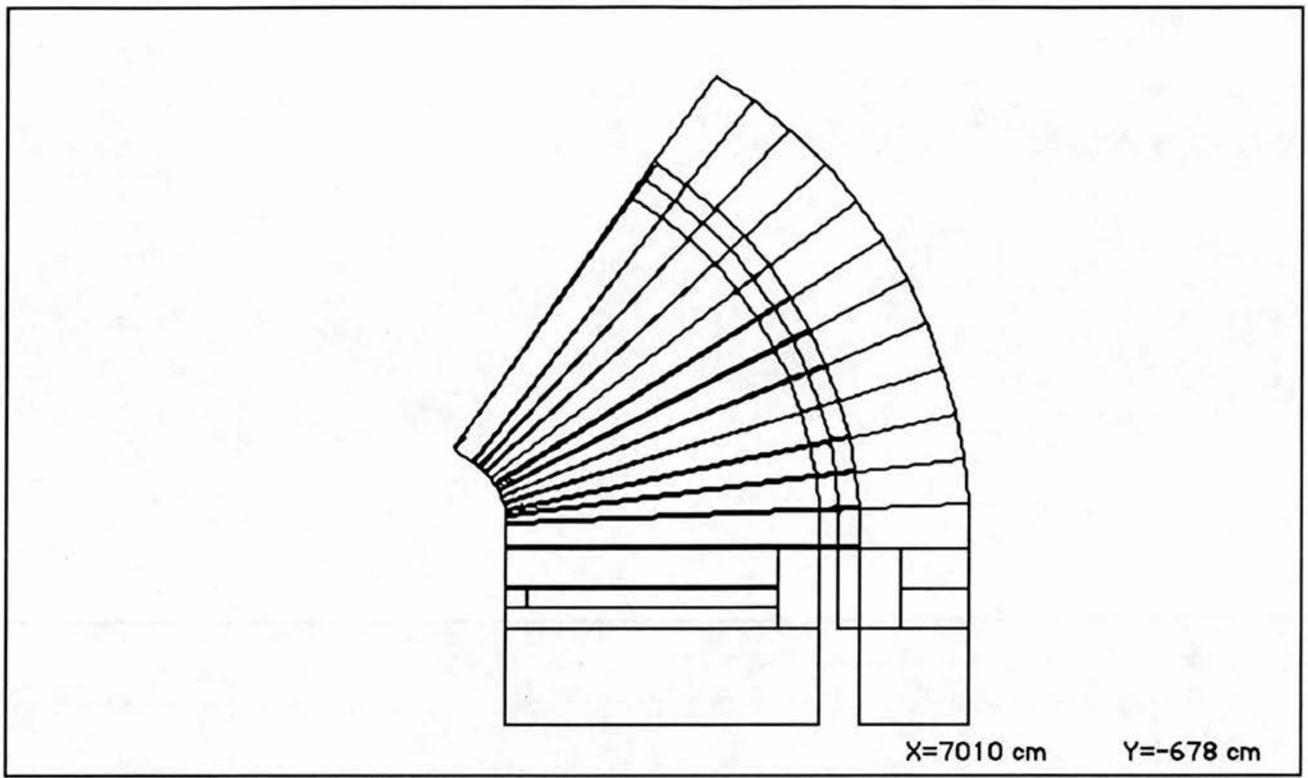
Student B; Instance 126

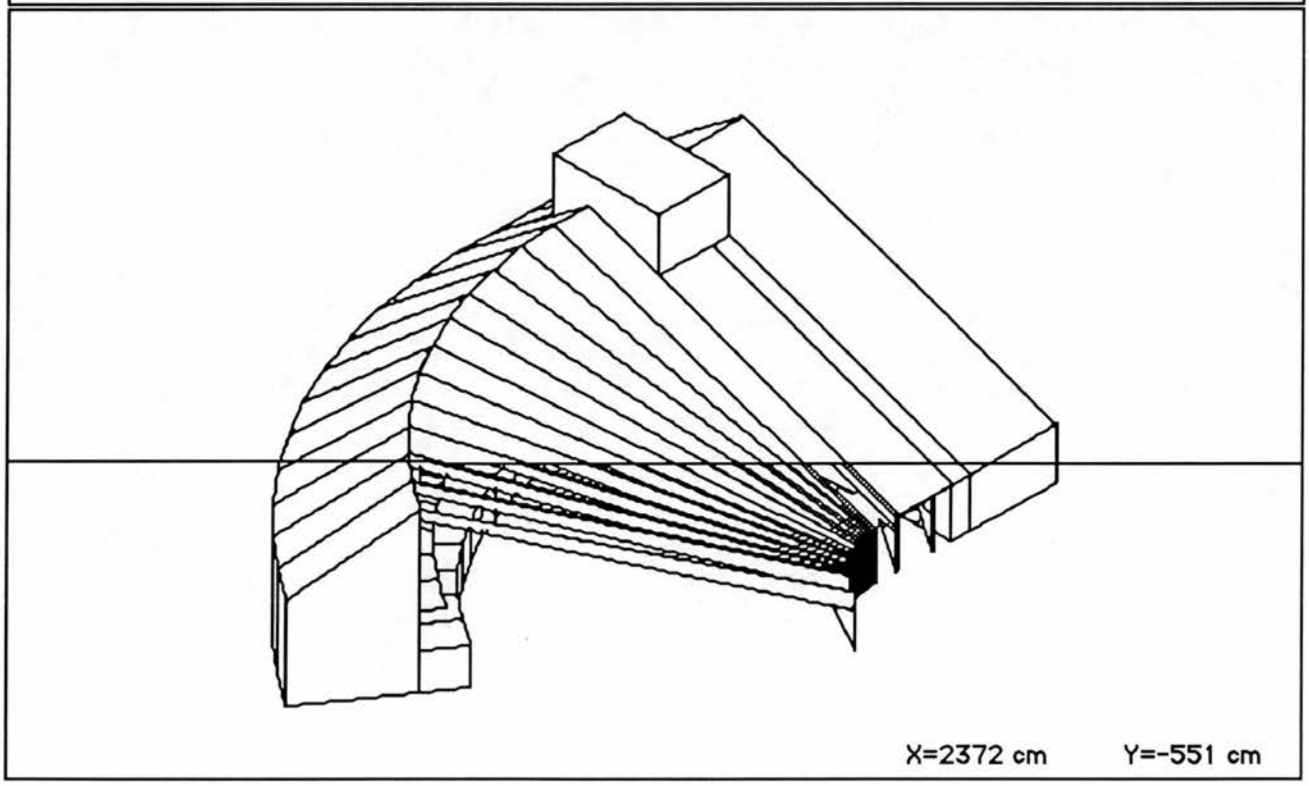


Student B; Instance 127

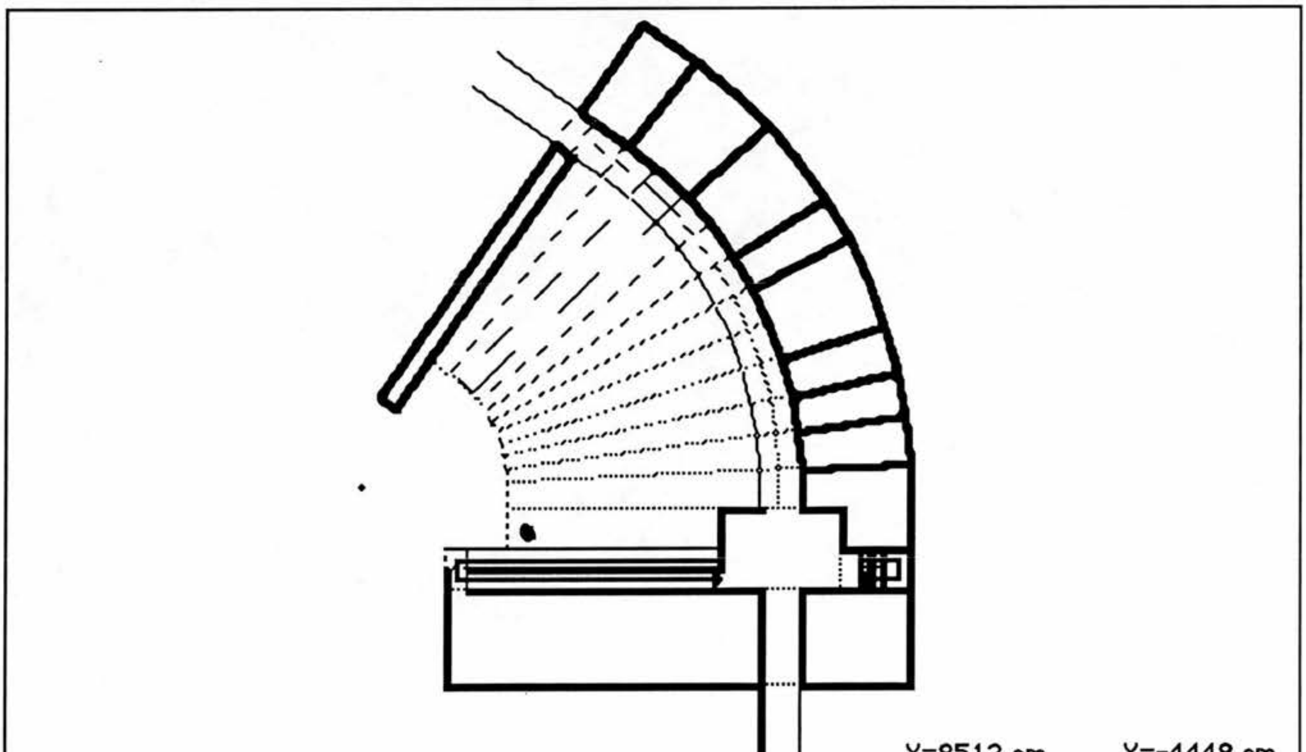


Student B; Instance 129

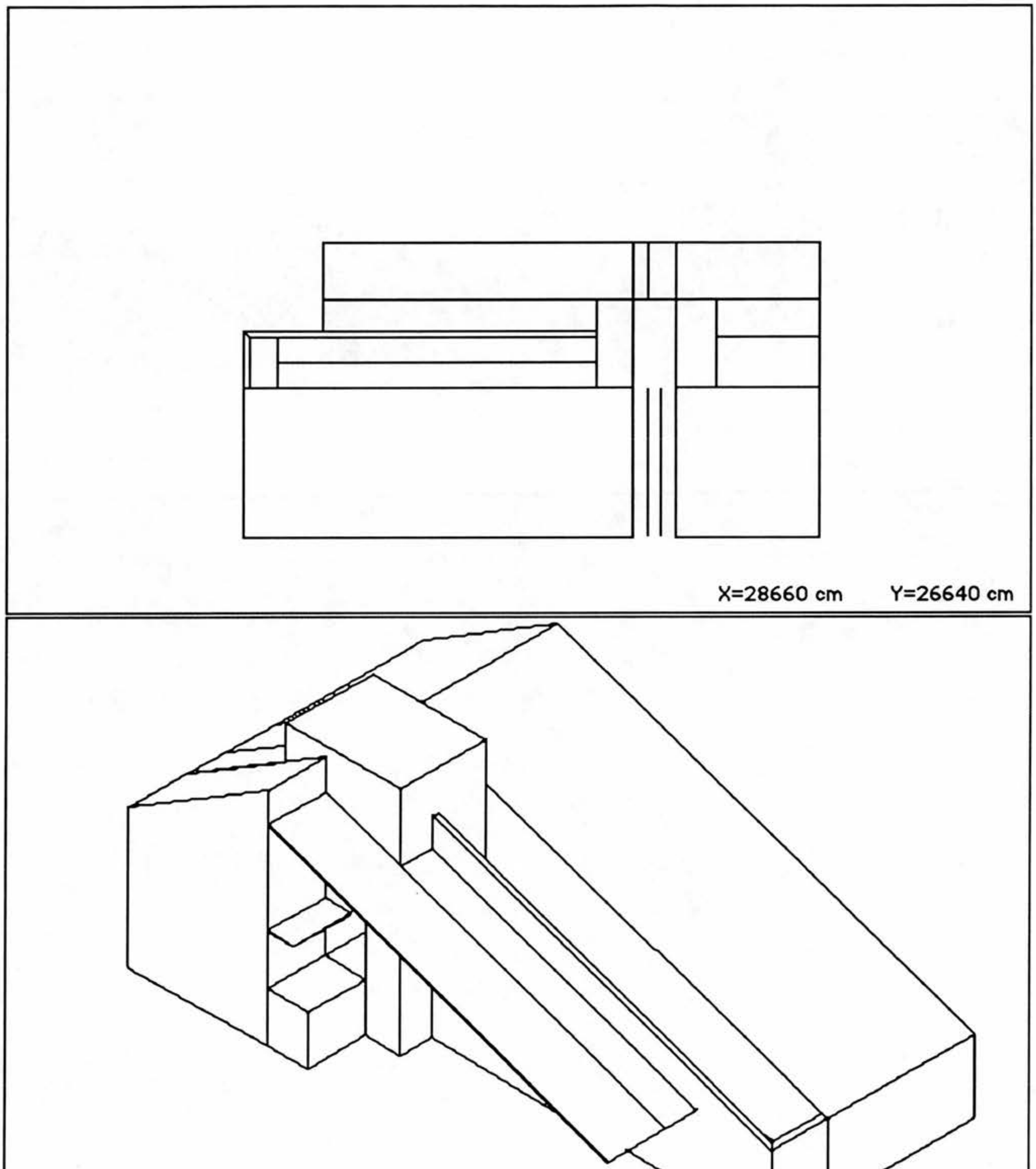




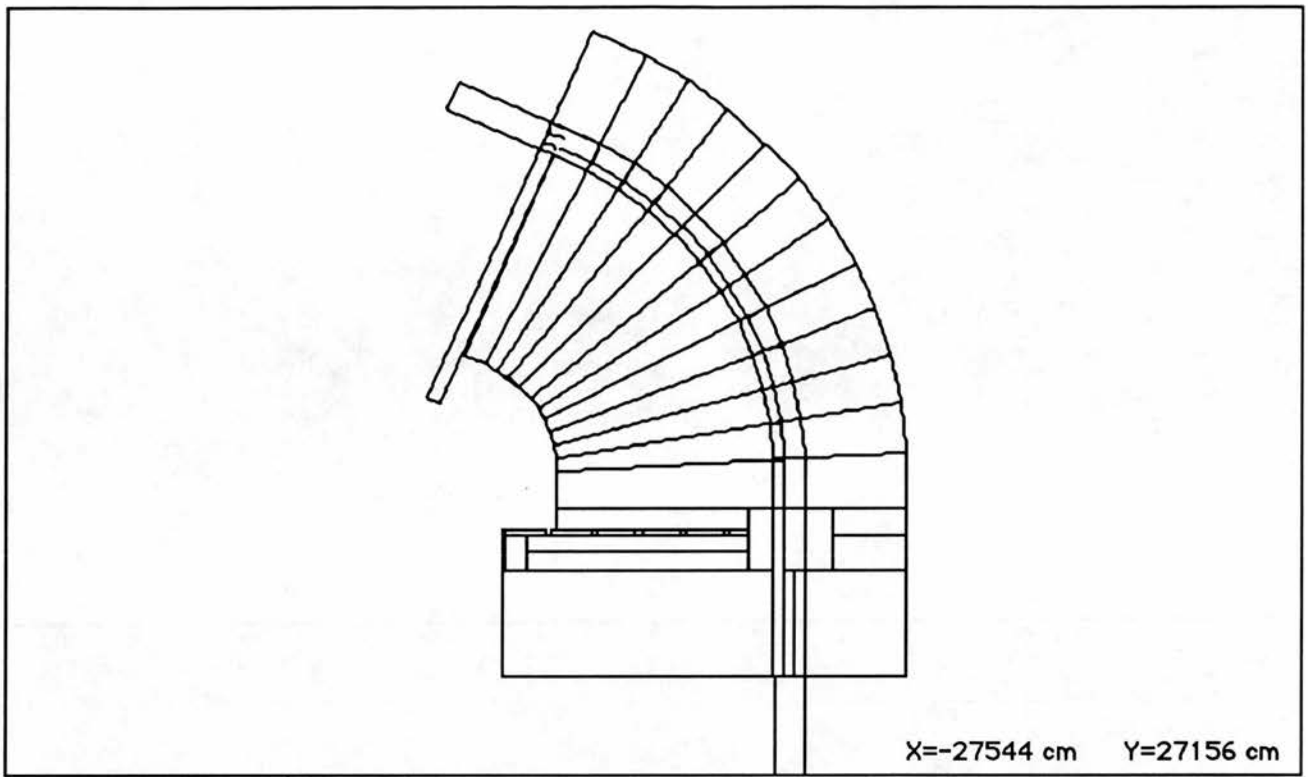
Student B; Instance 135

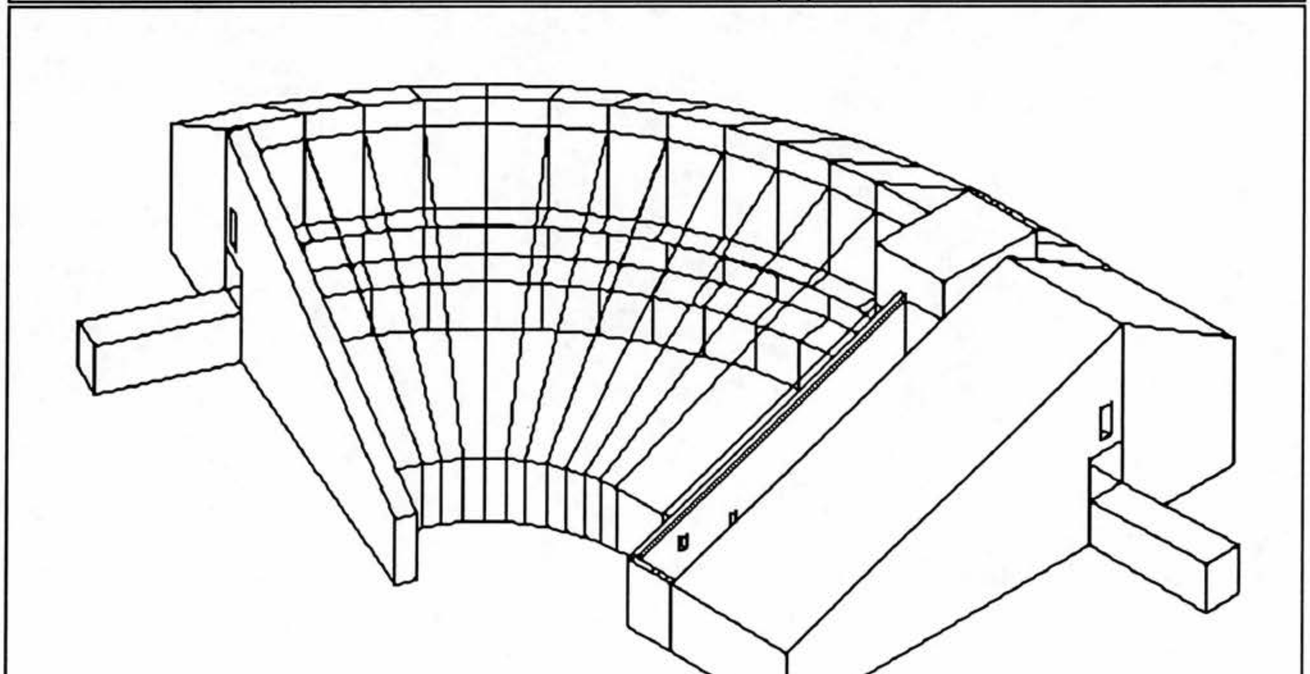


Student B; Instance 138

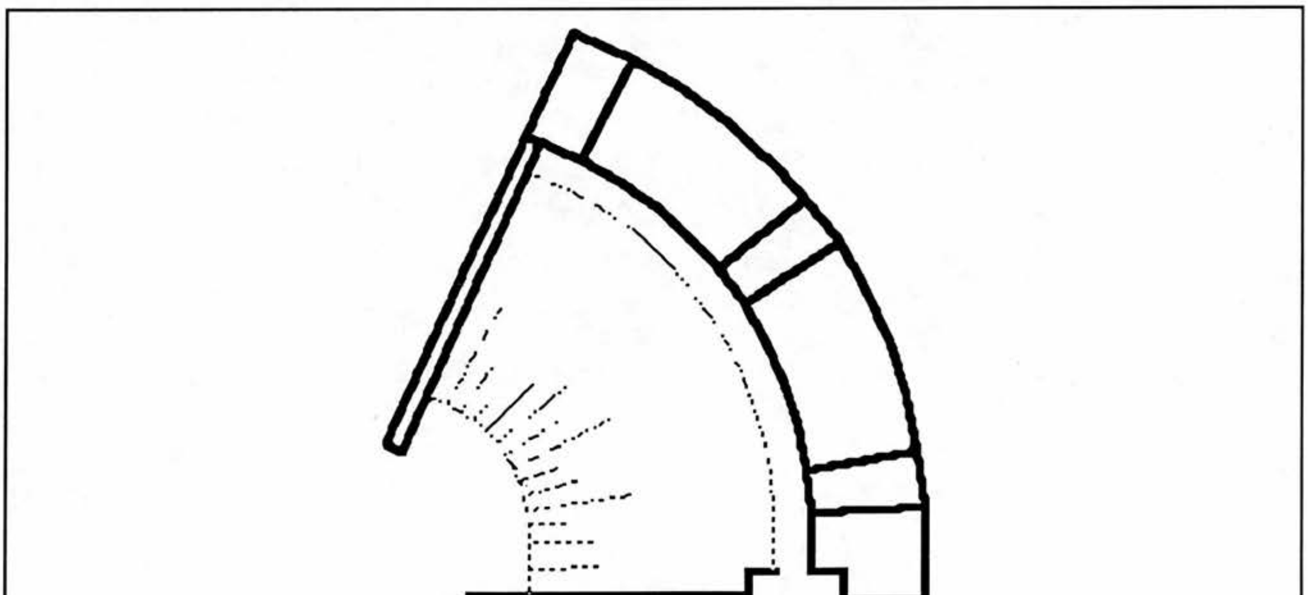


Student B; Instance 143

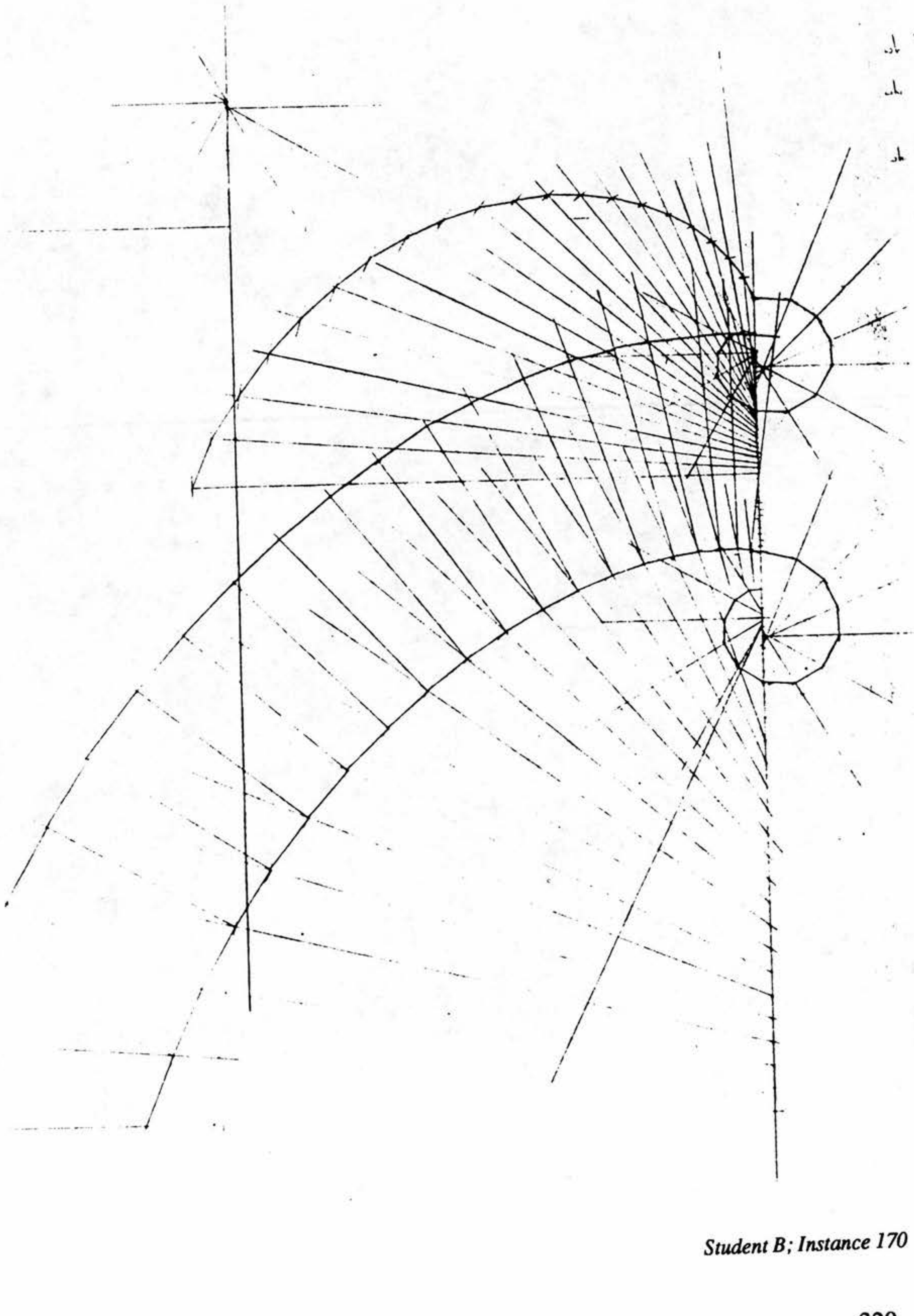




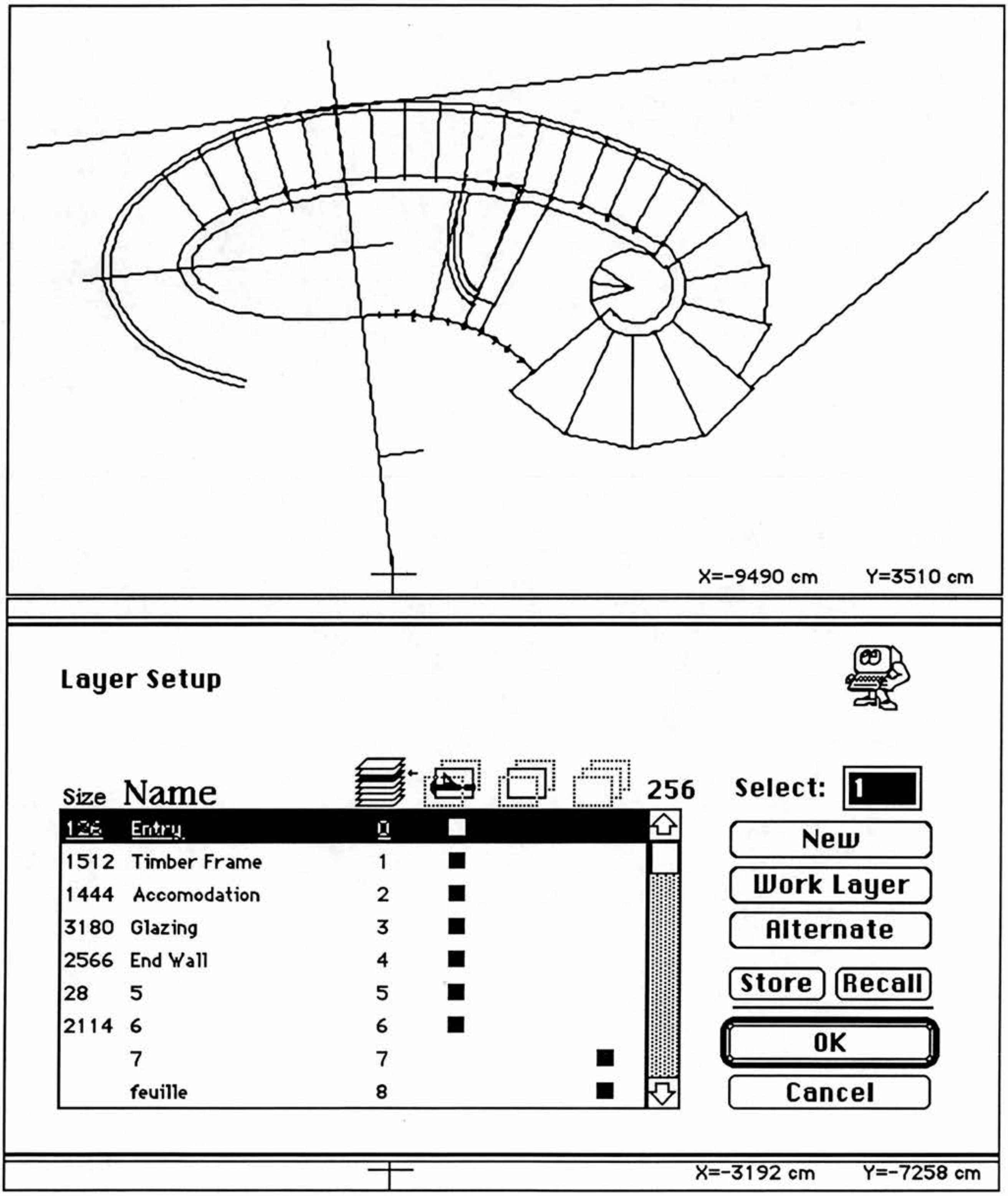
Student B; Instance 155



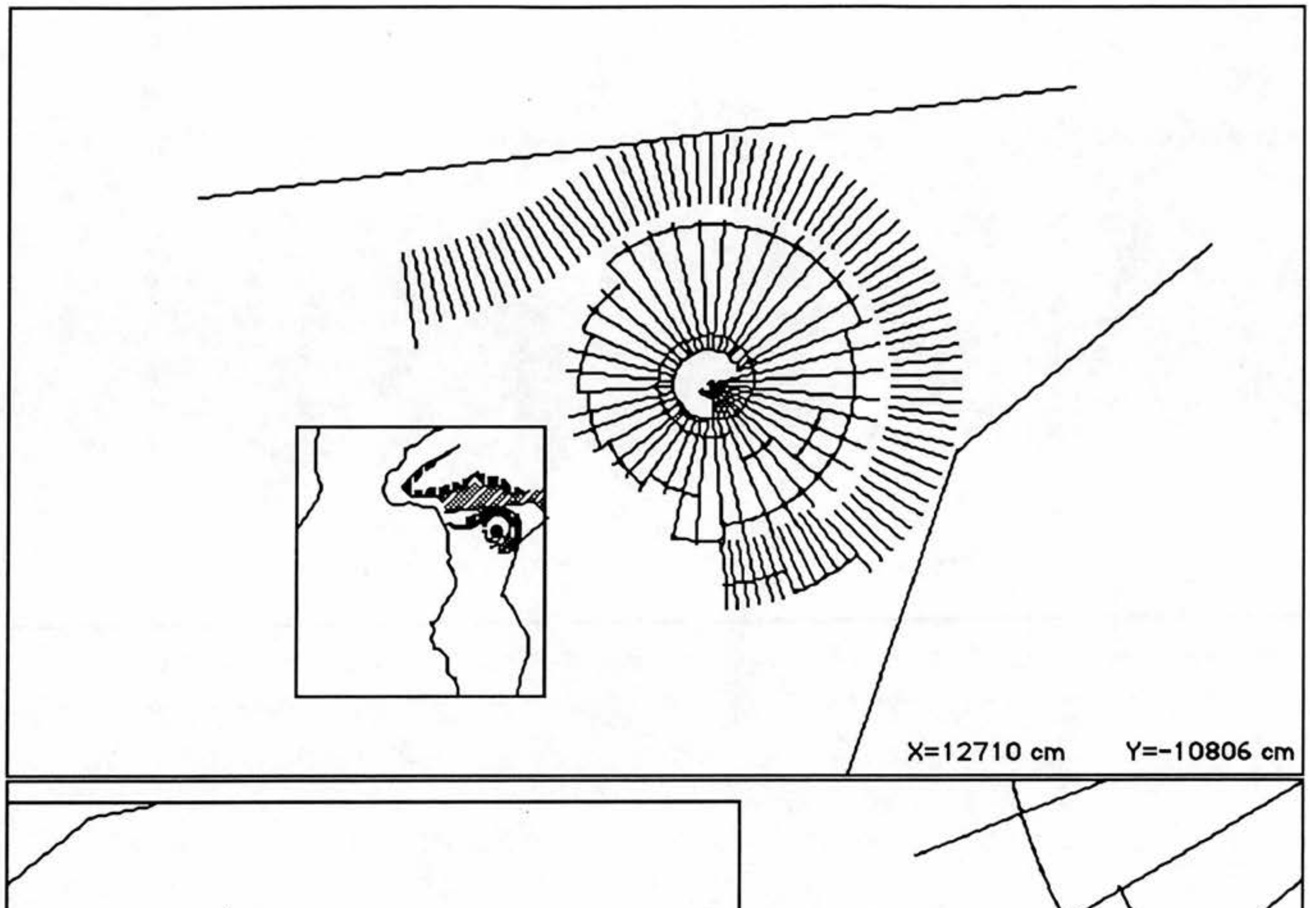
Student B; Instance 159



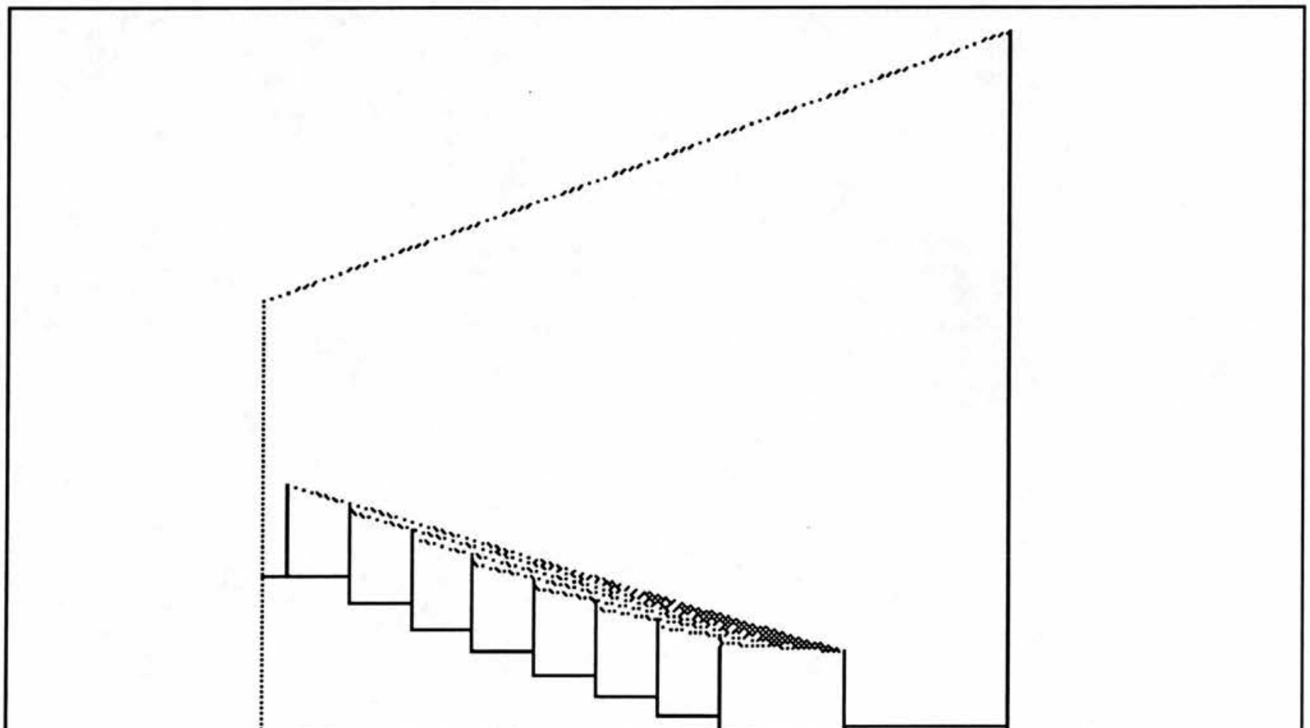
Student B; Instance 170



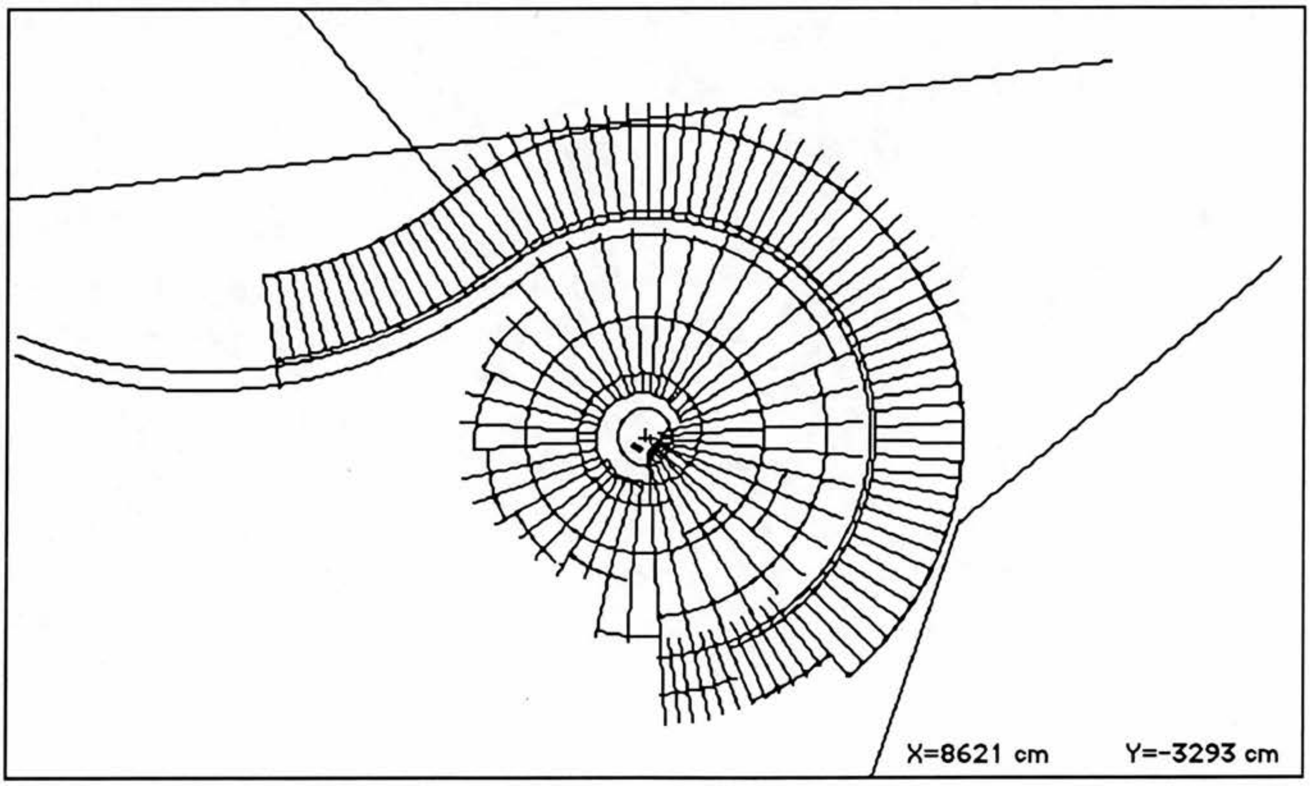
Student B; Instance 181



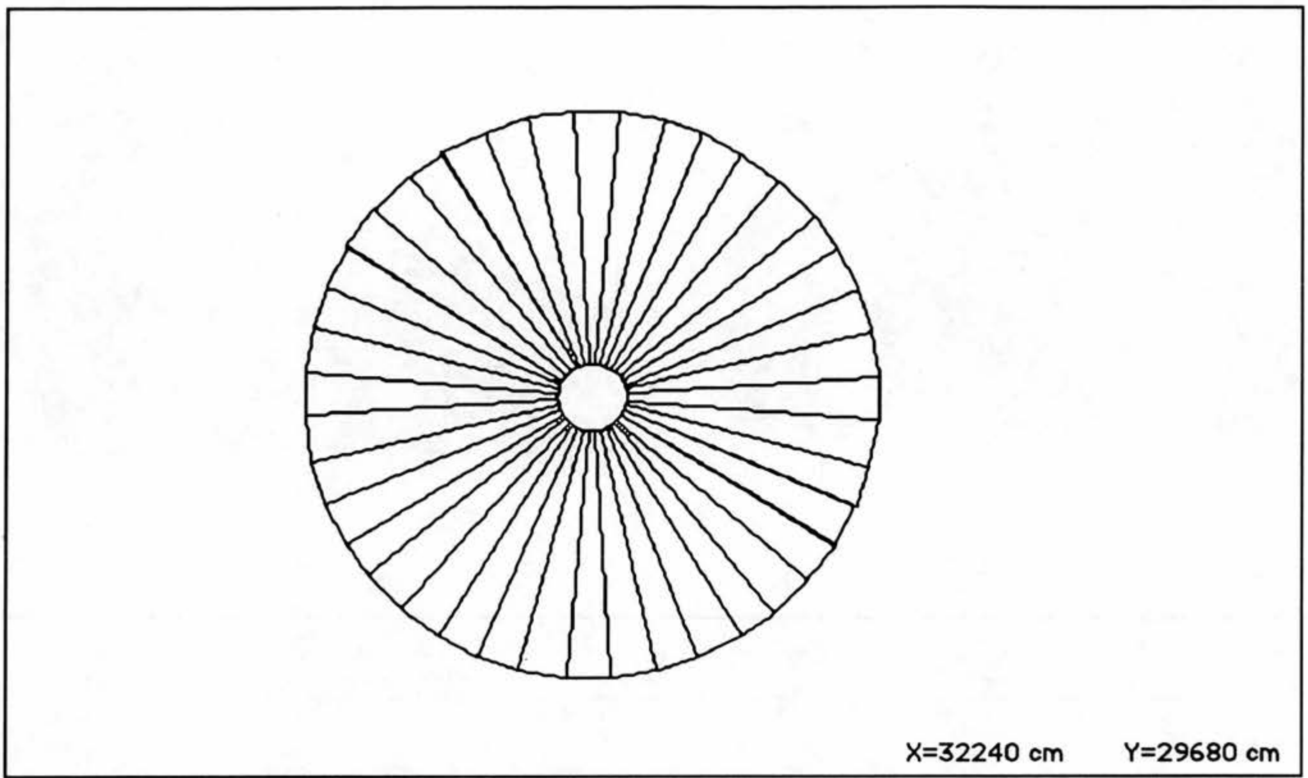
Student B; Instance 187

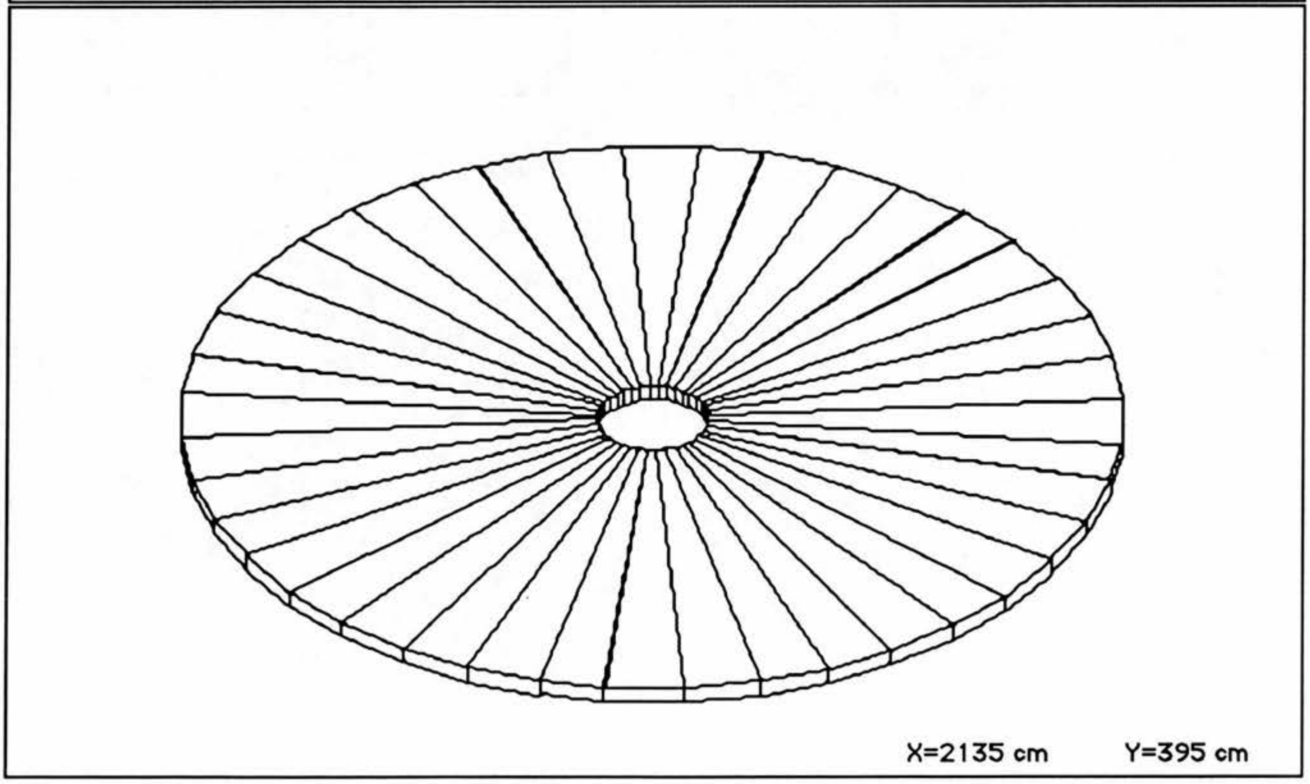


Student B; Instance 188

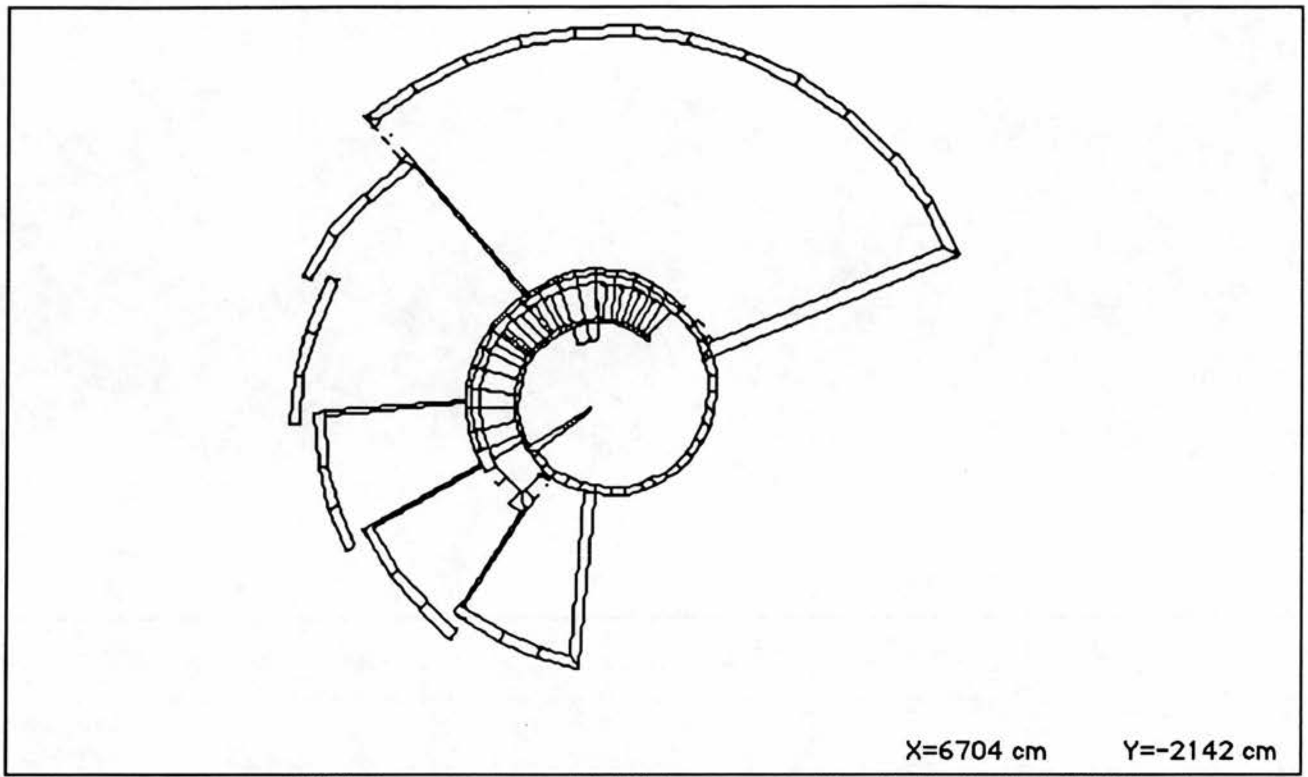


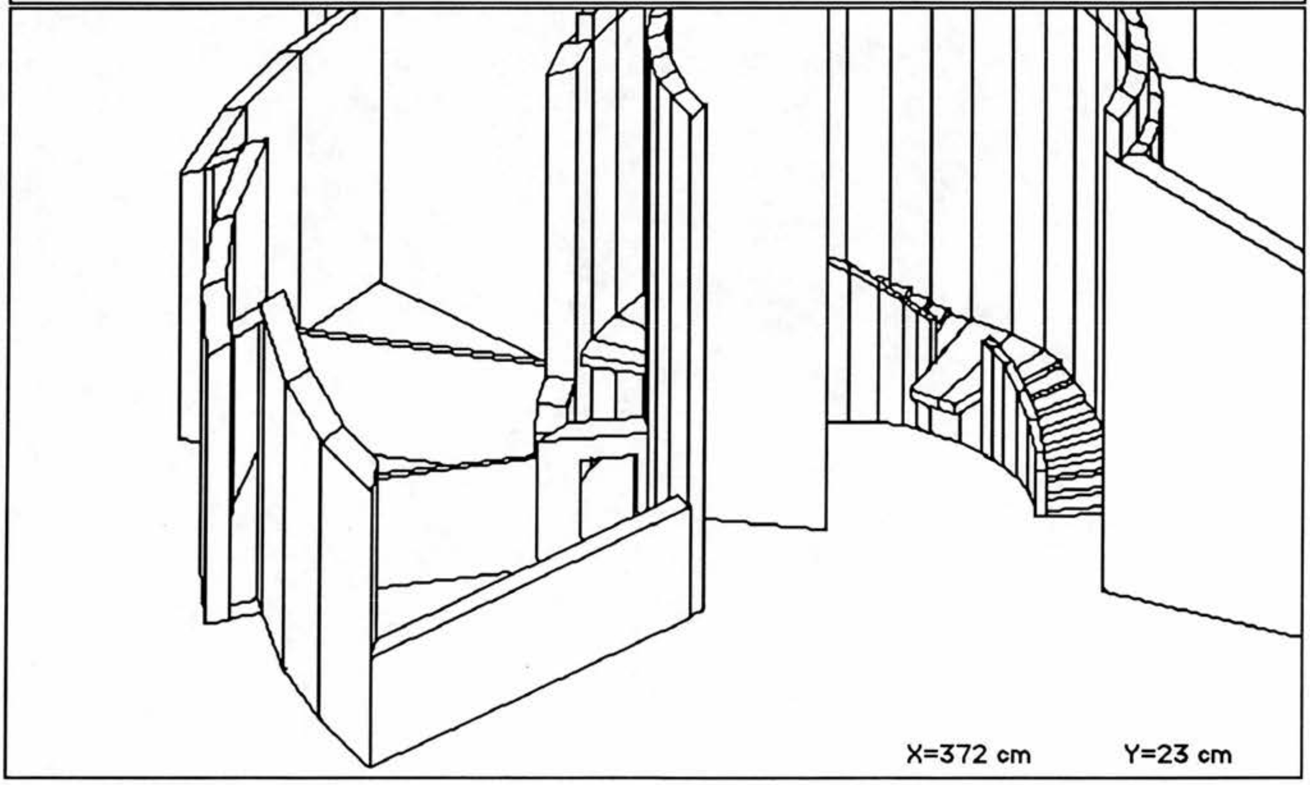
Student B; Instance 189



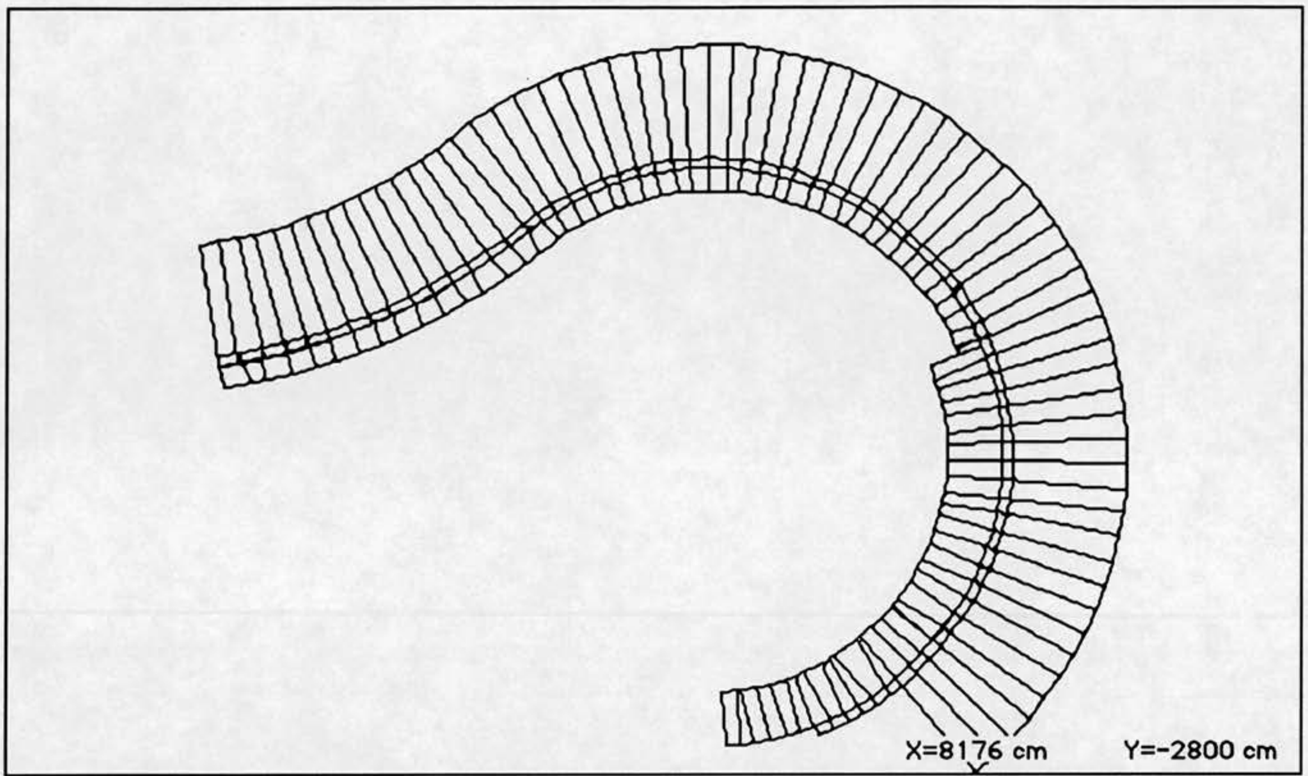


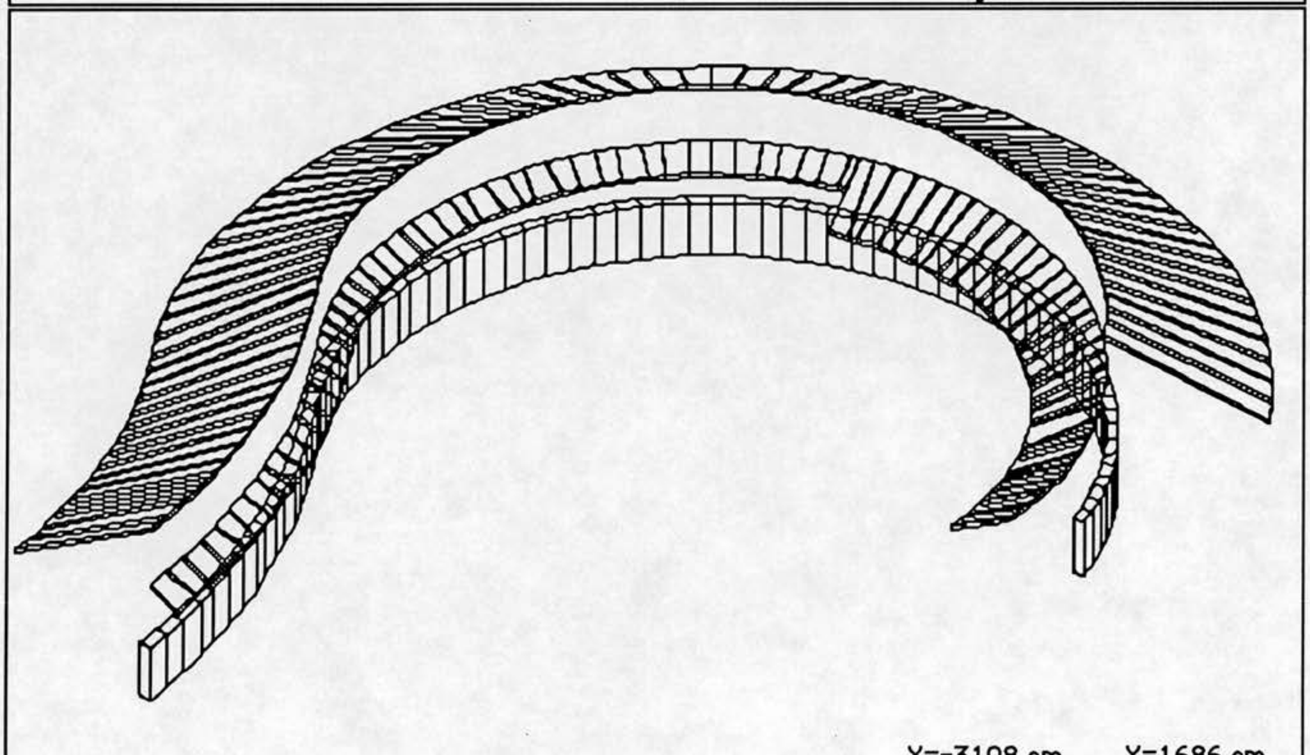
Student B; Instance 190





Student B; Instance 195





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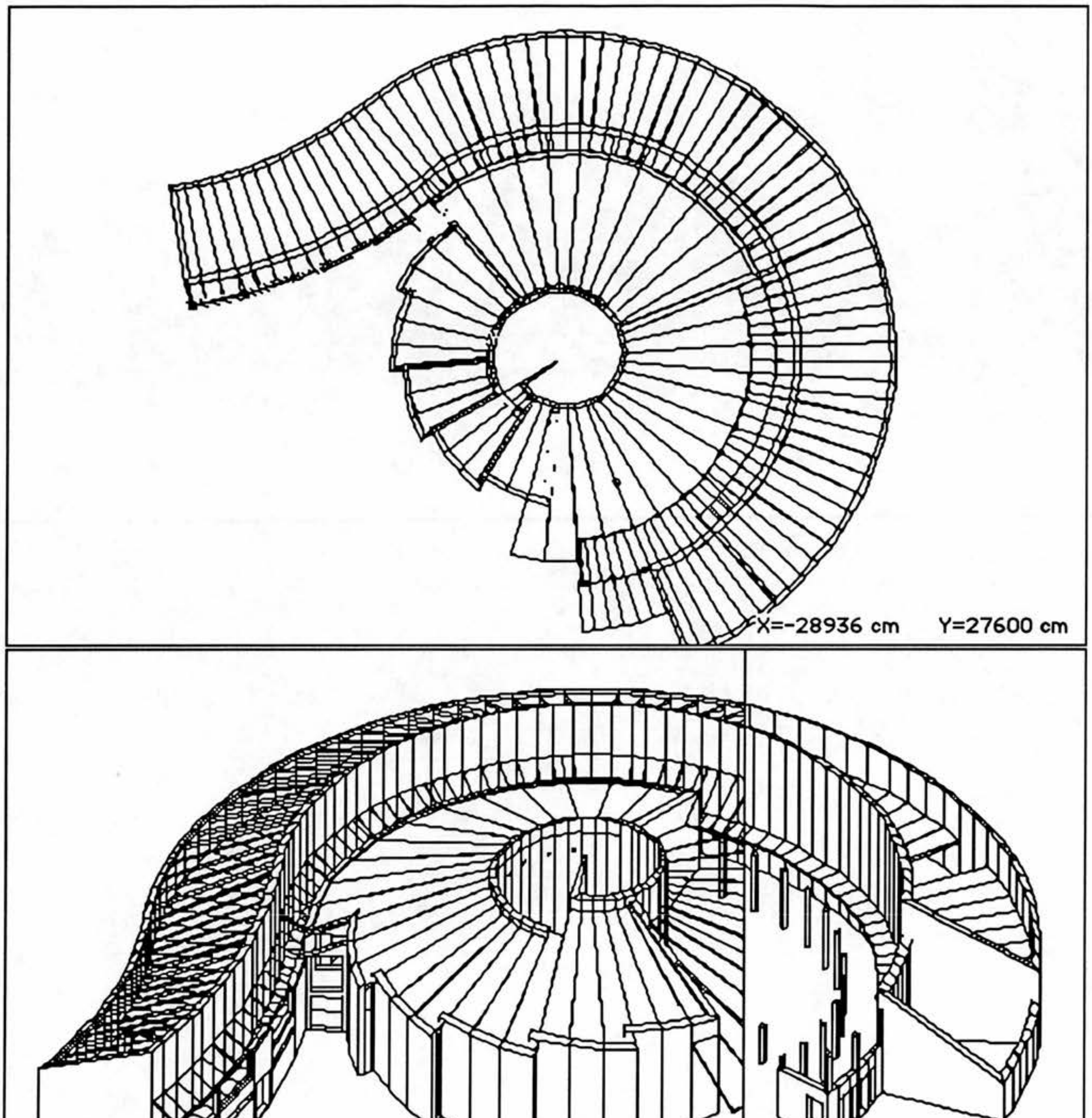
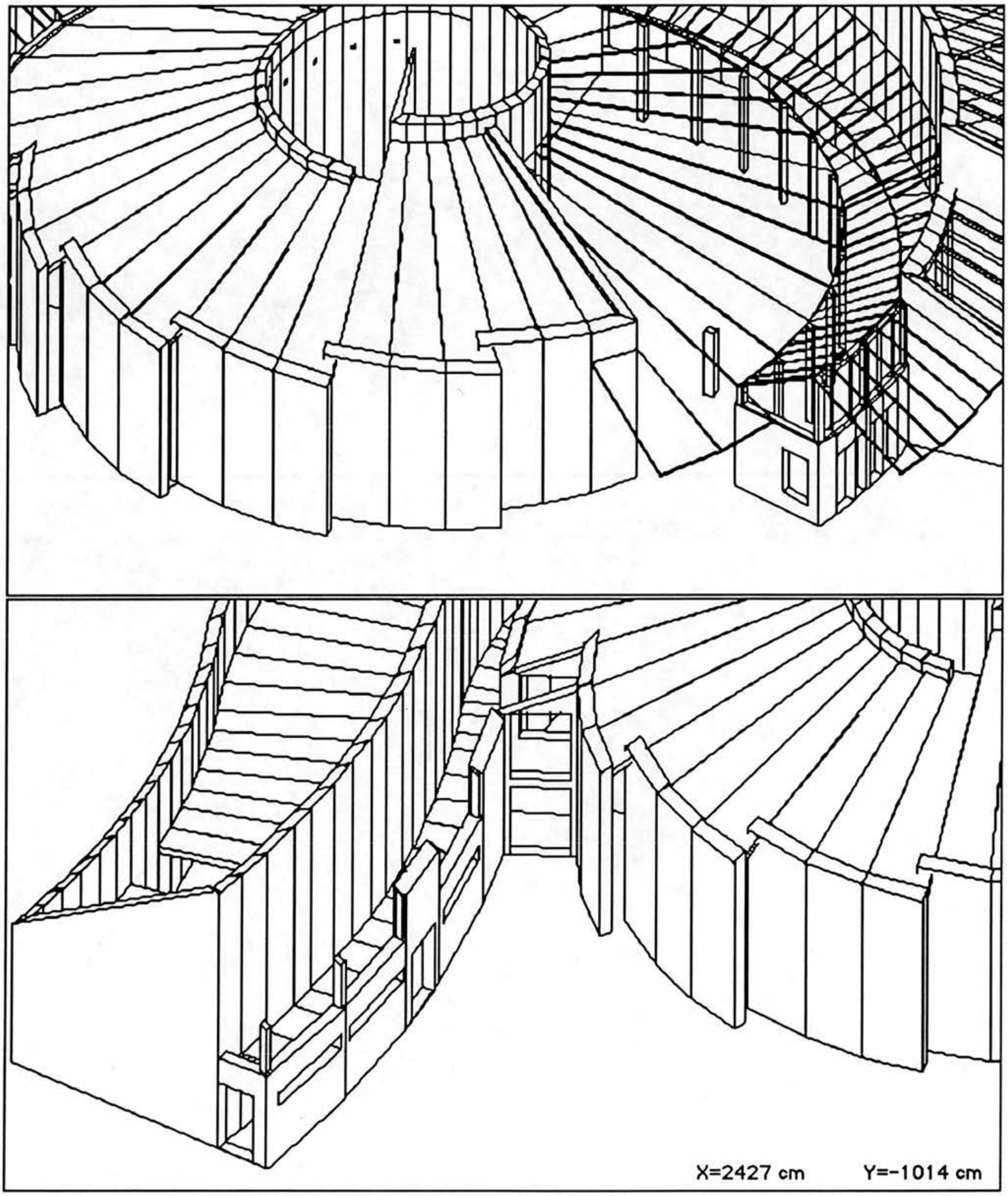
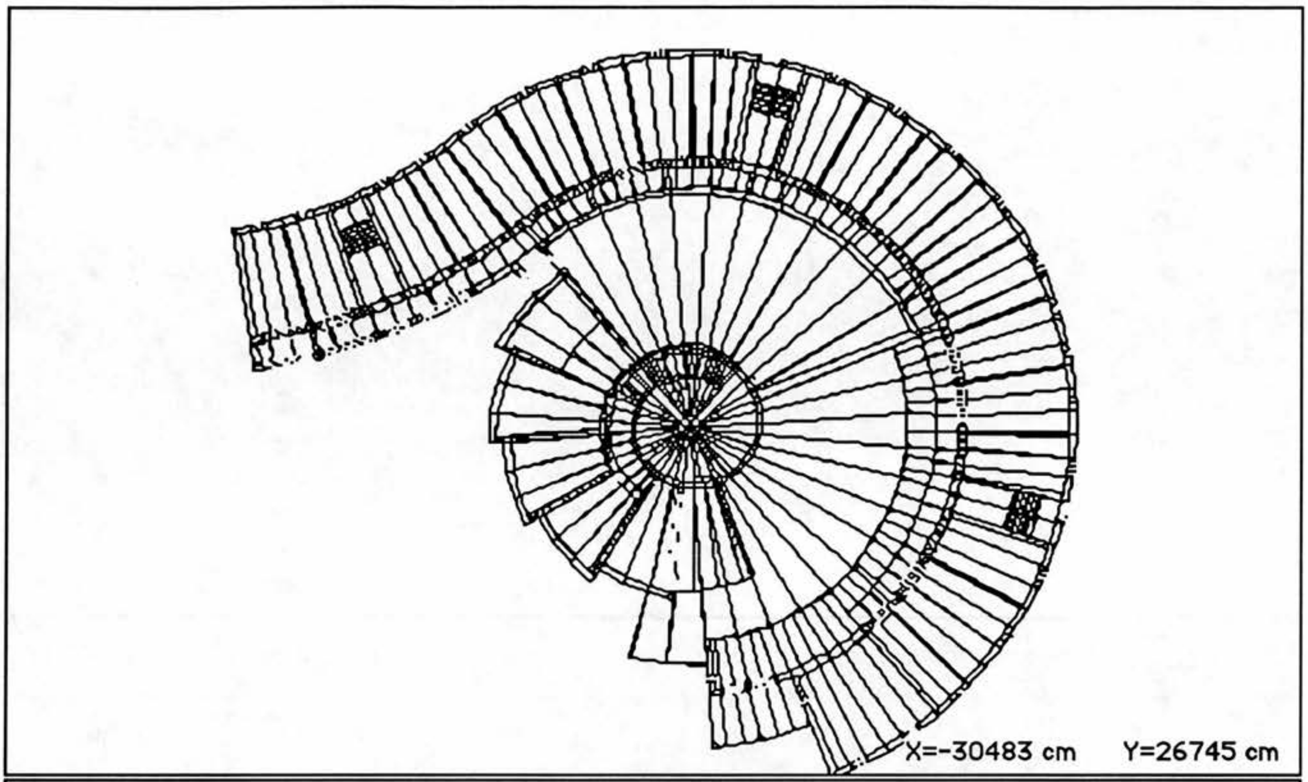
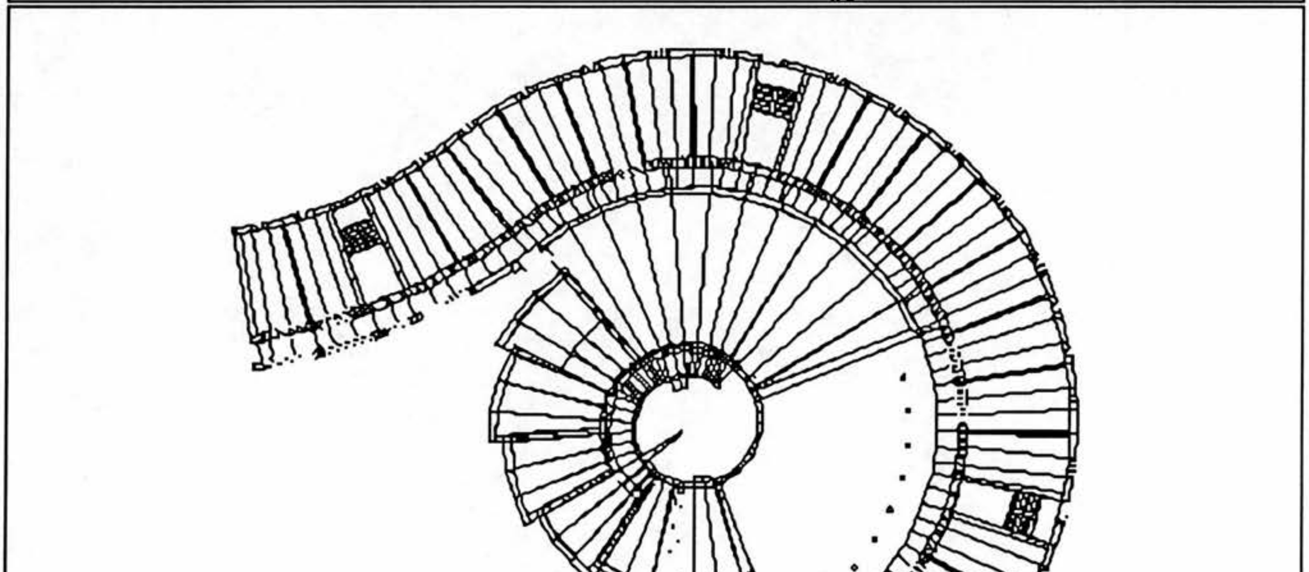


Student B; Instance 214.a



Student B; Instance 214.b





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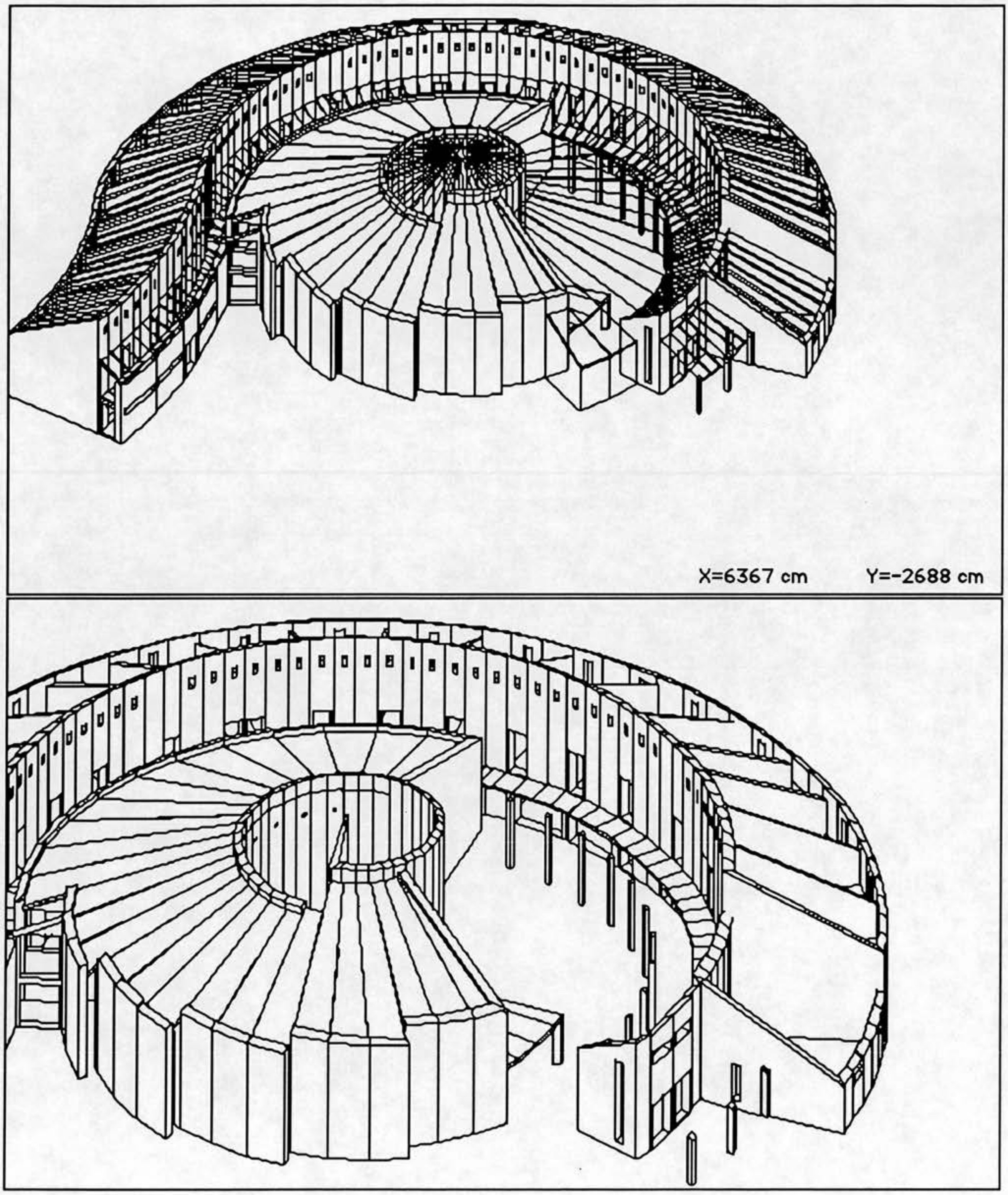

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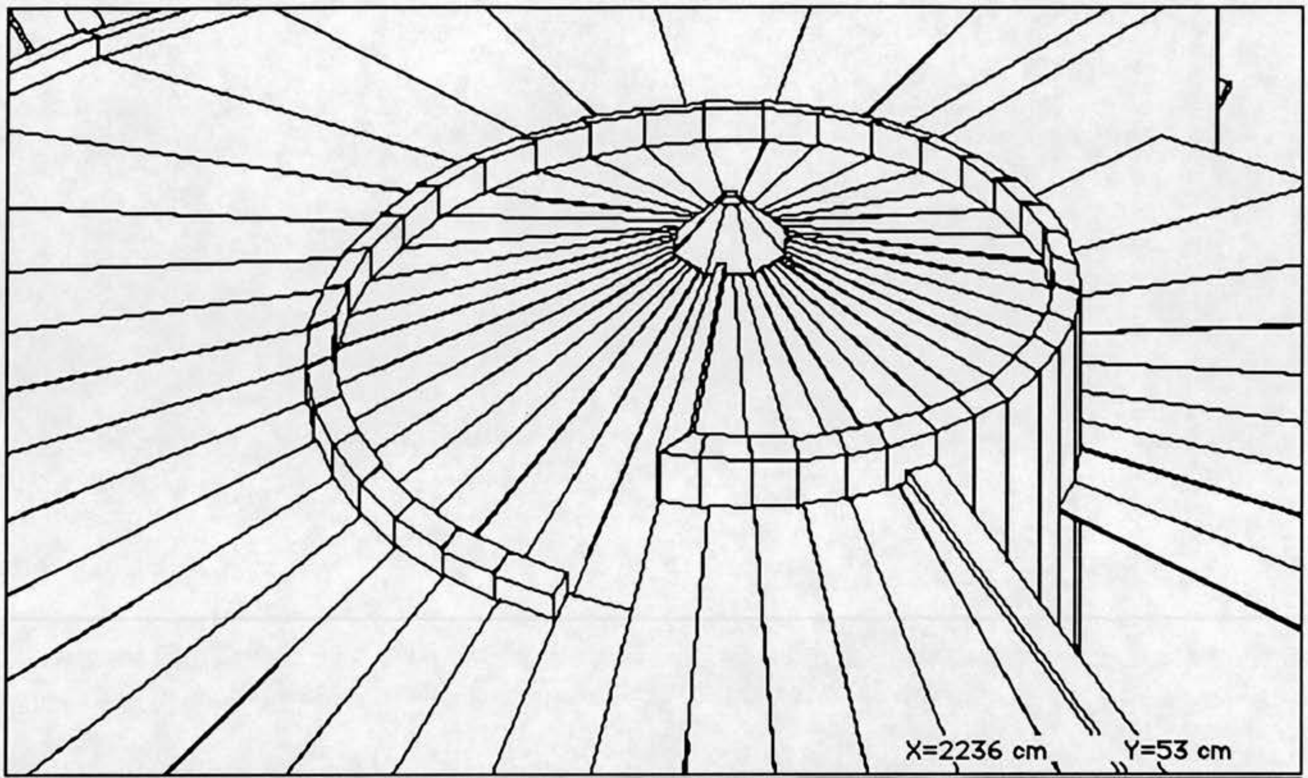

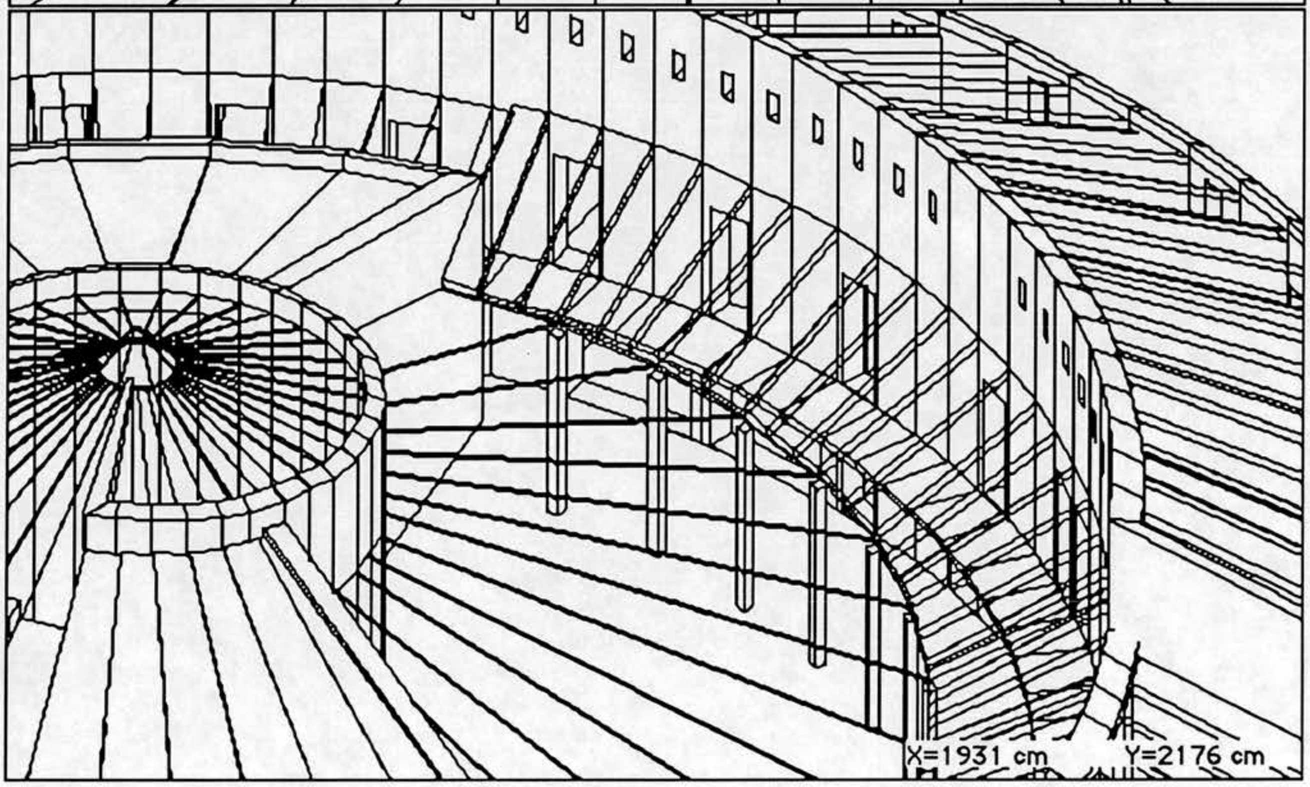

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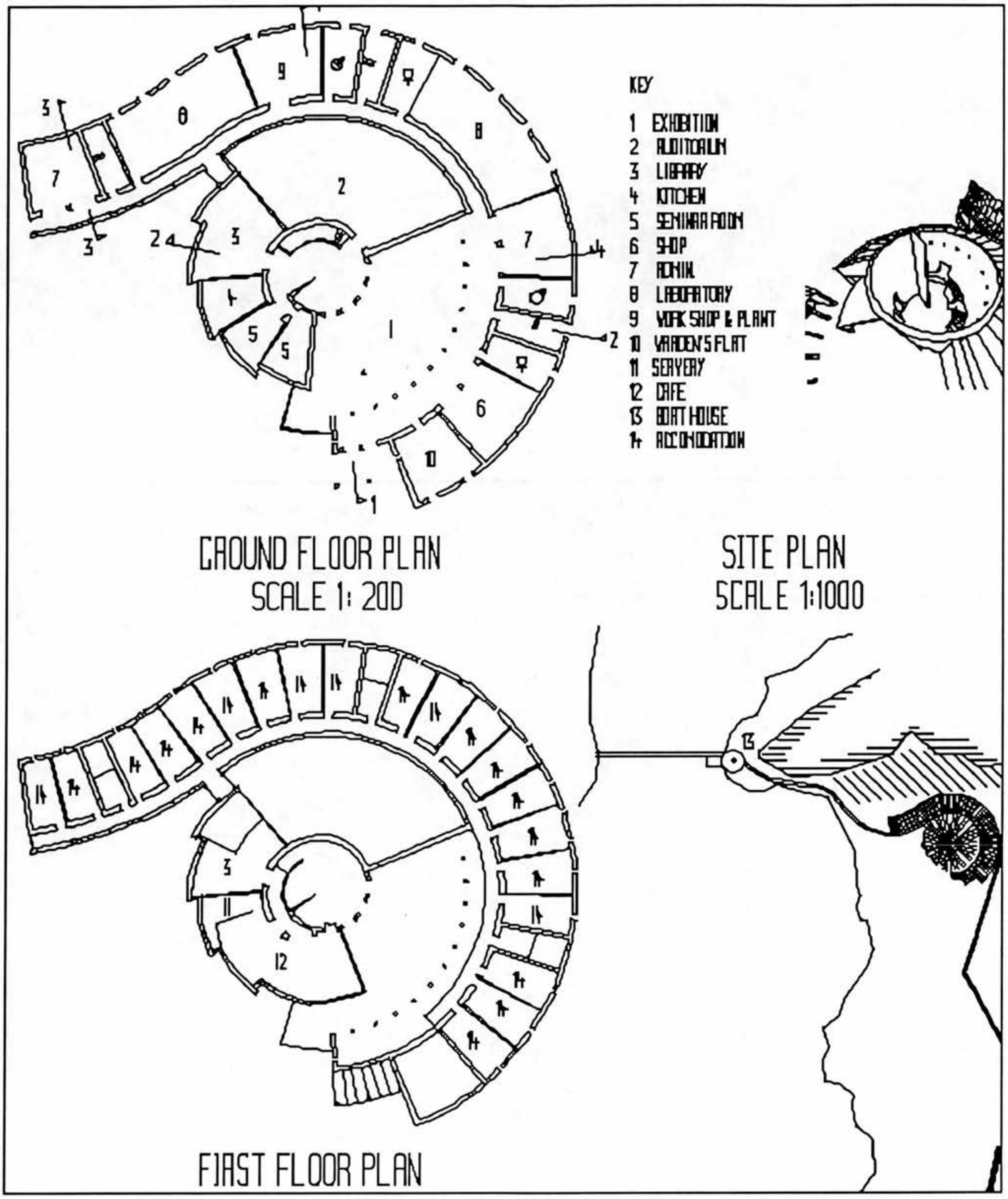
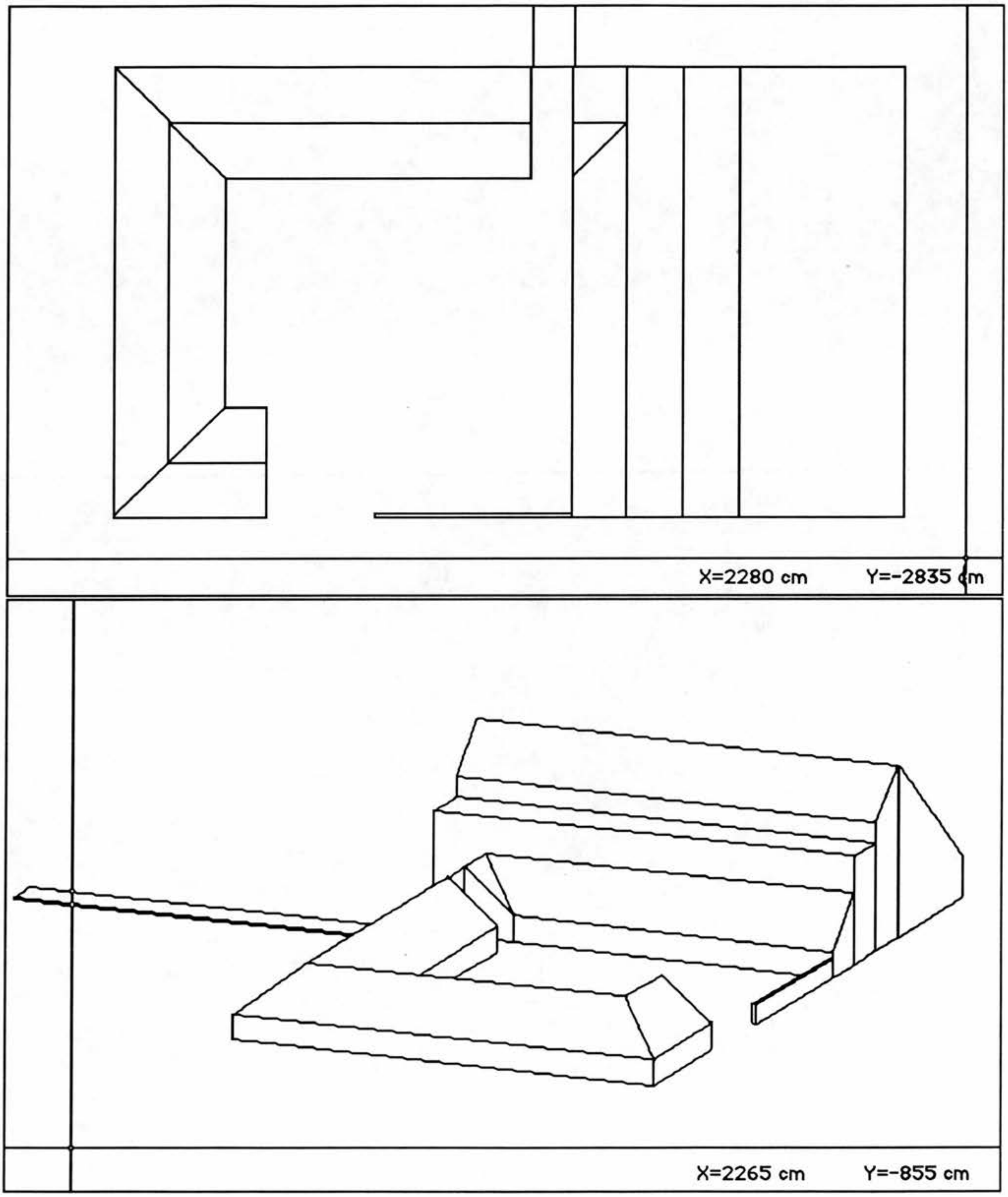
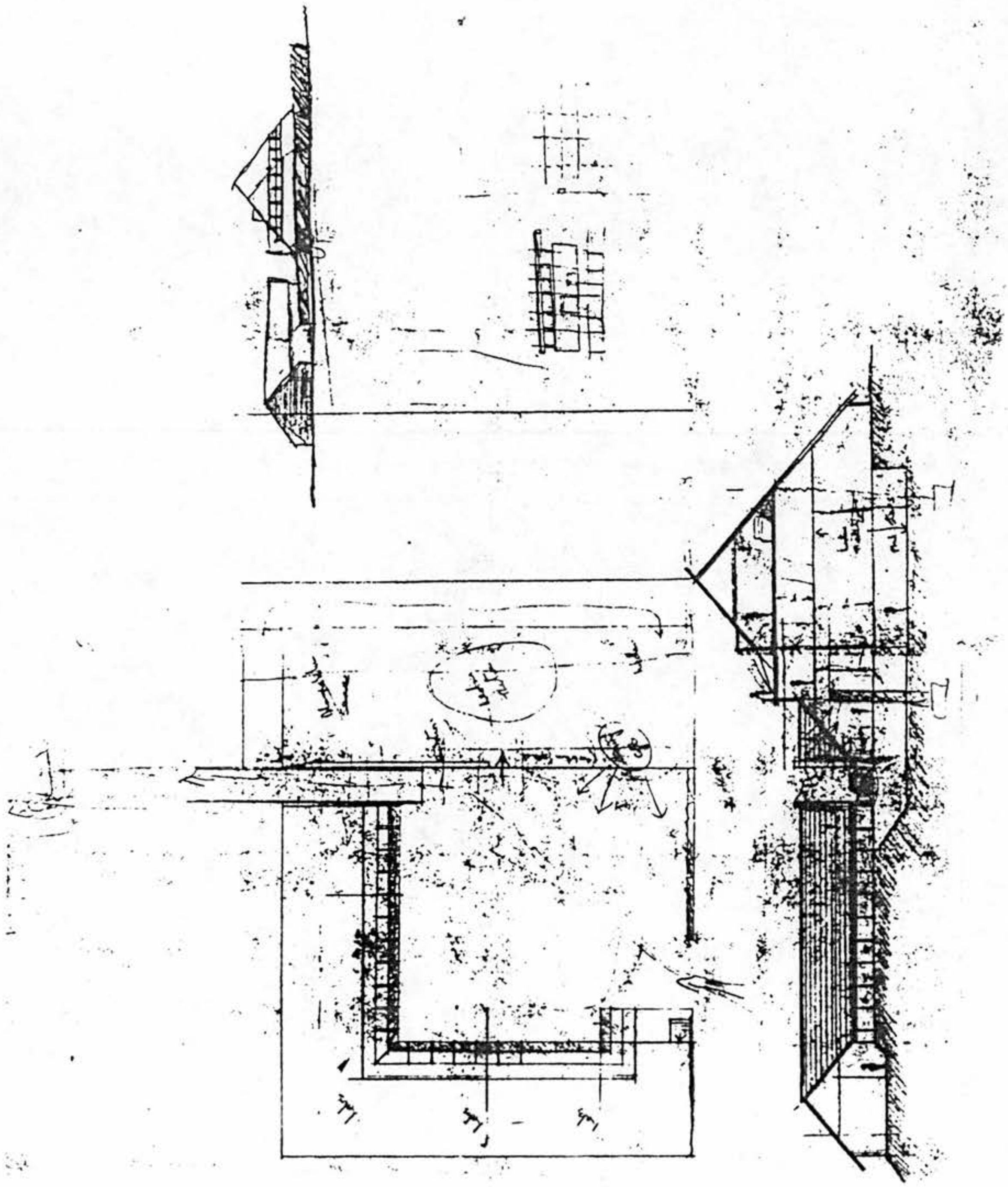


Student B; Instance 242

B.3. Student C



Student C; Instance 008



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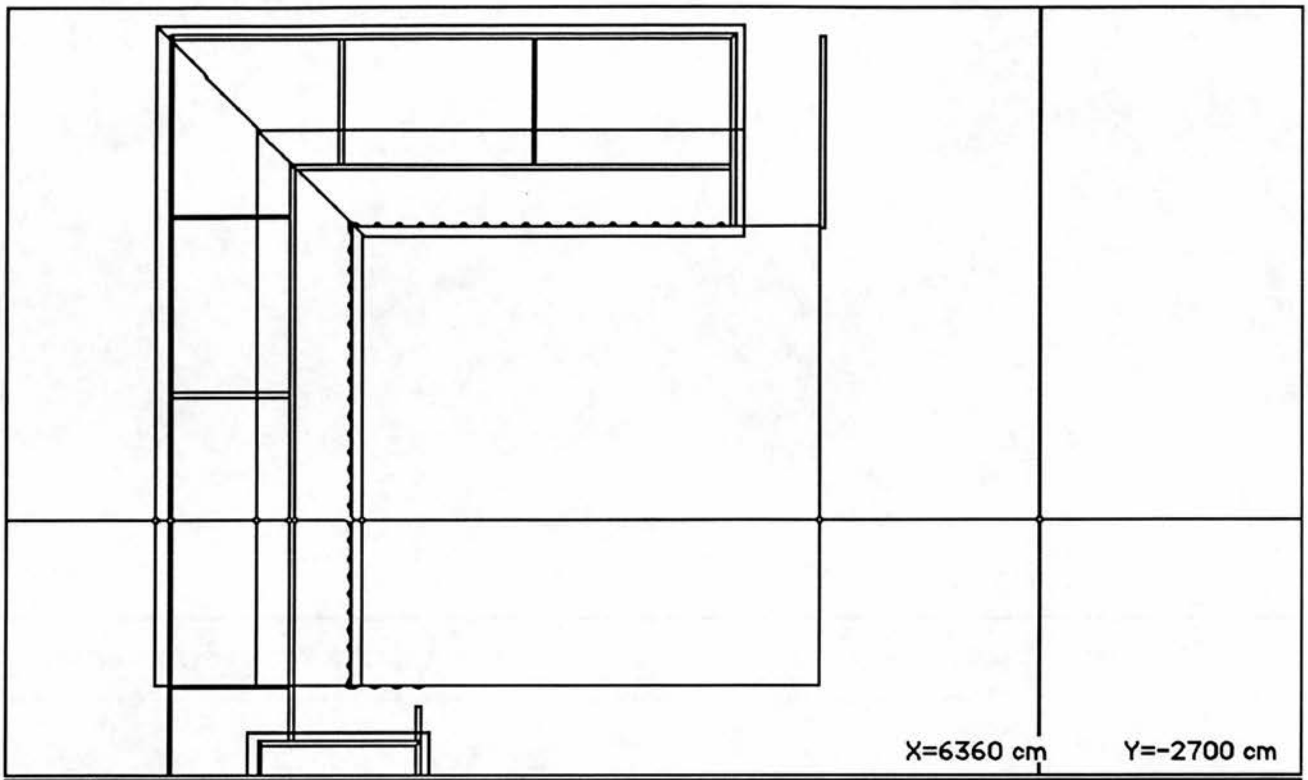

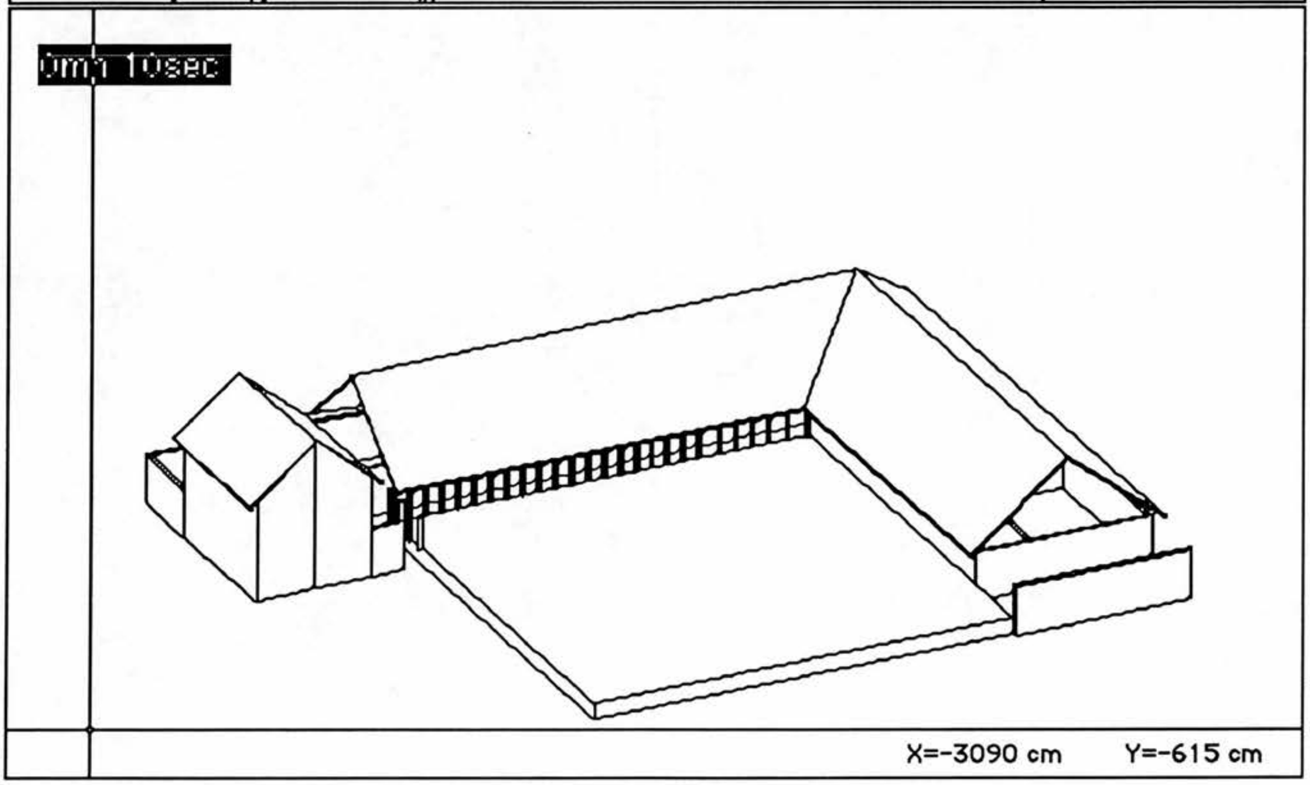

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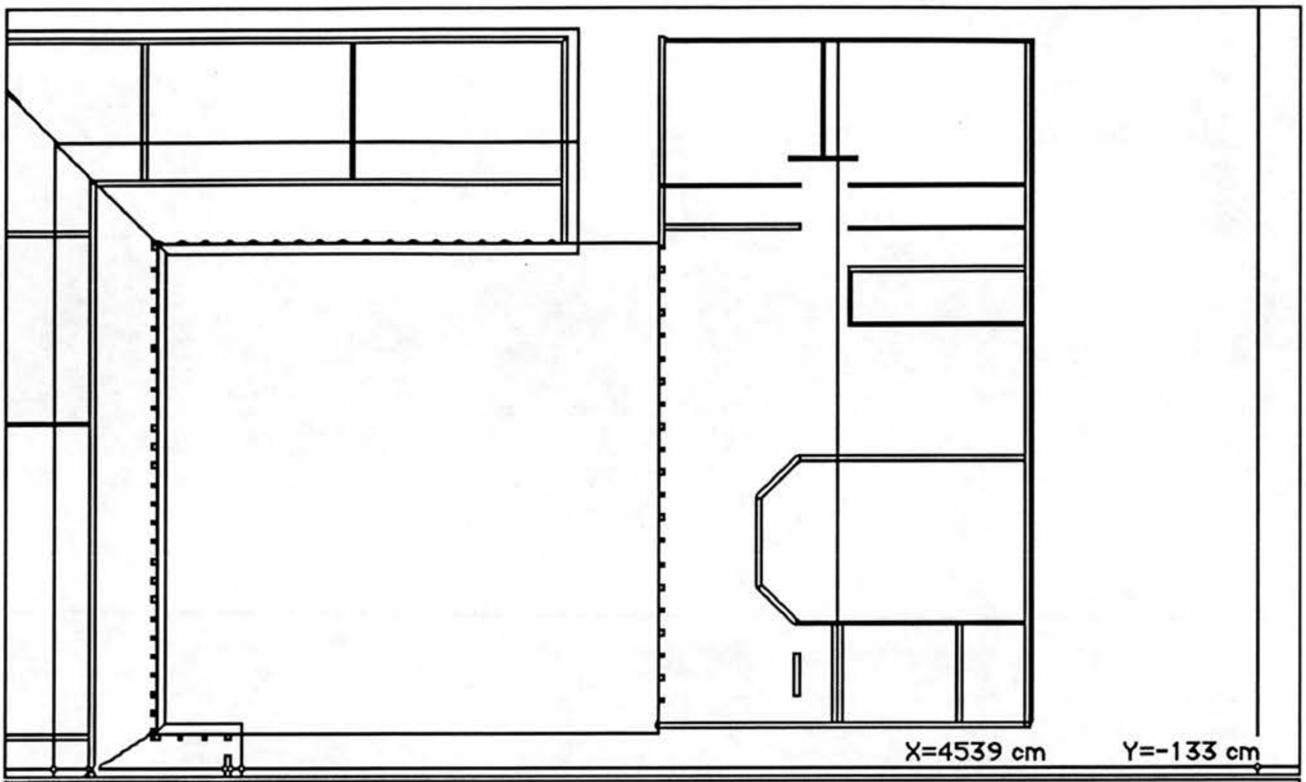

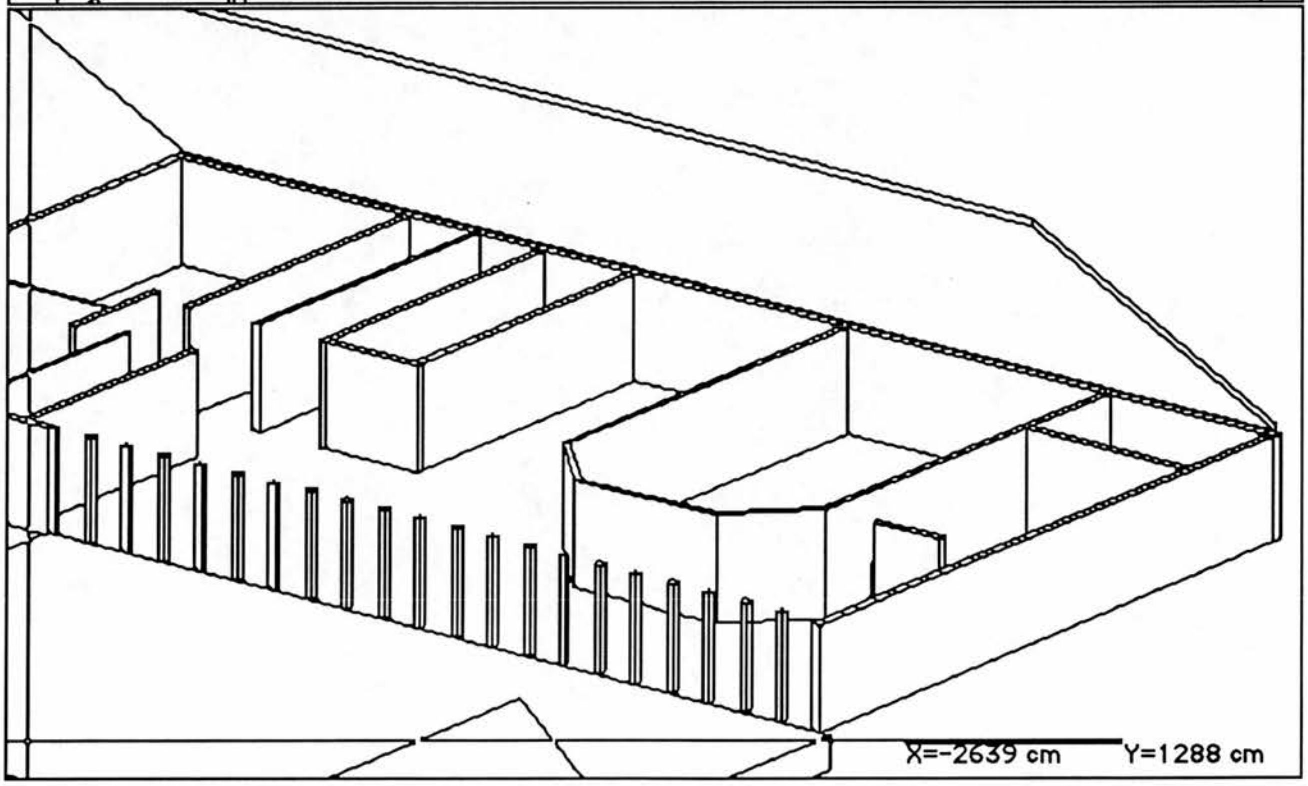

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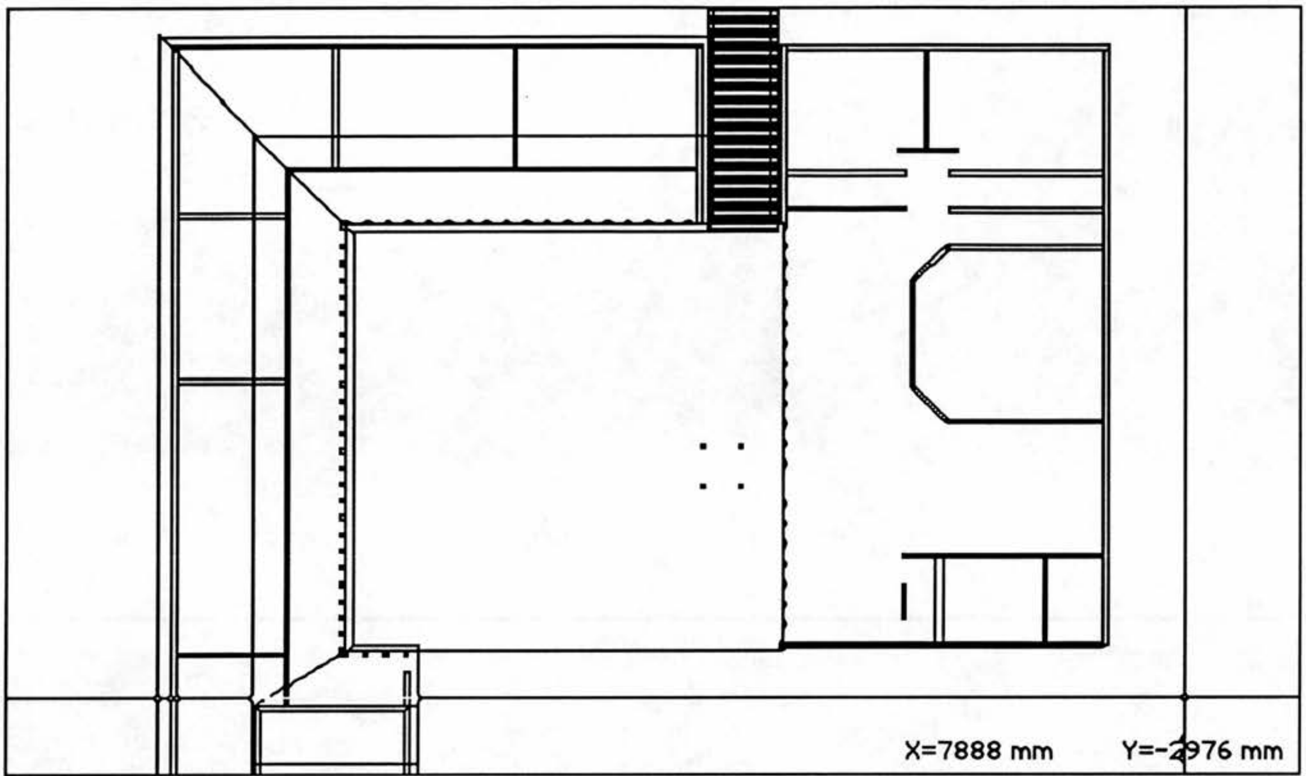

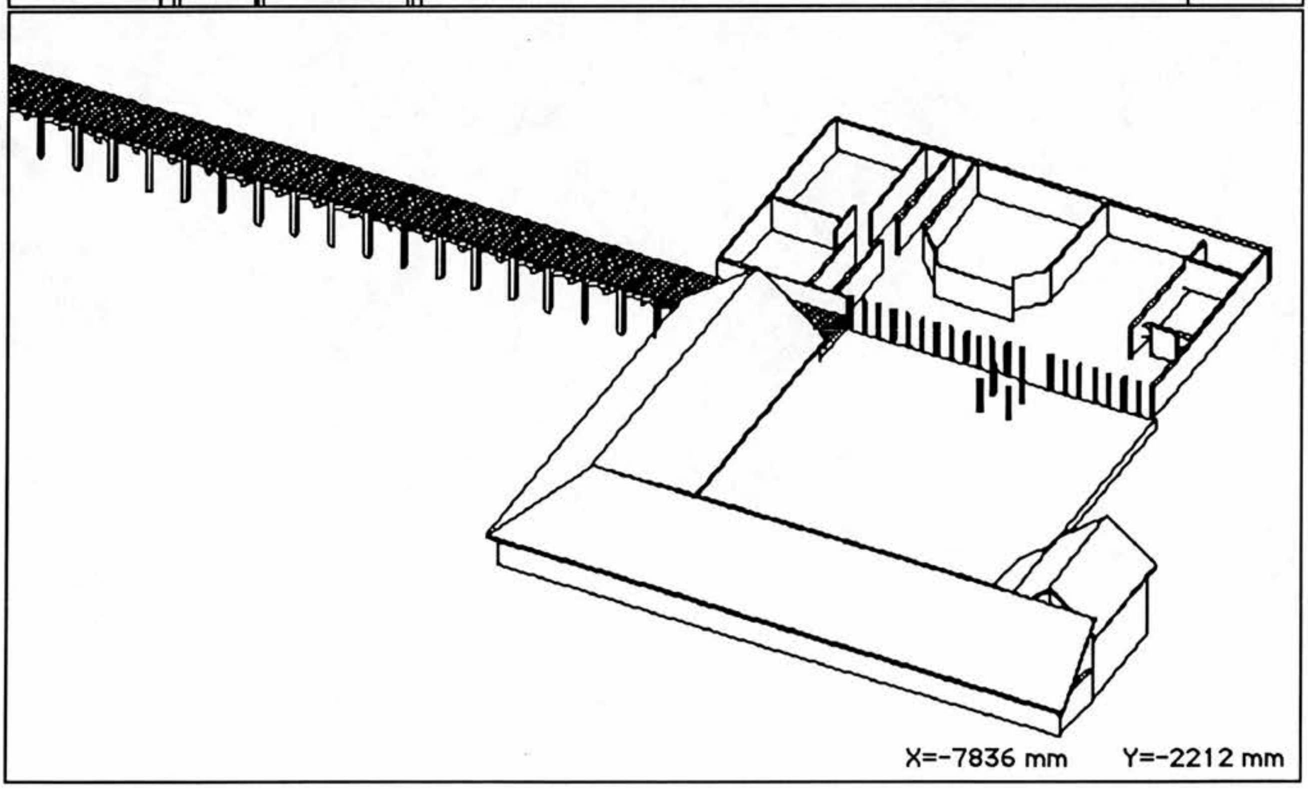

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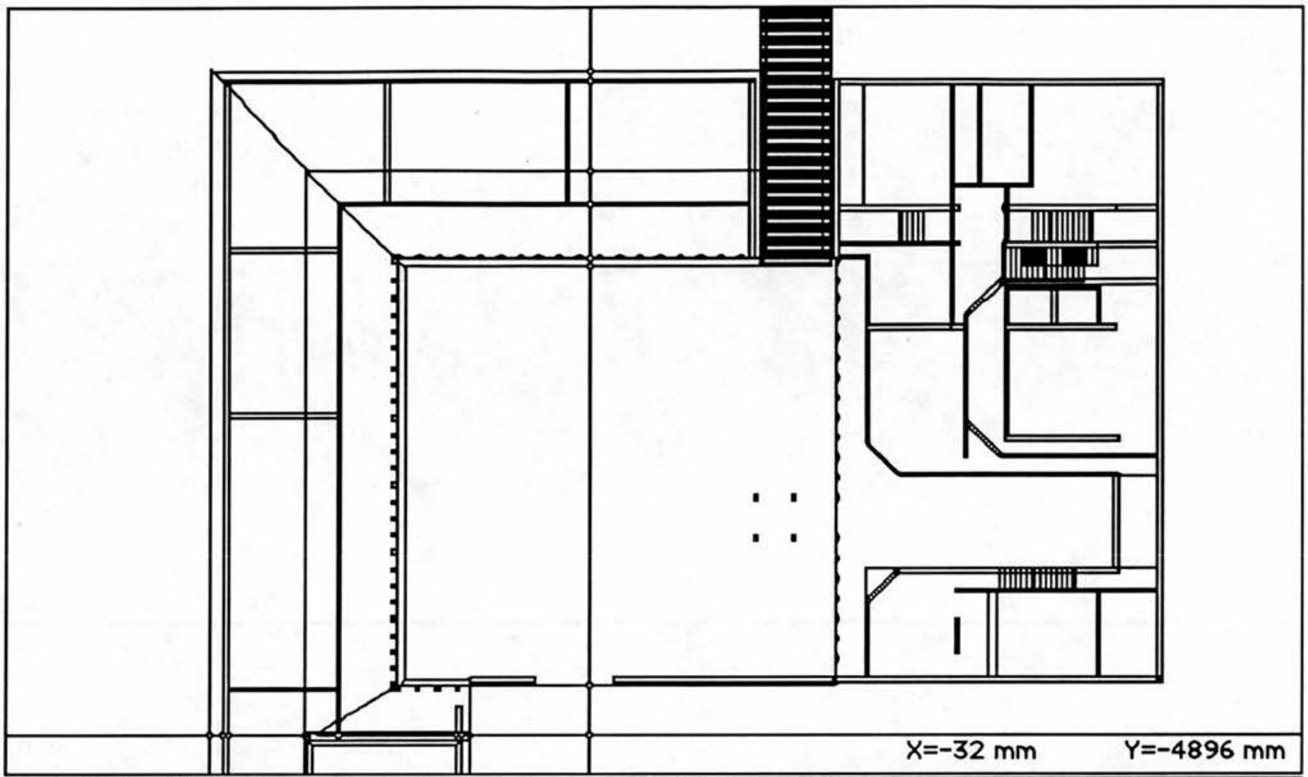

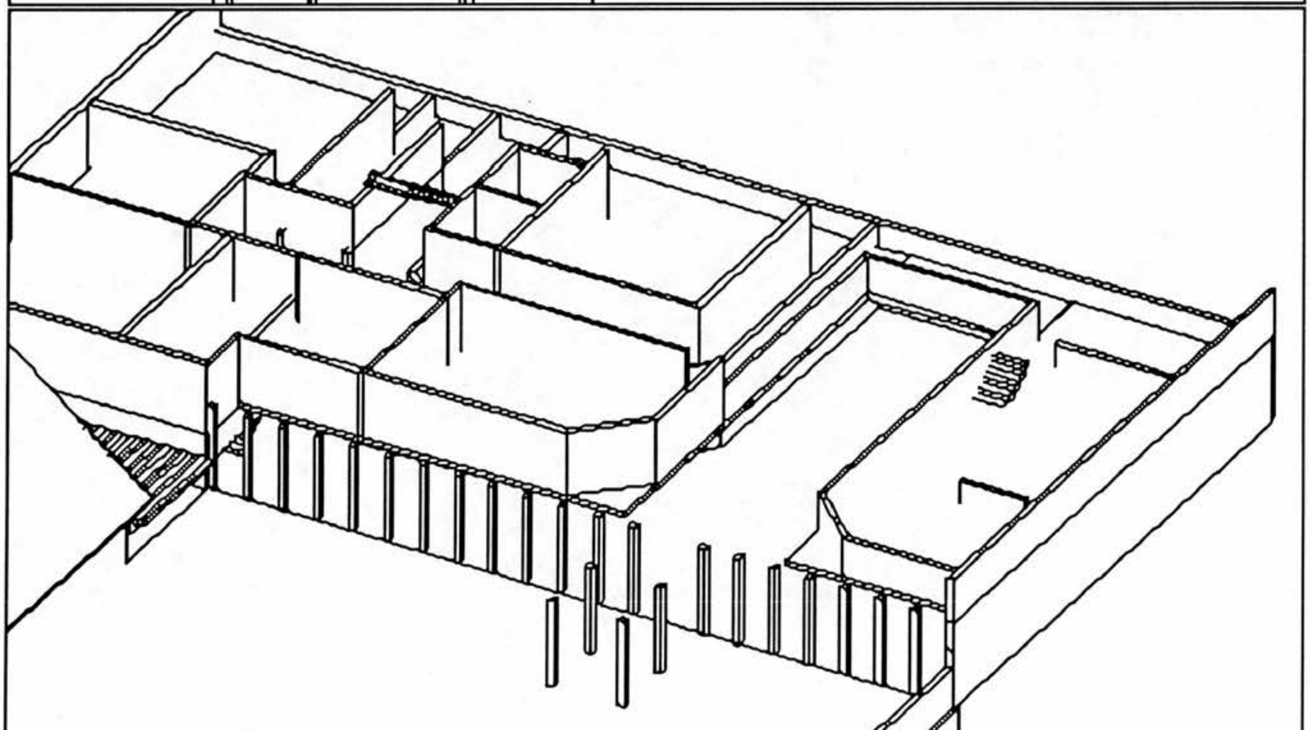

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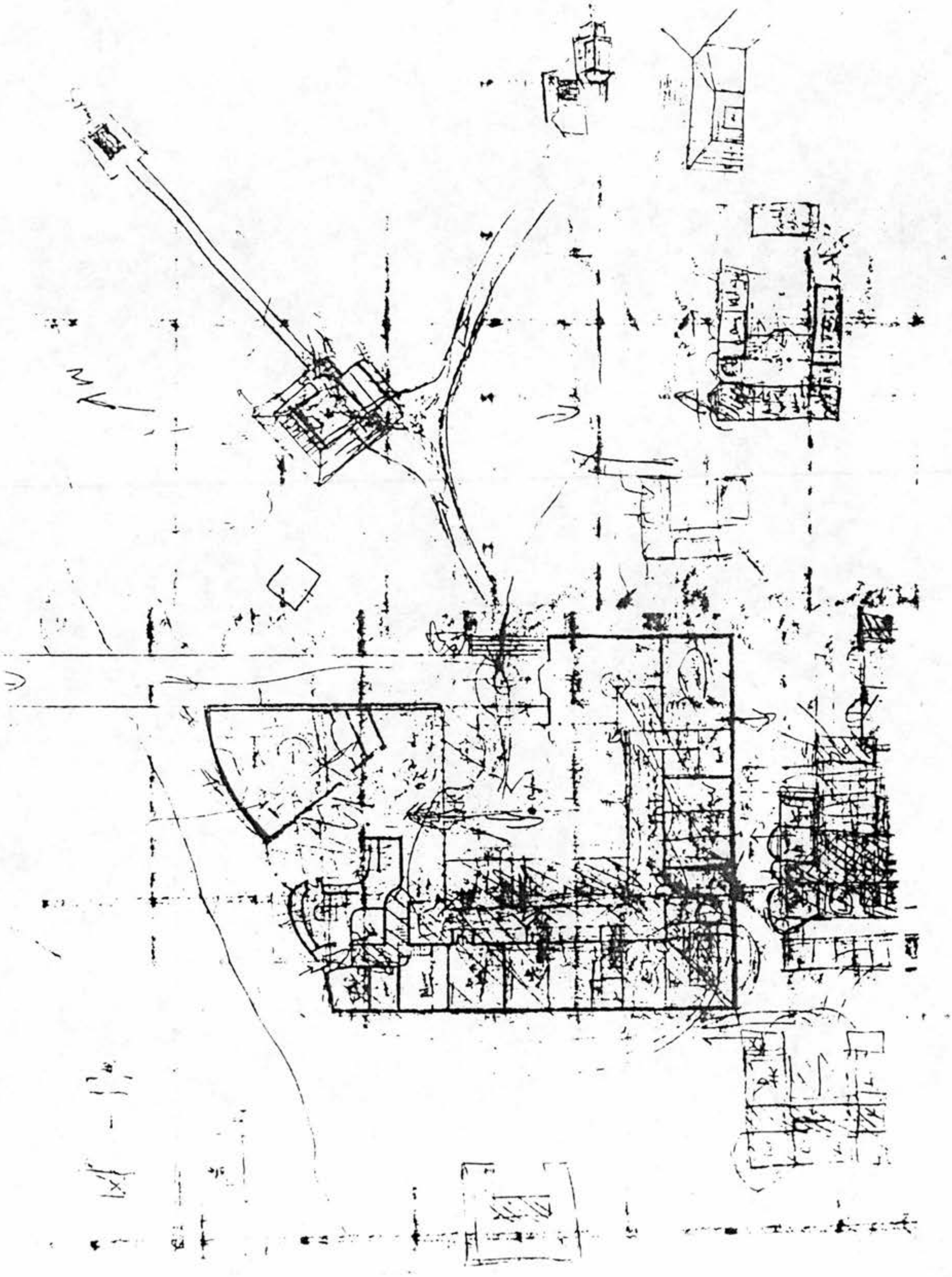
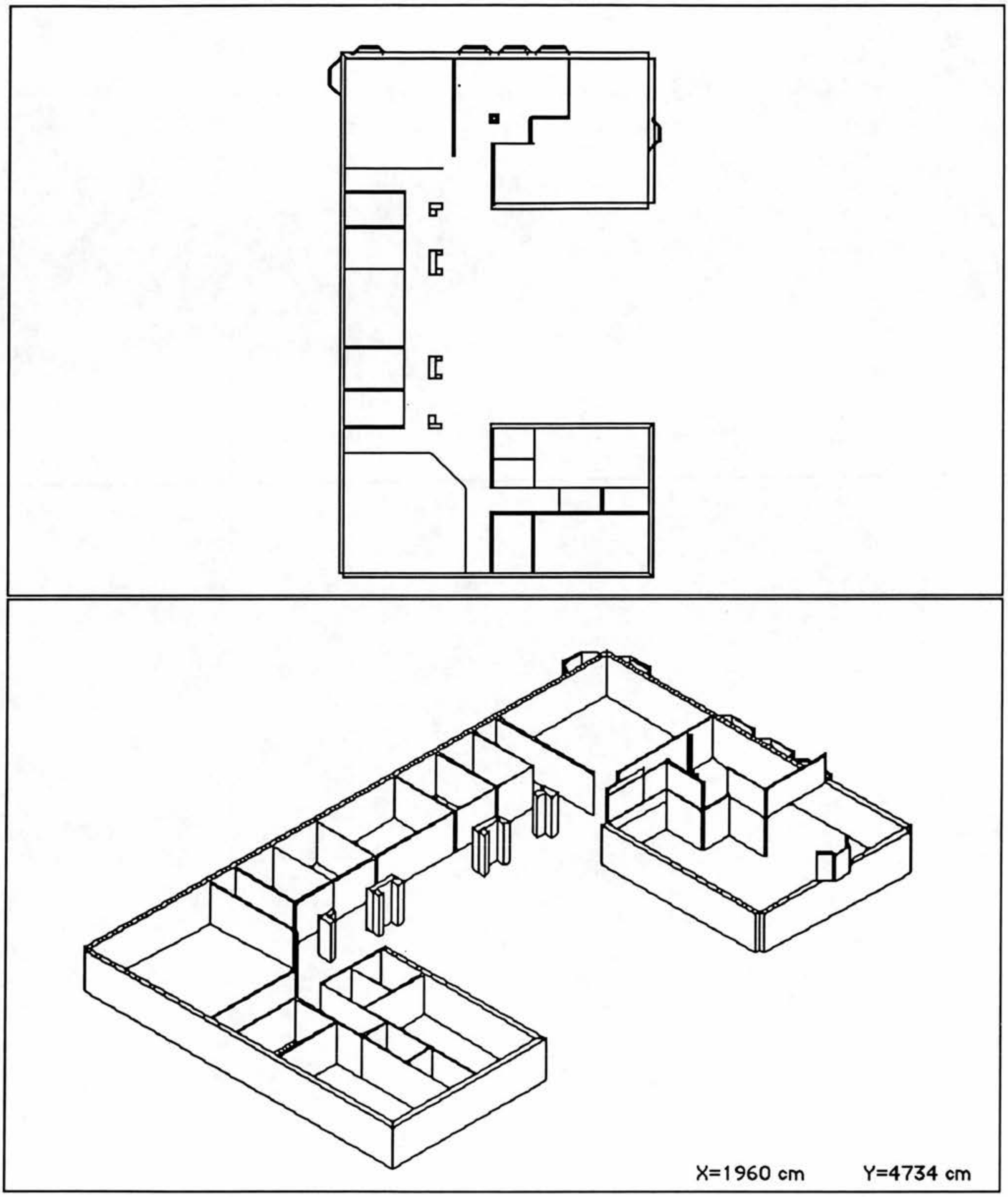
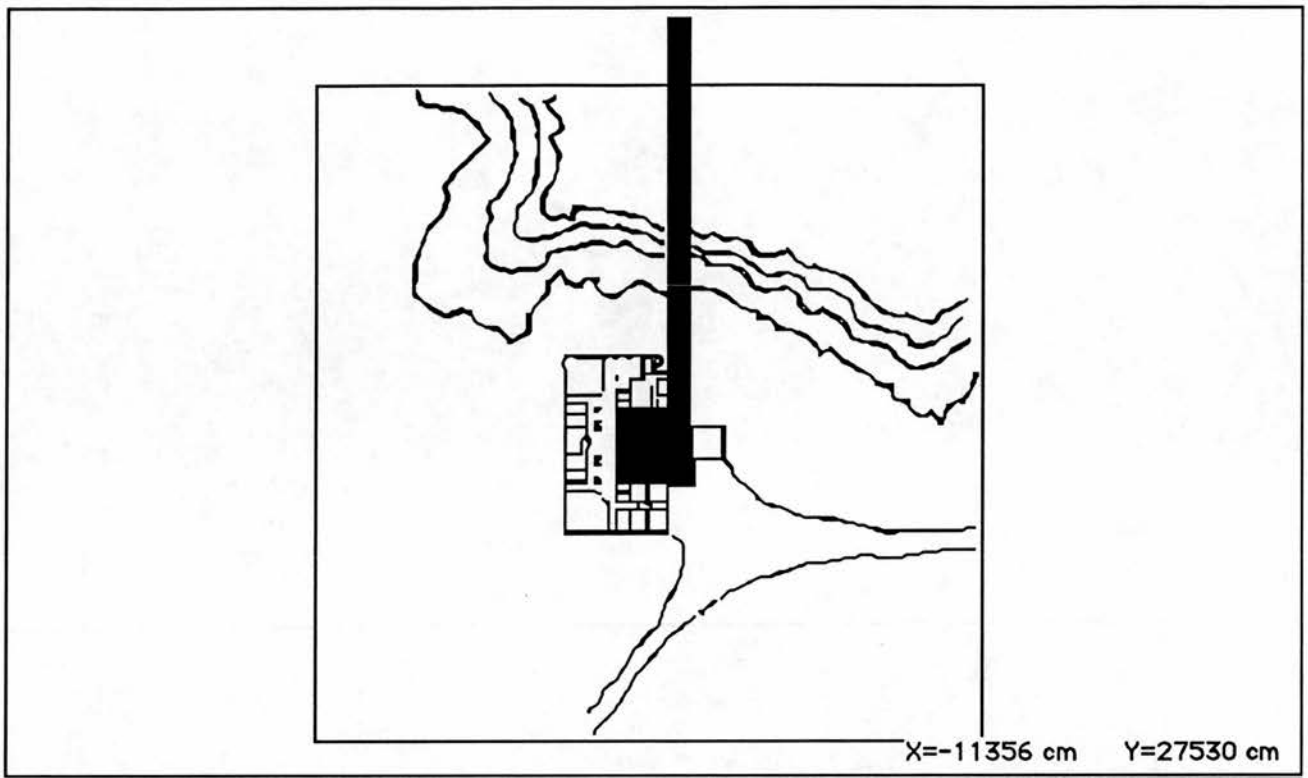
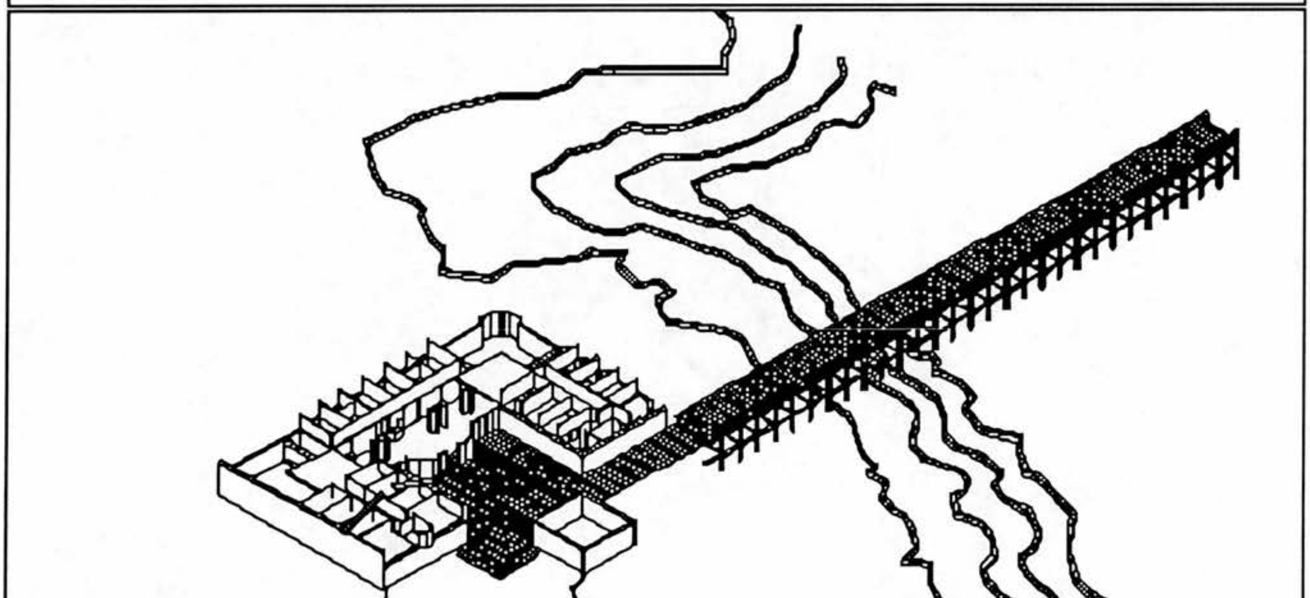


Student C; Instance 069

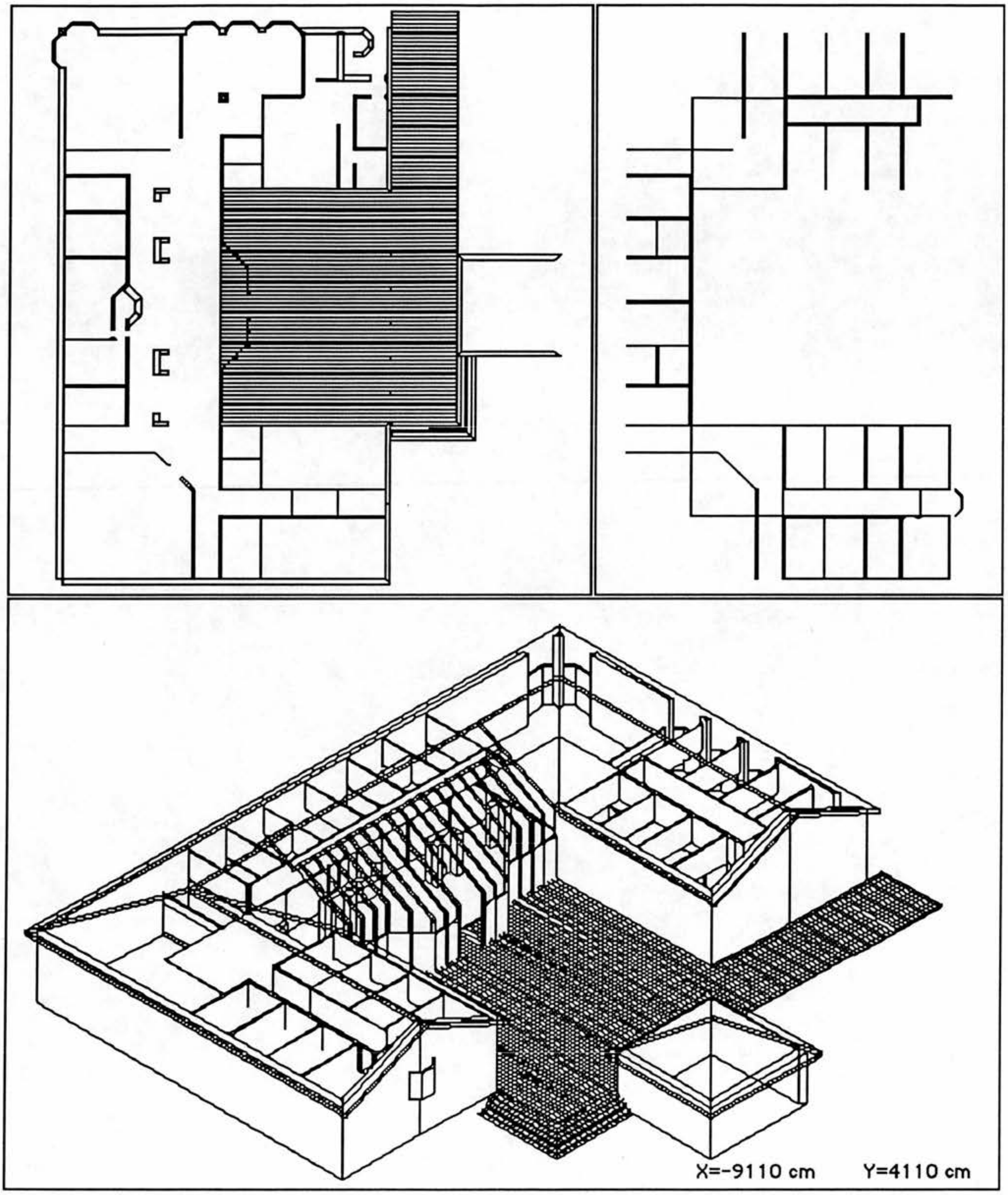


Student C; Instance 076

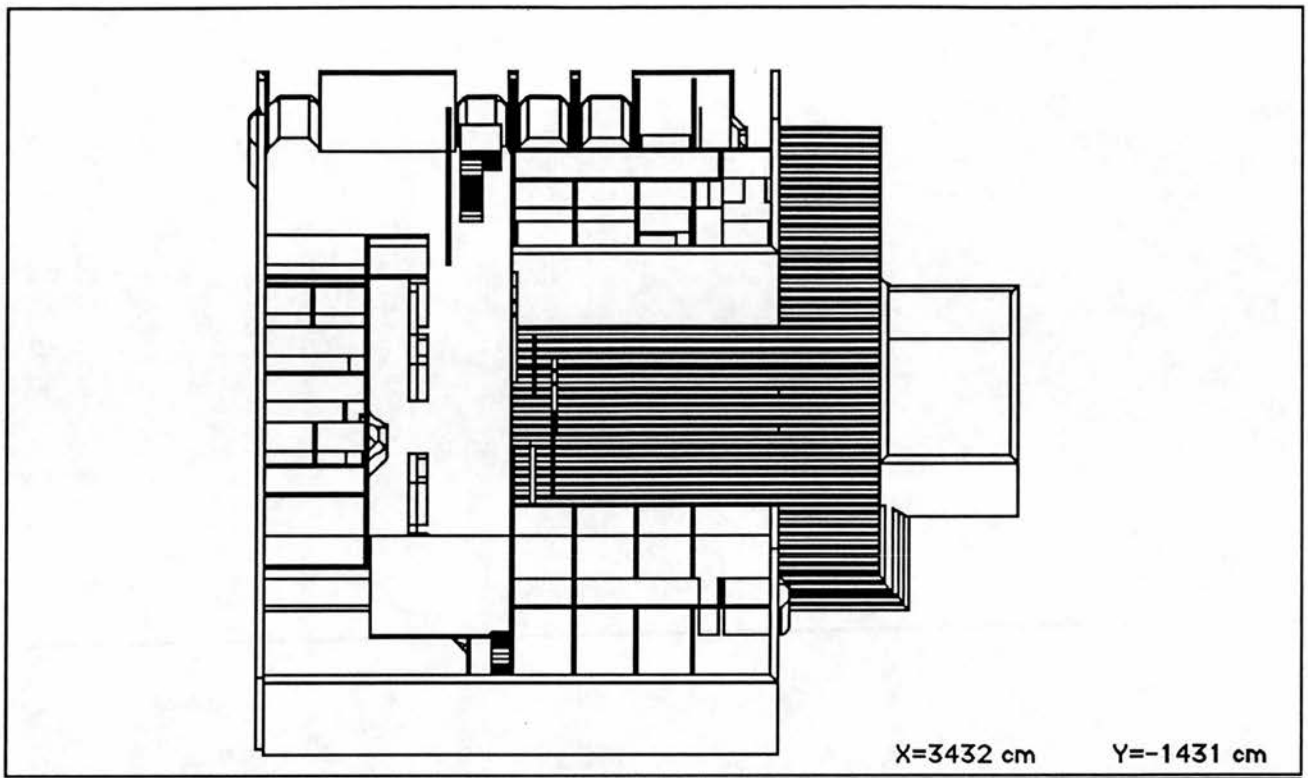


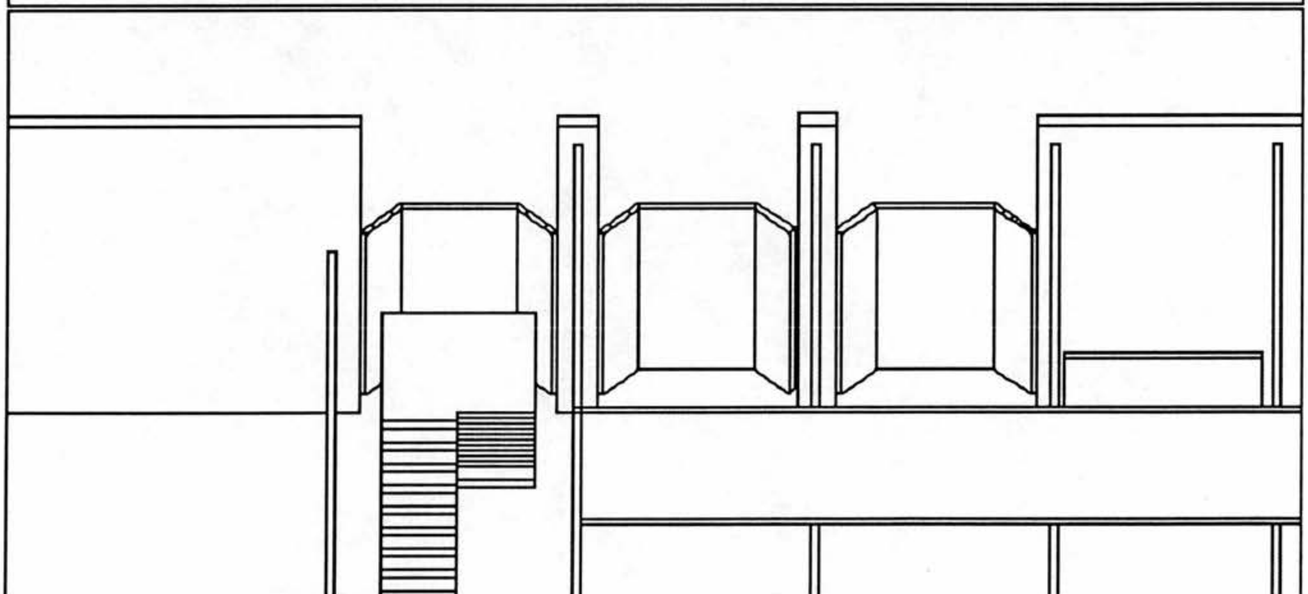


Student C; Instance 080

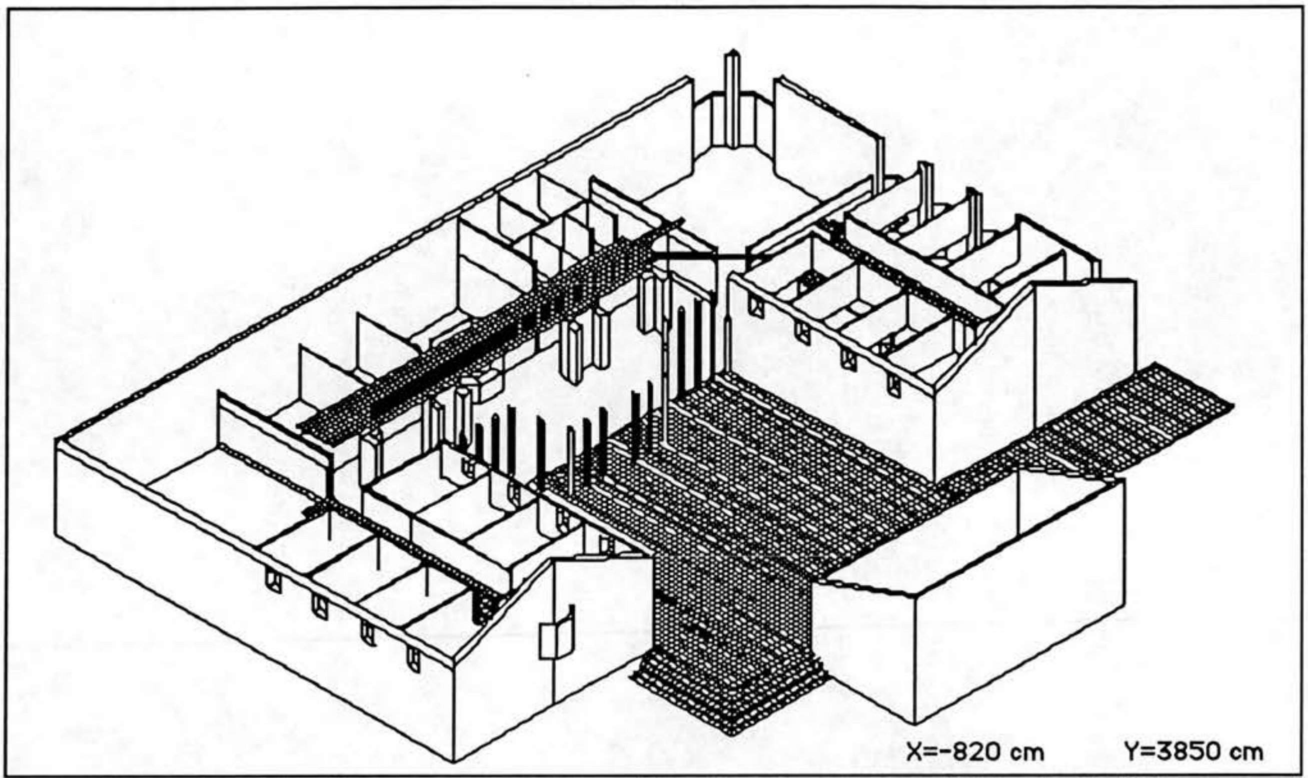


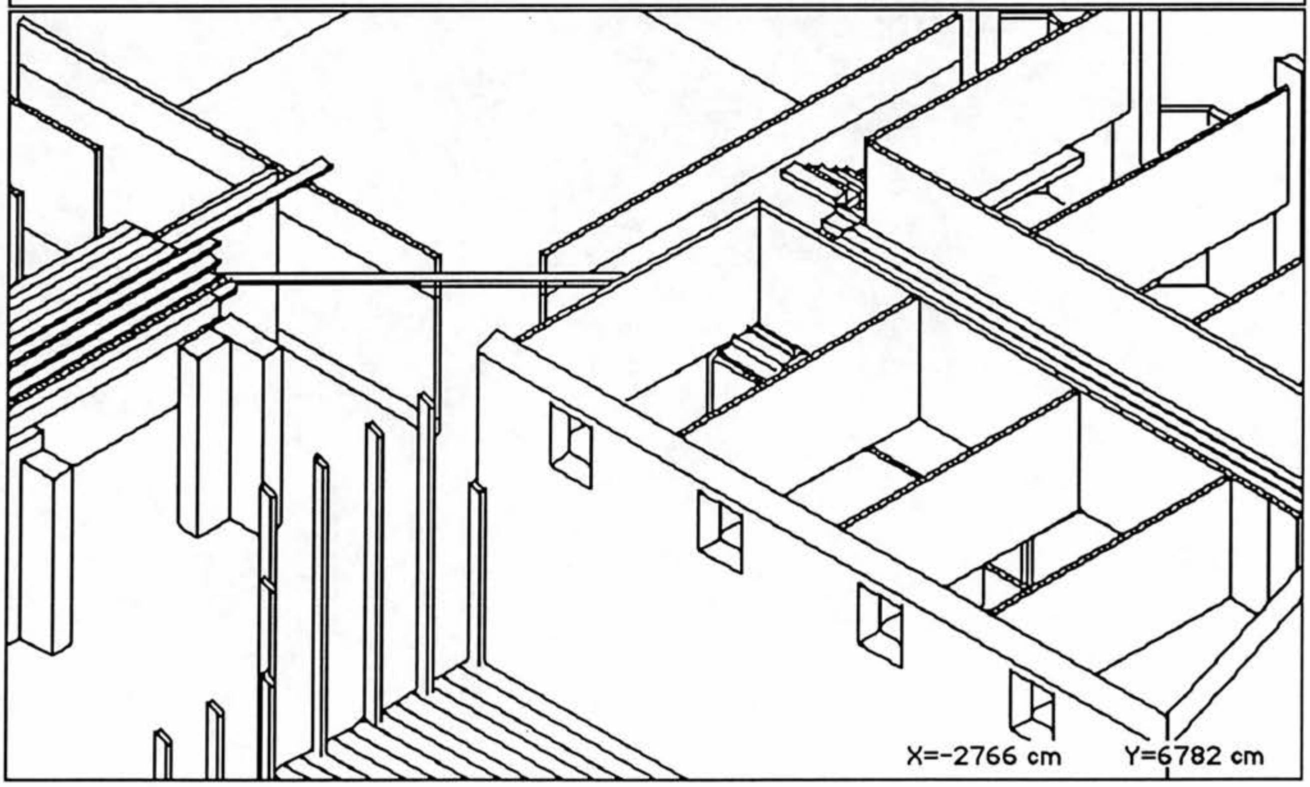
Student C; Instance 091





Student C; Instance 094





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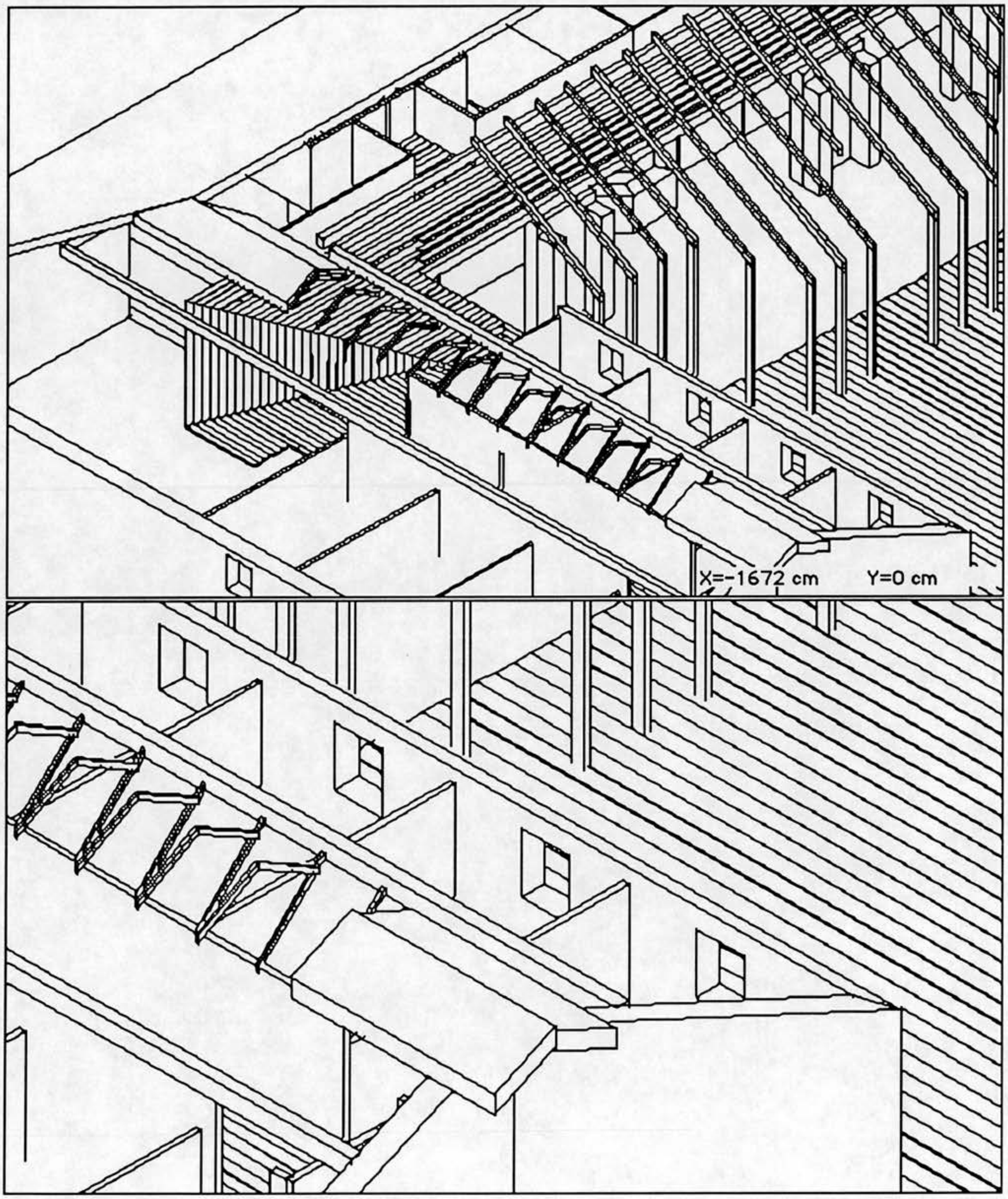
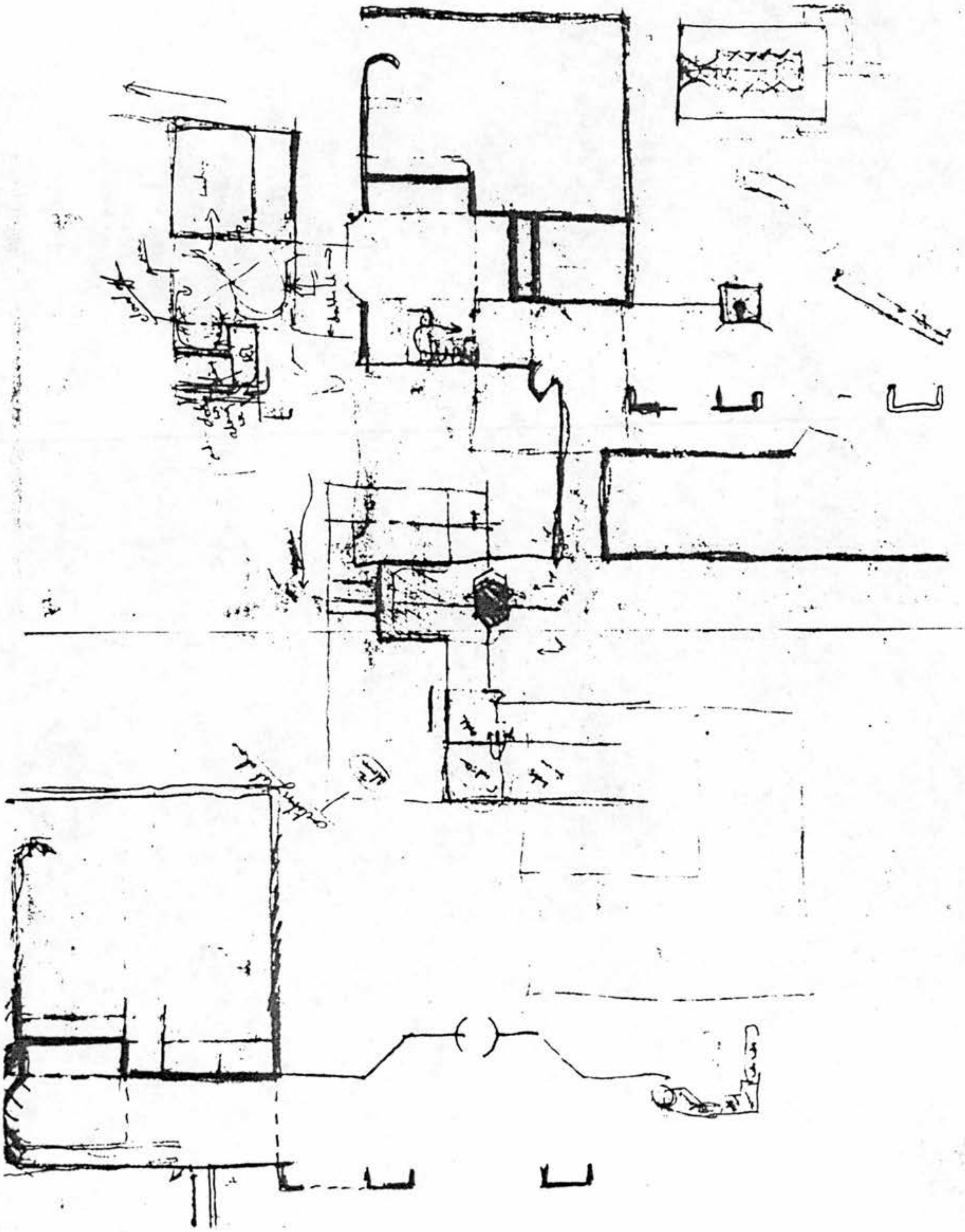
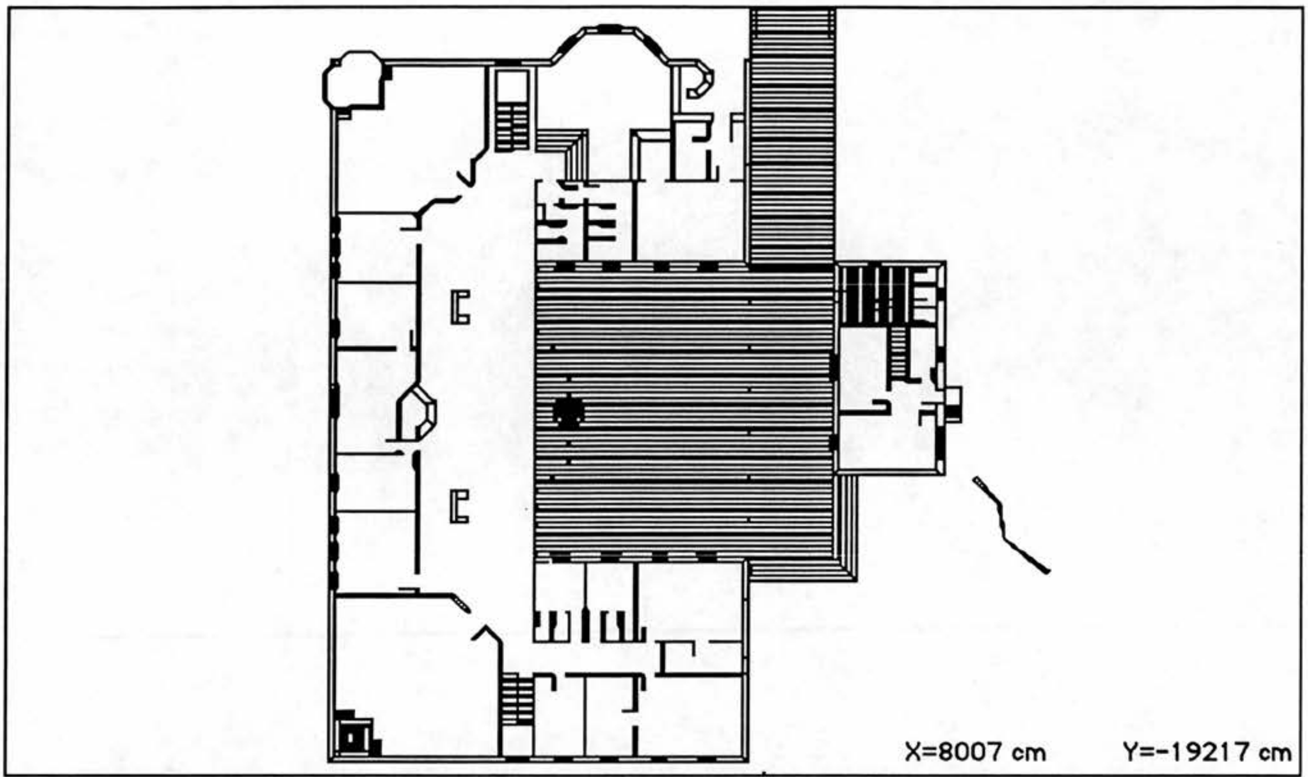
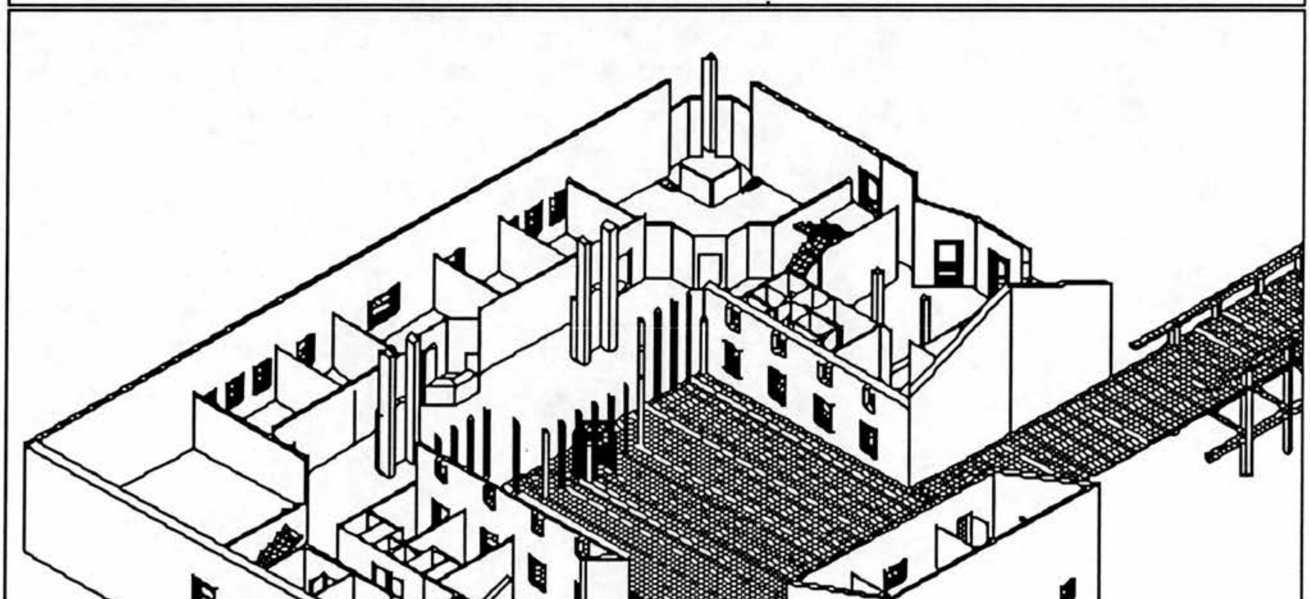


Student C; Instance 104

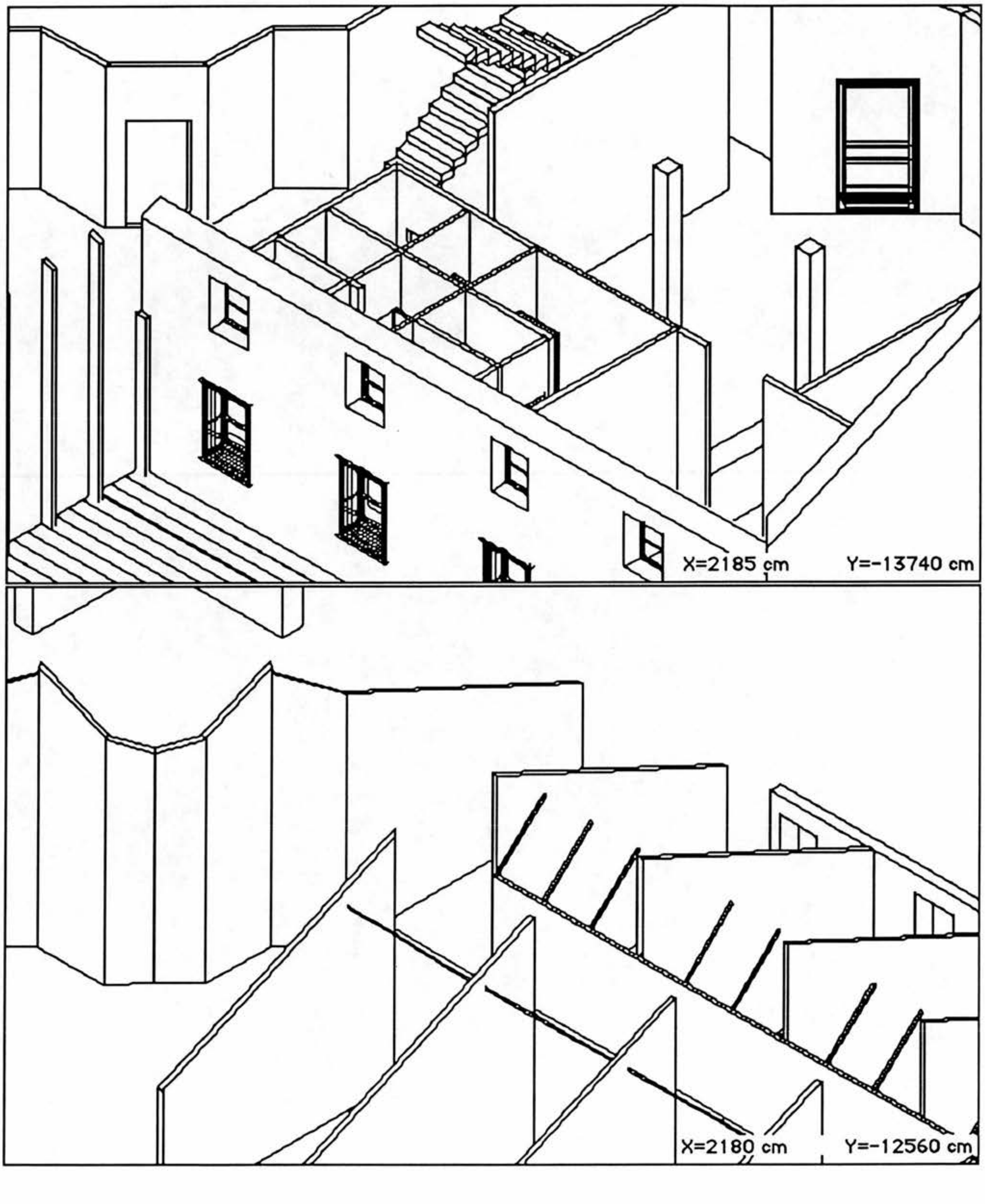


Student C; Instance 111

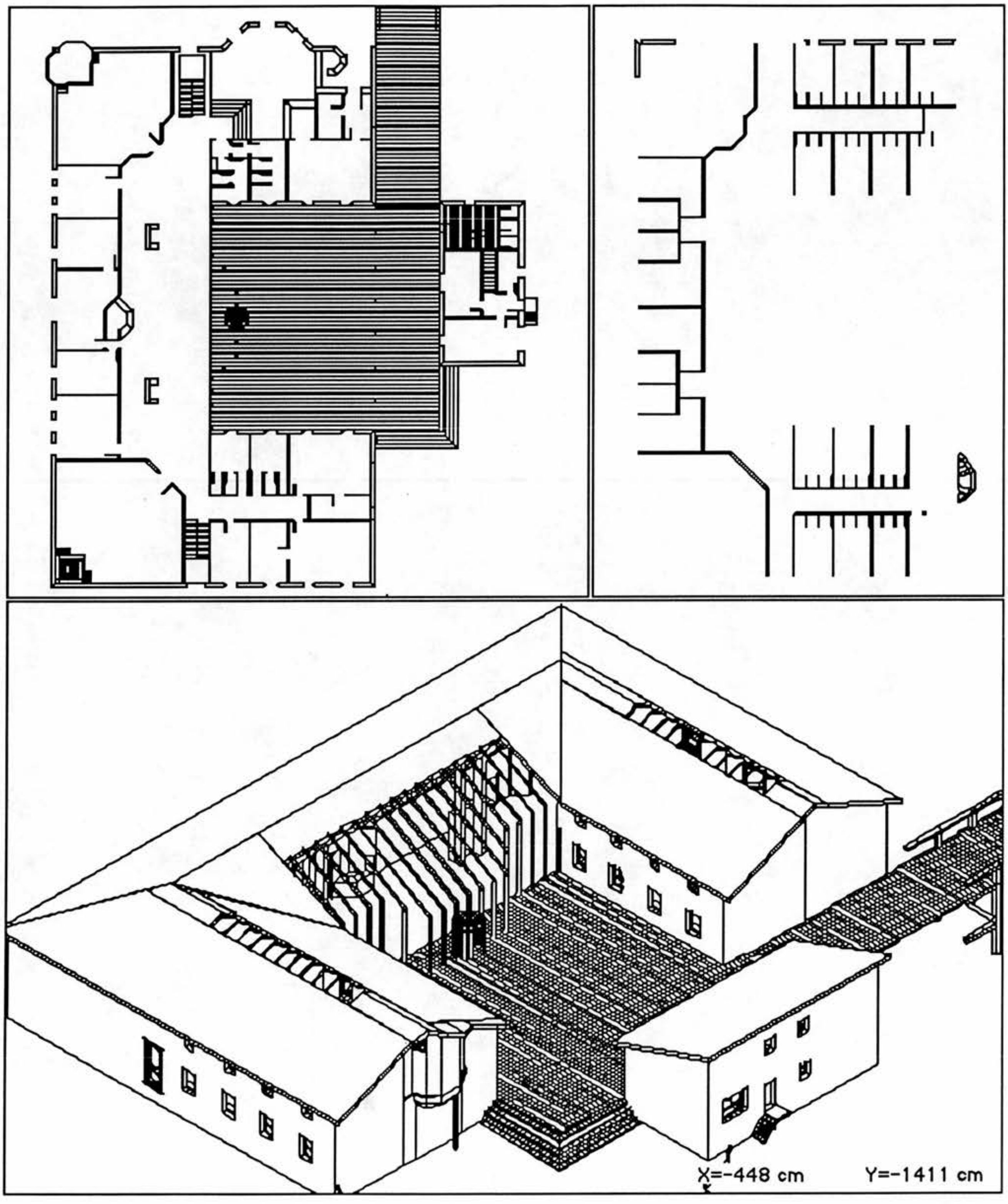




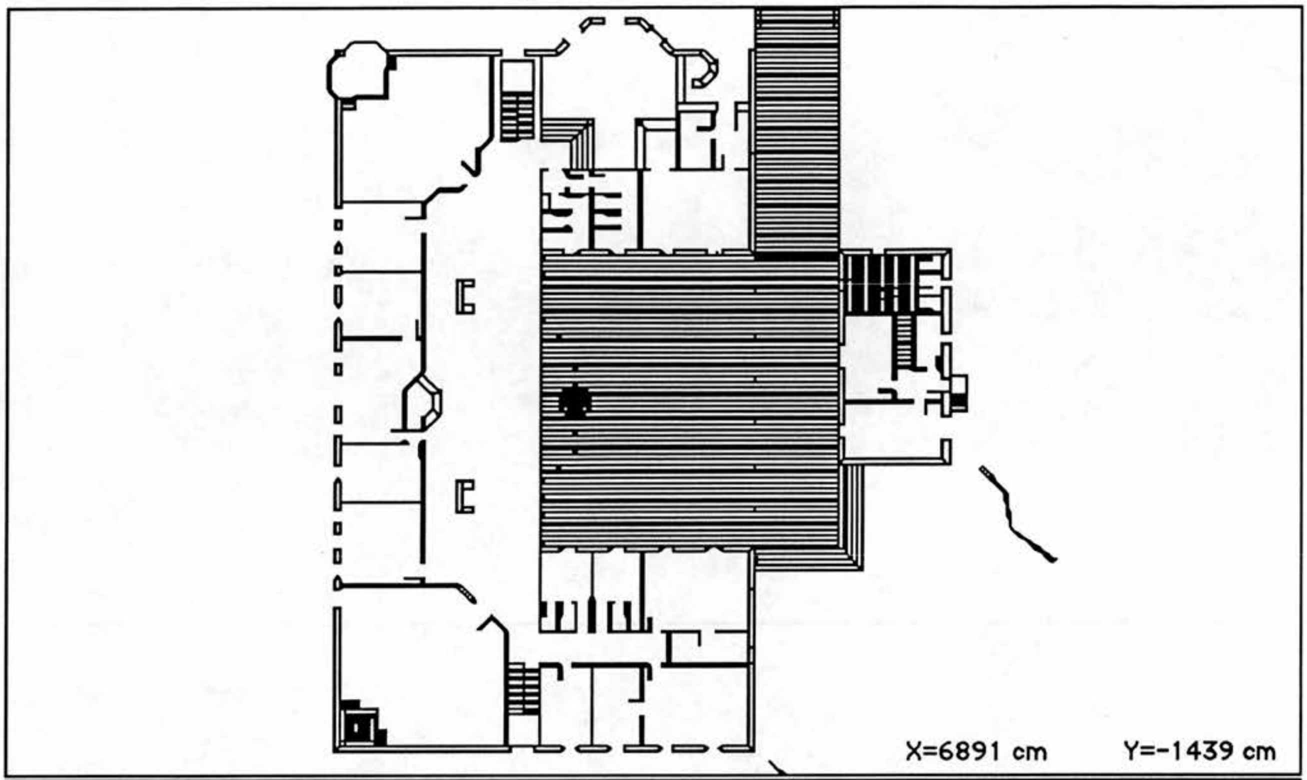
Student C; Instance 117.a

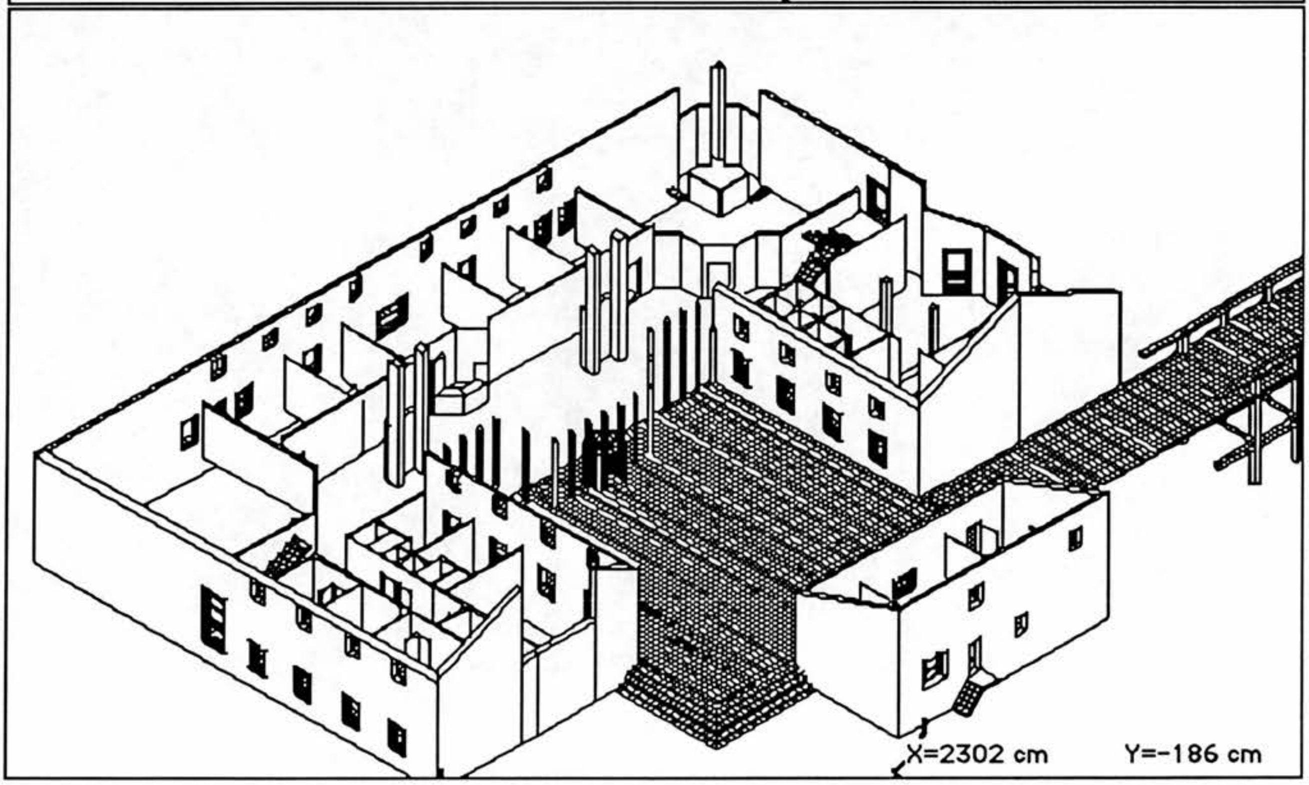


Student C; Instance 117.b

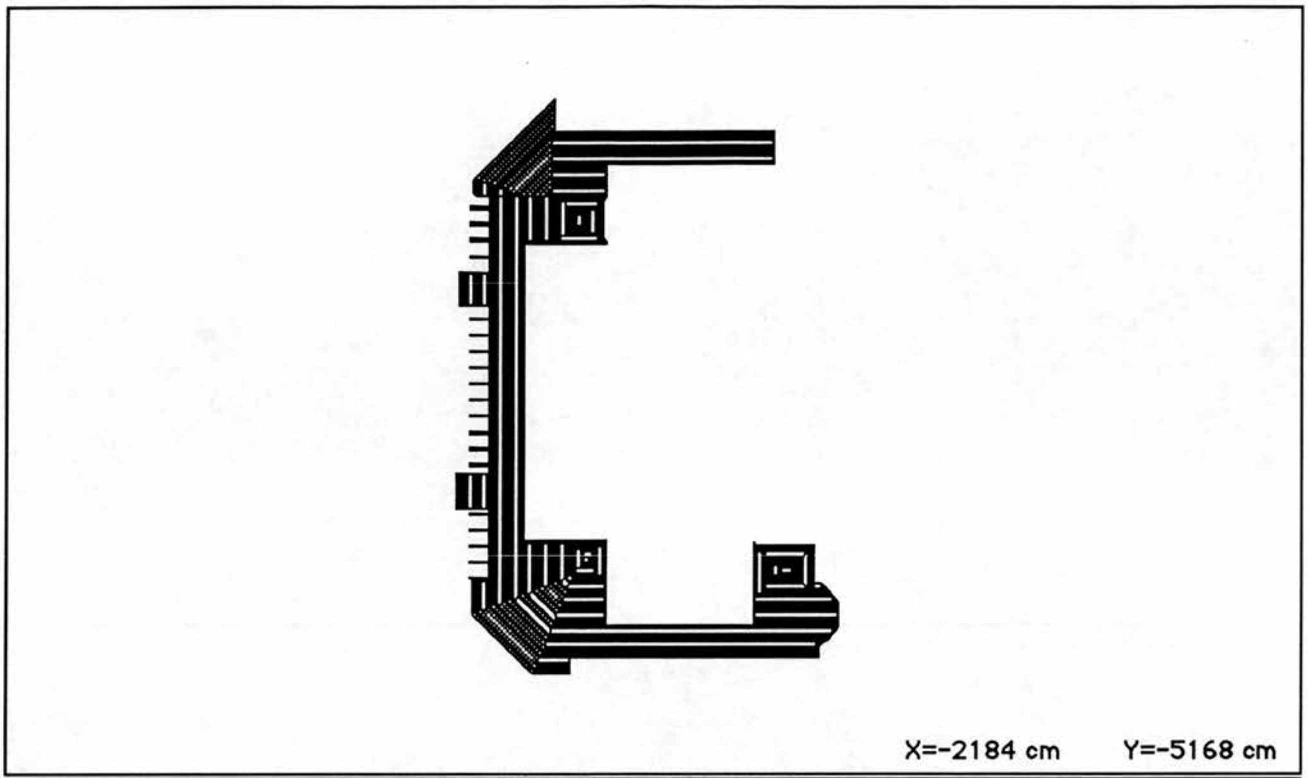


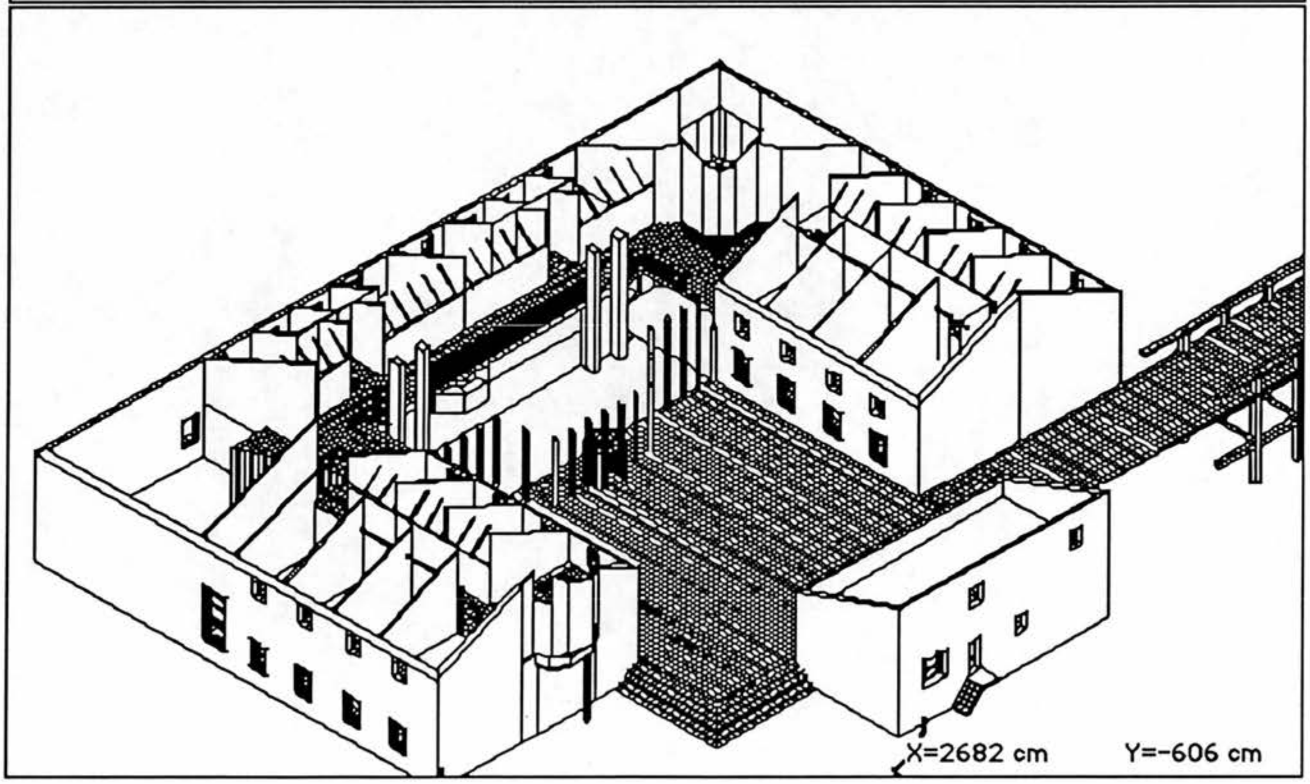
Student C; Instance 119



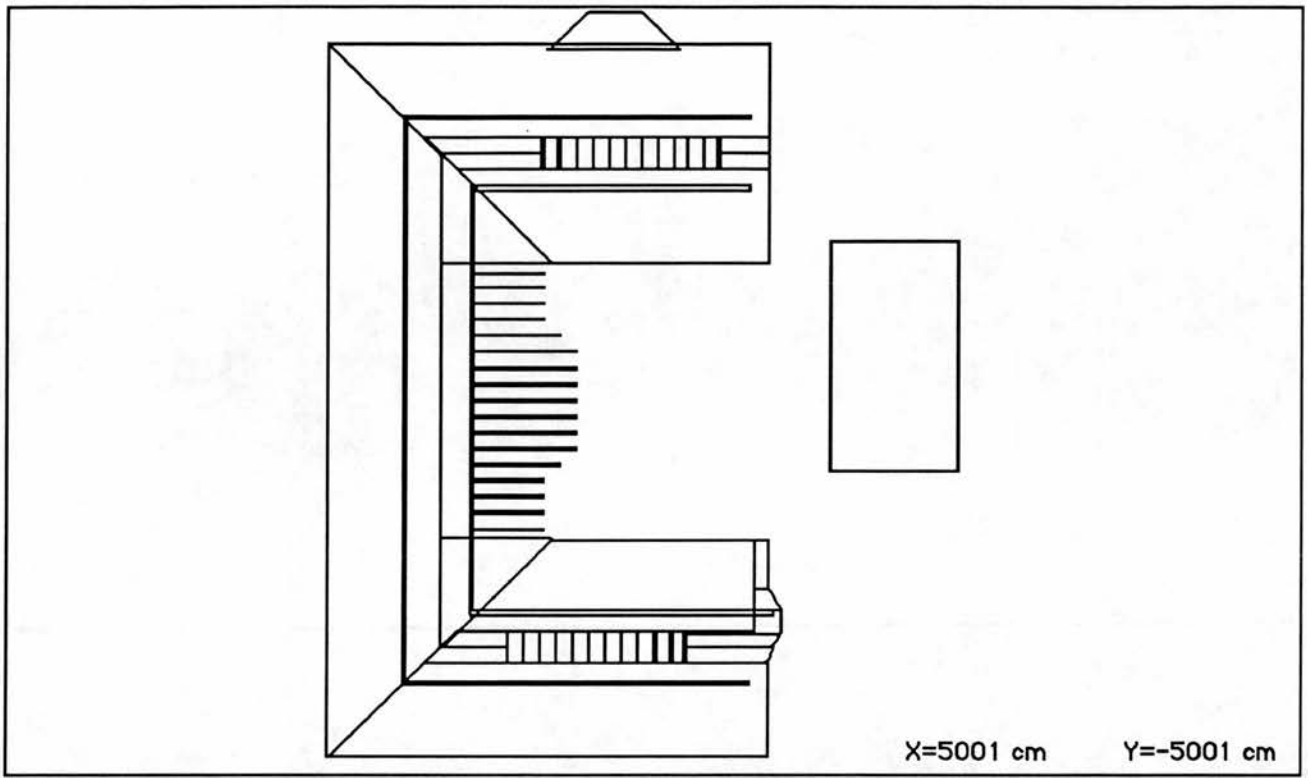


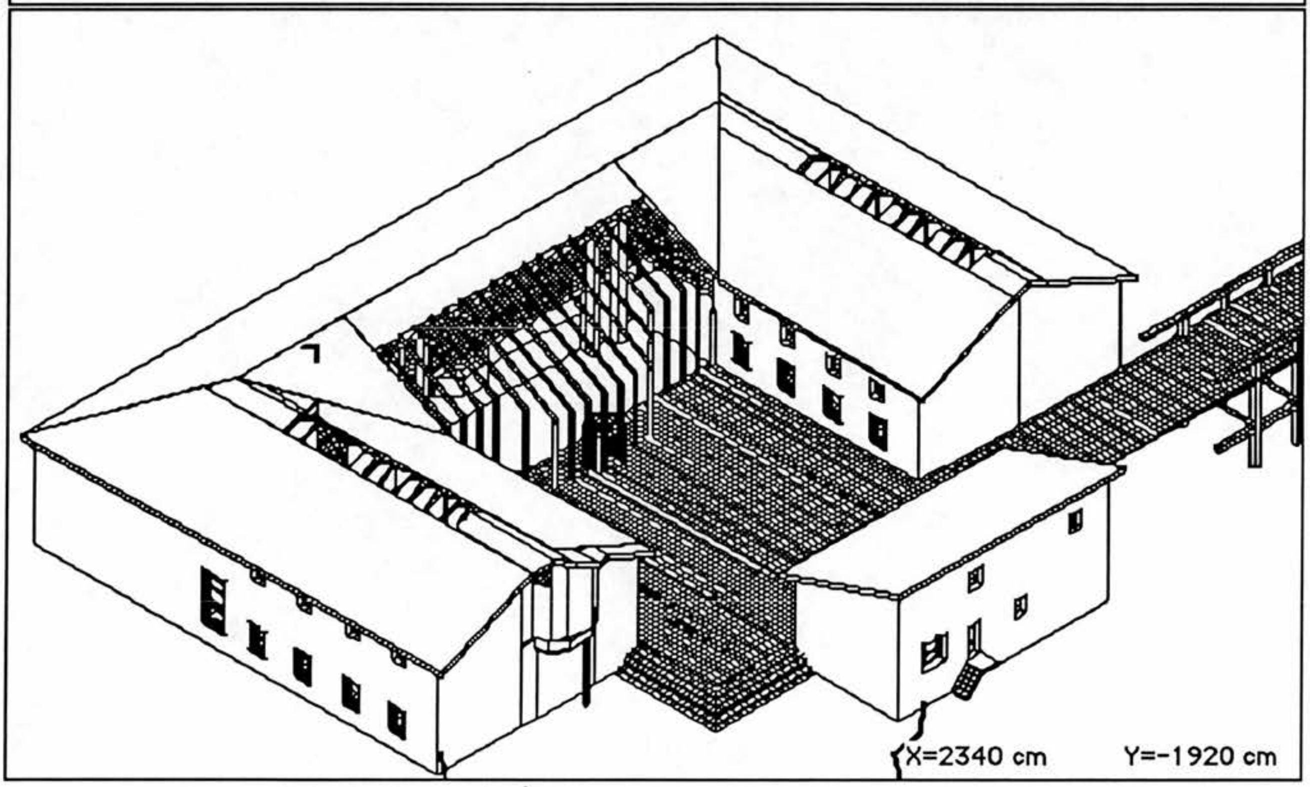
Student C; Instance 125.a



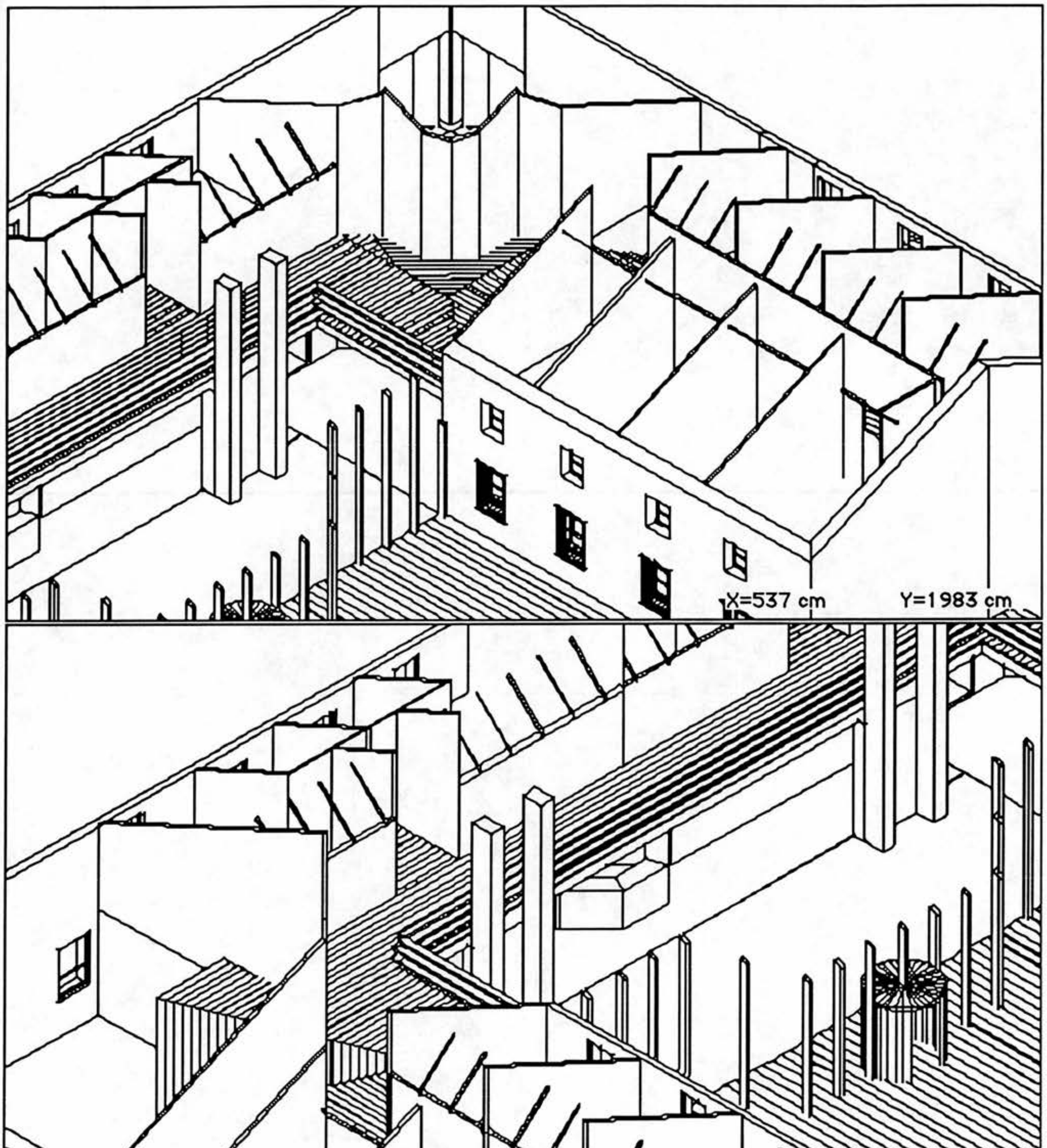


Student C; Instance 125.b

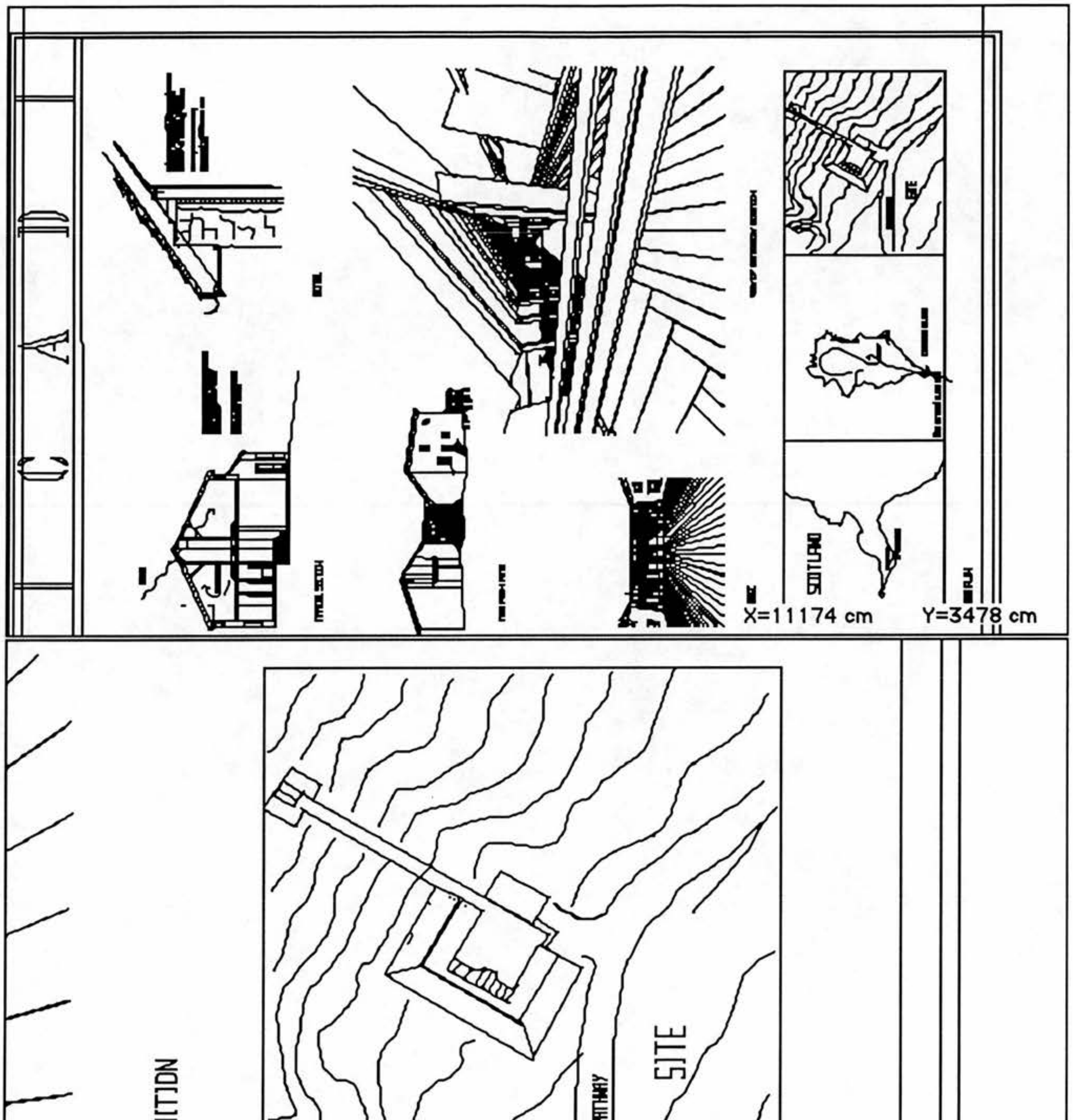




Student C; Instance 125.c

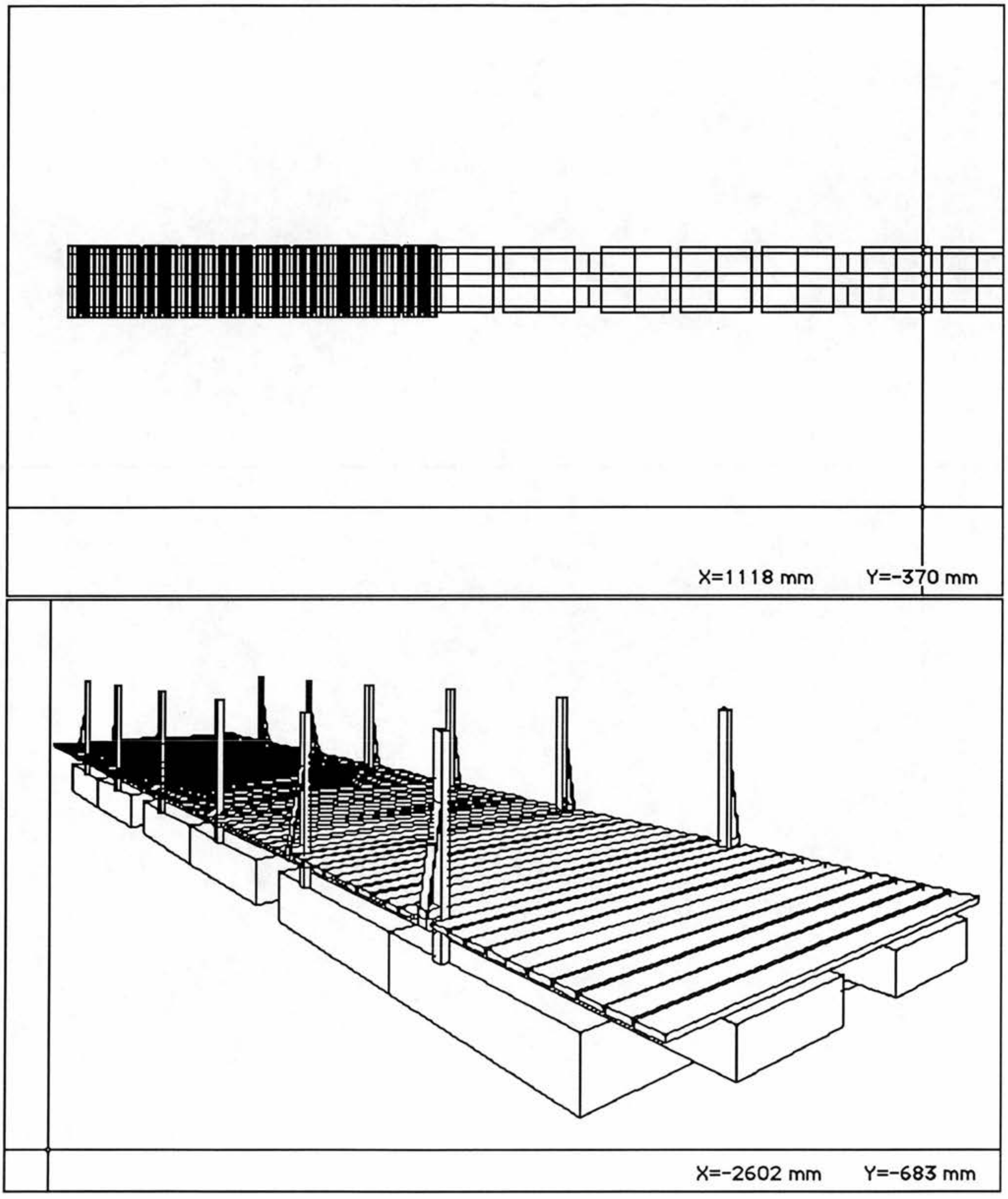


Student C; Instance 125.d

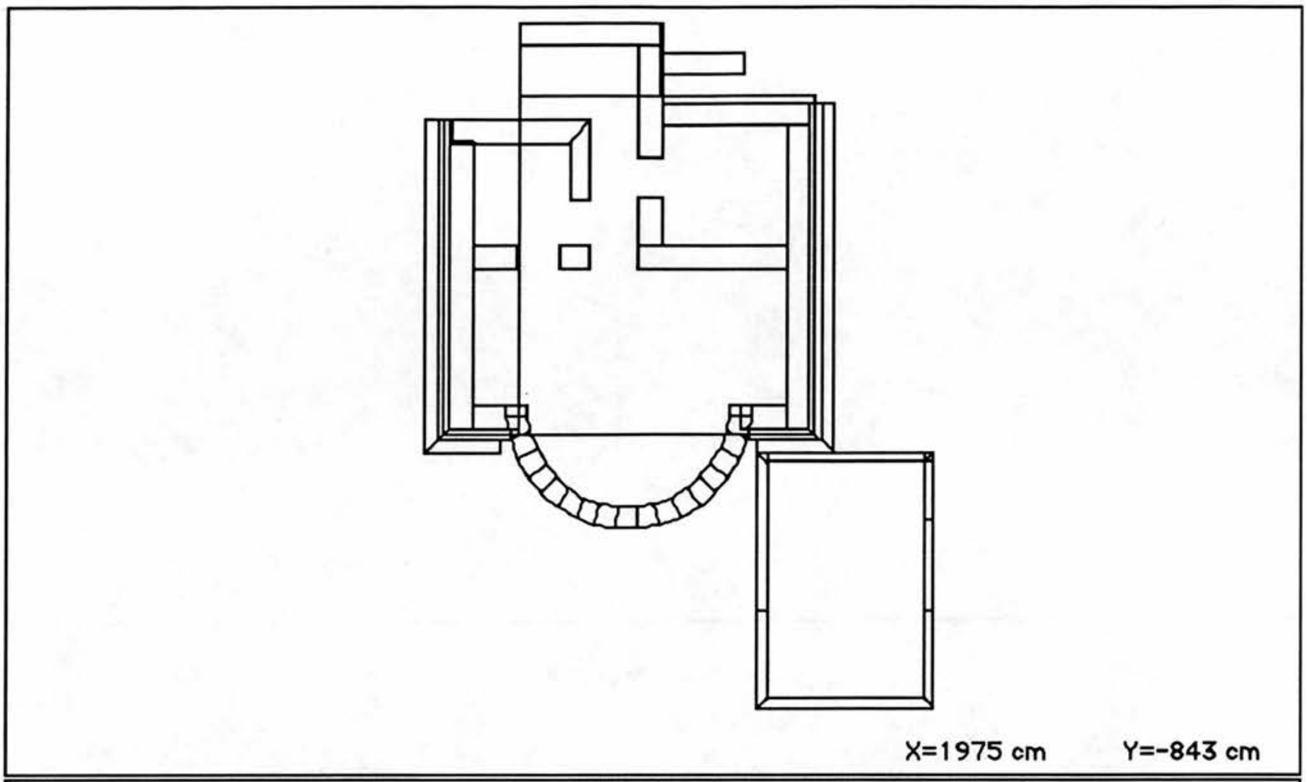


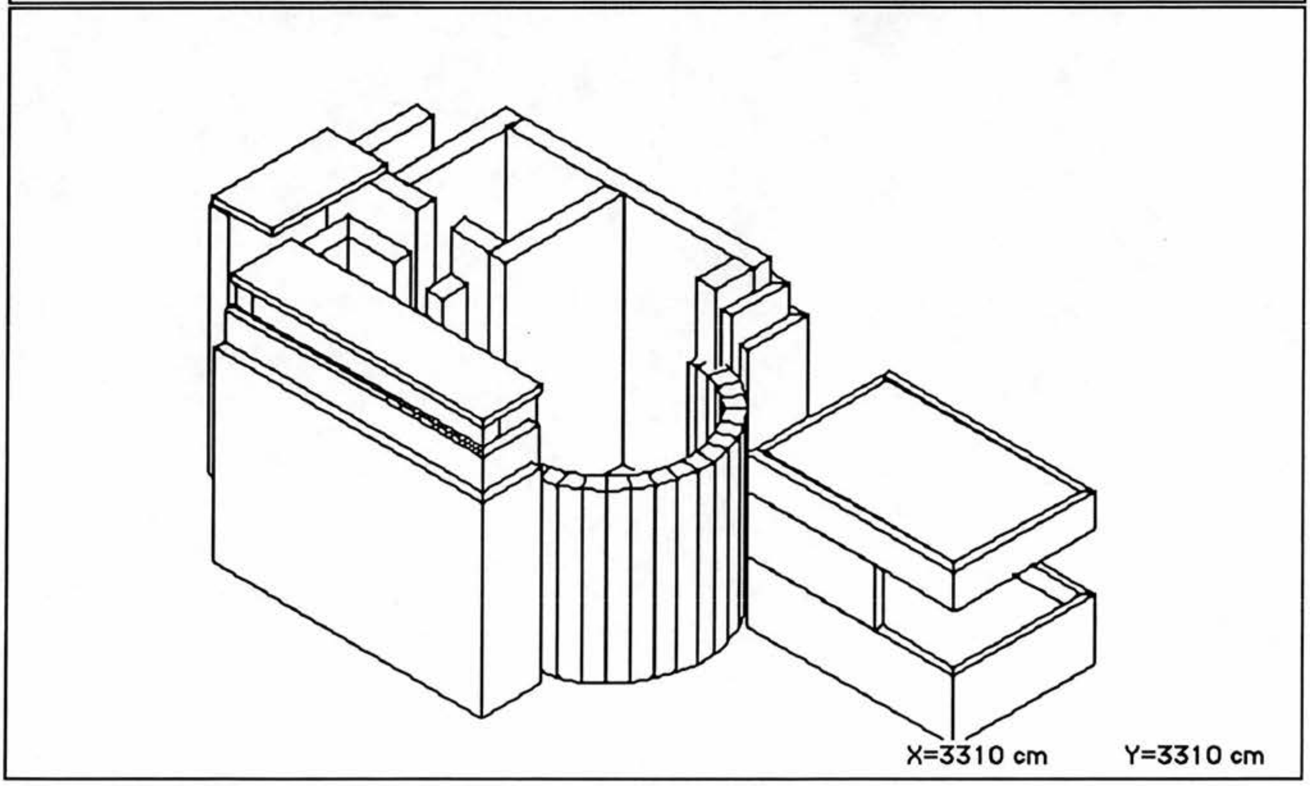
Student C; Instance 186

B.4. Student D

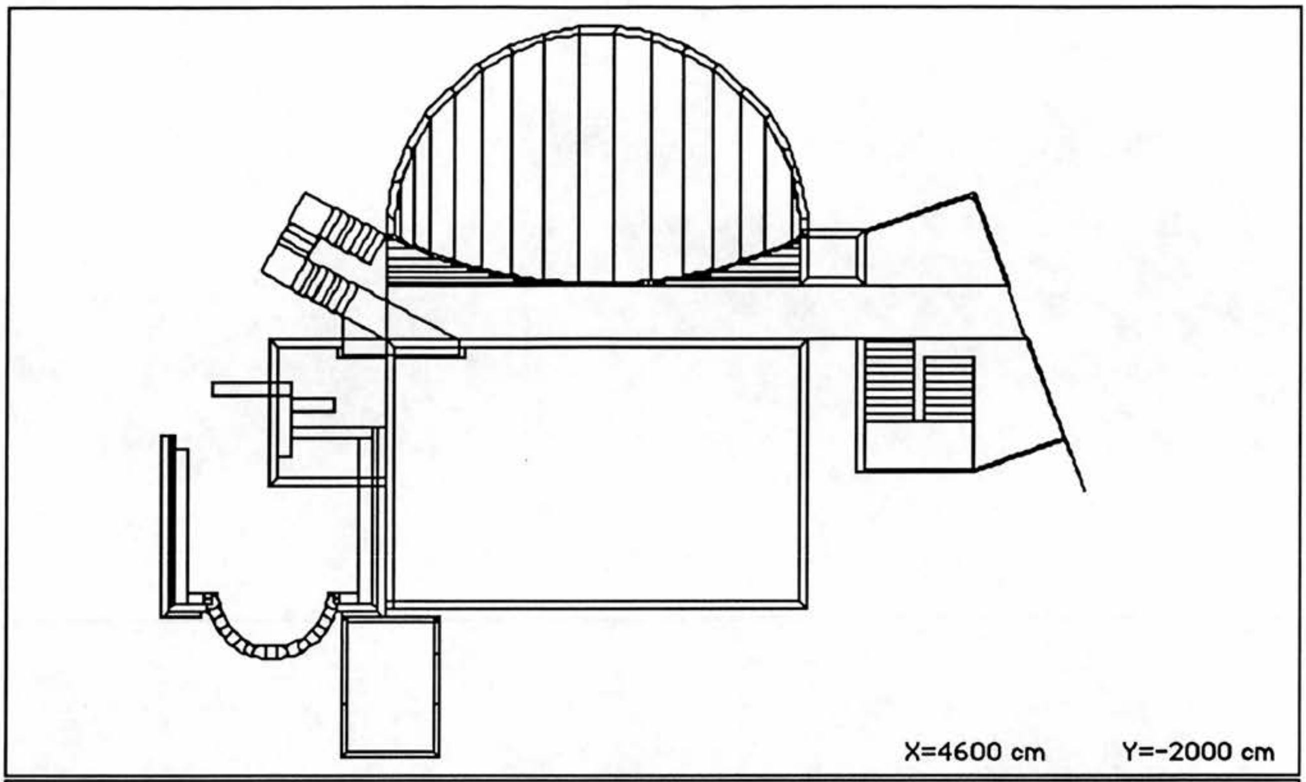


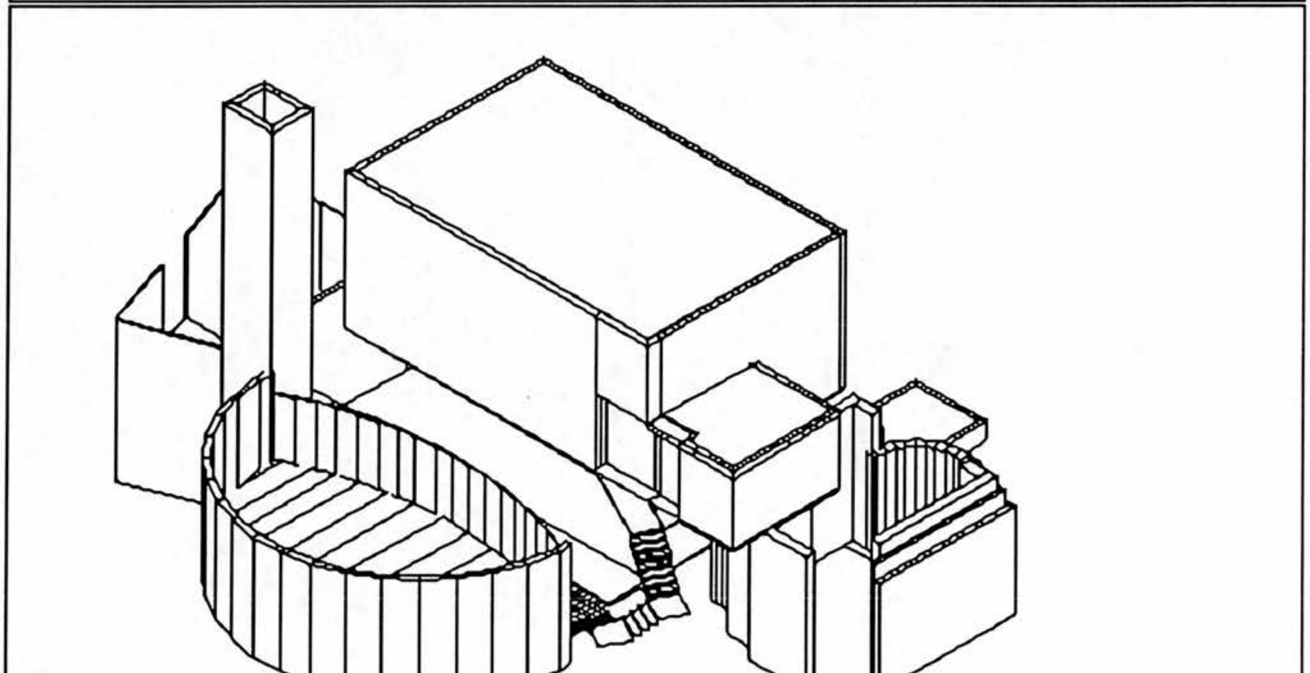
Student D; Instance 010



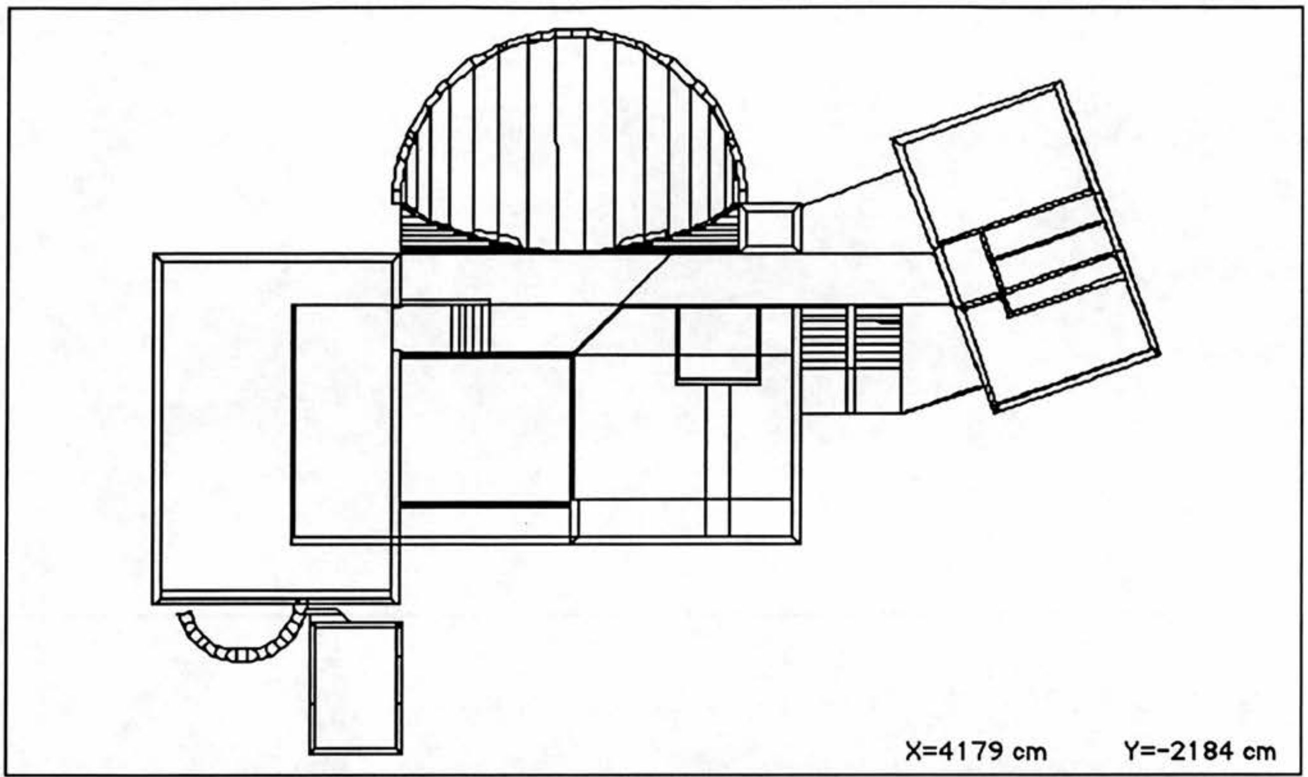


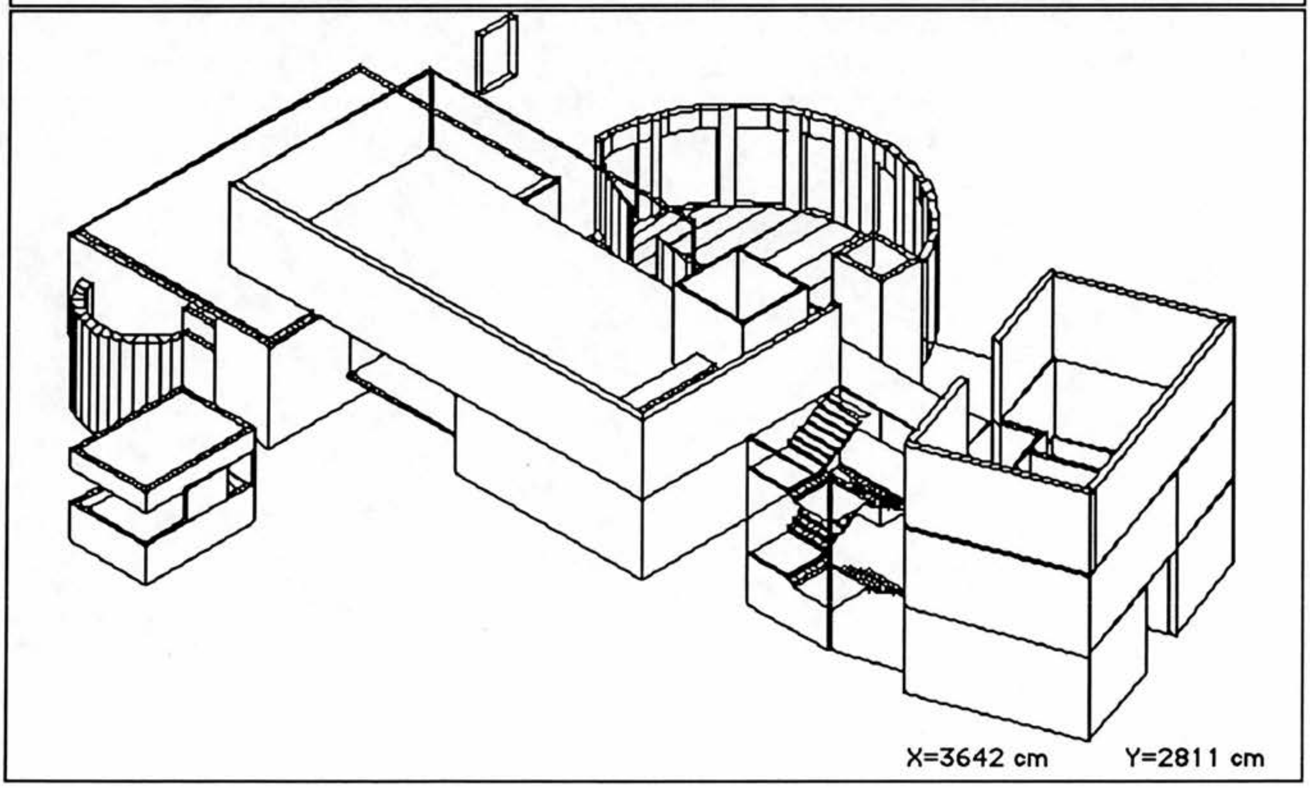
Student D; Instance 021



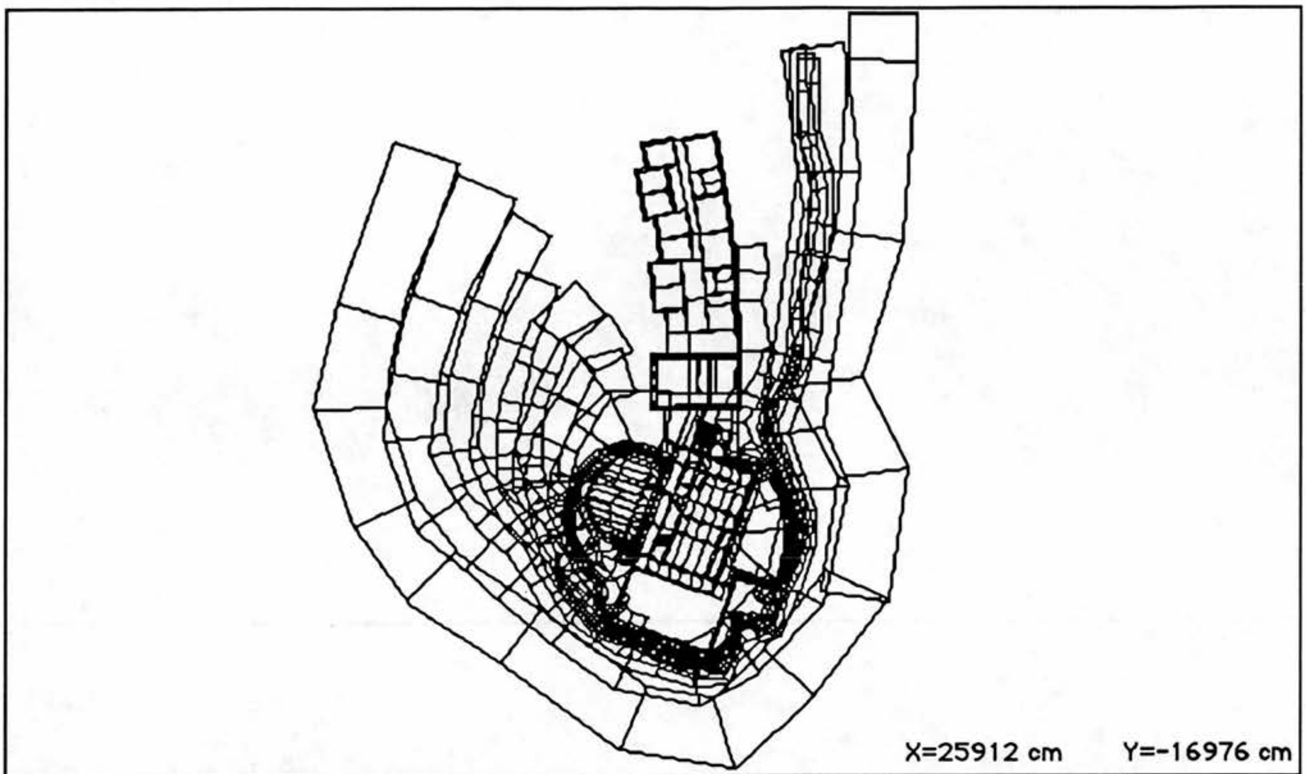


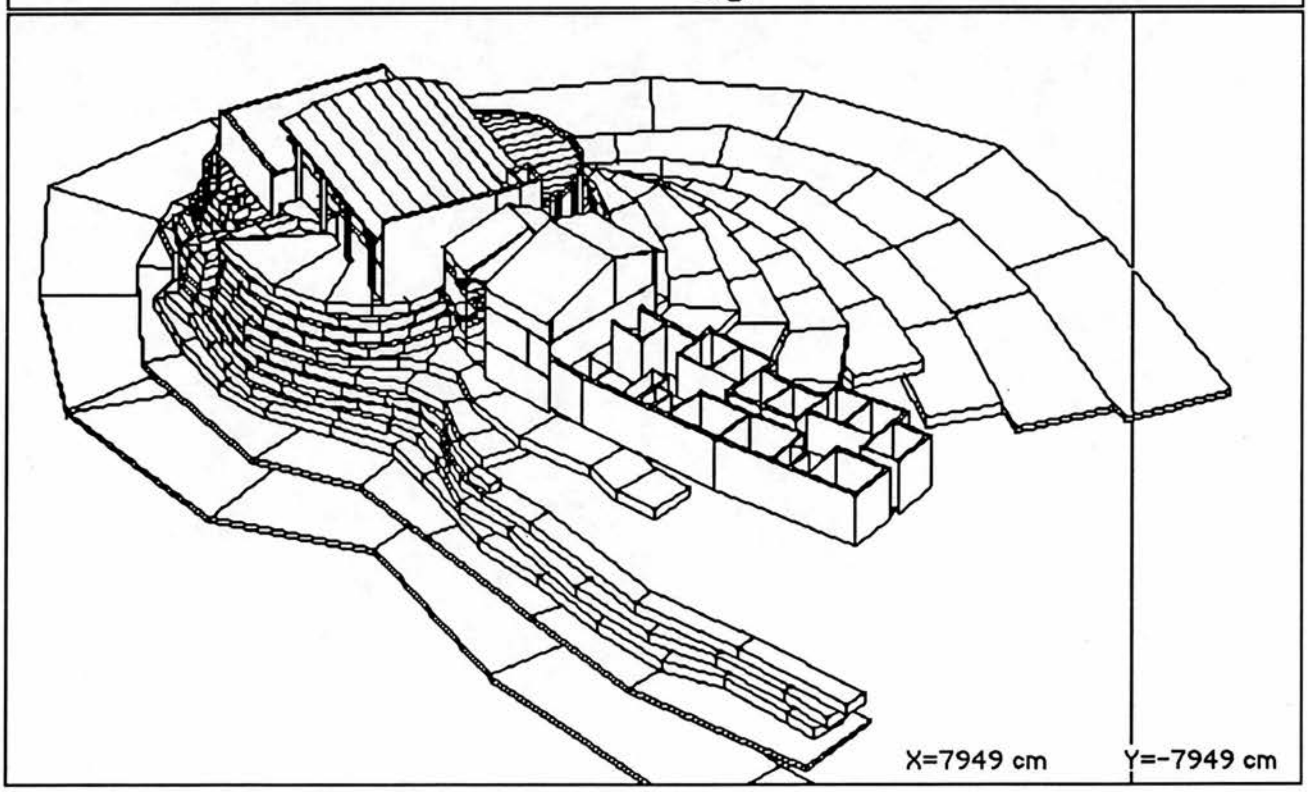
Student D; Instance 042



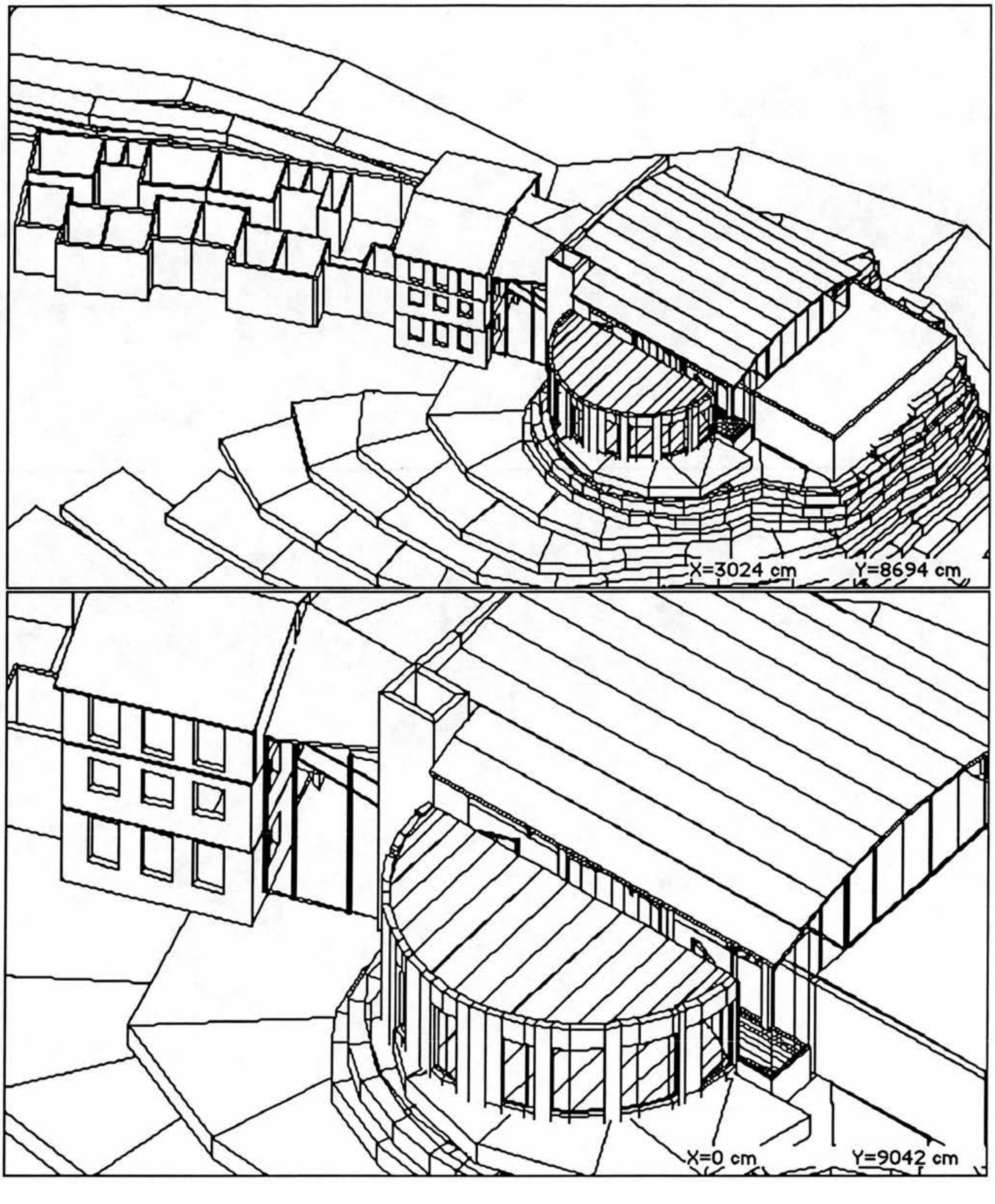


Student D; Instance 049





Student D; Instance 055



Student D; Instance 076

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