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THE PROCESS OF CONSTRUCTION PLANNING

William Henry Stockings
The Process of Construction Planning

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr. R.A. van Santen, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op donderdag 31 januari 2002 om 16:00 uur

door

William Henry Stockings

geboren te Hemel Hempstead
(Engeland)
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References / Bibliography

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1. Introduction

1.1 THE FIELD OF RESEARCH

This research is an investigation into the process of construction planning, the types of problems that construction planners have to deal with and the way in which they individually go about dealing with them.

1.2 THE FORMS OF ‘DESIGN’ WITHIN THE TRADITIONAL CONSTRUCTION PROCESS

The traditional construction process starts with a client need: a requirement to house a particular type of activity, be it one of leisure, commerce, shelter, or whatever. The client lists his set of requirements, be they detailed or vague, and engages the services of an architect to ‘translate’ these requirements into an architectural design. The architect engages himself in an iterative design process where initial ideas are developed into a solution that reaches all or as many of the client demand criteria as possible, given the parameters of time and cost, of course. Client satisfaction having been reached, ignoring the contractual details, the design drawings are handed to a contractor who in turn translates the product information into process information regarding the ‘how’ and ‘with what’ the building can be best physically built.

![Diagram of the traditional construction process](image)

Figure 1.01 The traditional construction process.

It is the second form of translation that forms the focus of this research project, a translation that is complex and not yet fully understood. It is part of a process that can be further complicated by the chosen form of contract but where in this research only technical factors are examined, ignoring aspects of organisation and management. It is a research that concentrates on the type of problems that construction experts have to deal with during the planning phase of construction projects and how they go about tackling these problems.
Described in terms of Figure 1.01 this research examines the activity in the central ‘box’ i.e. planning the construction phase.

1.3 CONSTRUCTION - A UNIQUE AND COMPLEX FORM OF PRODUCTION

Compared with other types of production construction clearly stands out as being sufficiently distinct from the rest to warrant it being given a unique classification. Not only is it a unique form of production one can also maintain that in many ways it also represents one pole of the spectrum of modern forms of production, mass manufacturing representing the other pole of the spectrum. To mention but a few of its characteristics construction projects are often very large one-off projects built by temporary organisations of contractors and sub-contractors of wide-ranging and diverse specialisms, subject to many uncertainties not least of which the vagaries of the weather, with pockets of it being highly mechanised but almost never highly automated, and other pockets being very much craft-related following long traditions. It is a very different world from factory-based mass production, although production of this type is clearly having an ever-increasing impact on methods on site.

Other forms of production mostly enjoy the benefits of occurring indoors in a controlled environment, with a constant number of workers that remains factory bound, where the flow construction enjoys none of these luxuries of certainty and therefore unaltered and the general logistics remain fixed throughout the production cycle. However, construction enjoys none of these luxuries of certainty and therefore each construction project has to be analysed individually so that the peculiar circumstances of that individual project are properly taken account of.

Consideration of the working space on a construction site needs to be considered not only three-dimensionally but also four-dimensionally because the nature of the product is such that spatial arrangement and flows of material, etc, can evolve constantly throughout the life of a project (Tommelein, Levitt & Hayes-Roth, 1987). There being as yet no way in which the production cycle can be accurately simulated by computer, for example, it is no wonder that problems arise that might possibly have been avoided by effective planning at an earlier stage (Laufer & Tucker, 1987). These ‘hiccups’ almost always negatively disturb the flow of production in some way causing almost always increased costs and delays.

1.4 CONSTRUCTION PLANNING PROBLEMS AND THEIR LEVEL OF DEFINITION

Construction planning problems can be problems of great complexity. There are different components to construction planning problems that require different problem solving skills and impact upon different knowledge sources. These various aspects are so entwined with one another that a conglomerate solution can be found to perfectly meet the demands of one aspect of the problem but fail in terms of other aspects. The construction planner therefore has to balance solutions by ‘weighting’ the demands and measuring the solutions against the weighted demand criteria. Often solutions will therefore be ‘best fit’ solutions that find the highest general degree of satisfaction. As Simon (1973) stated it is inappropriate to use the term ‘optimisation’ in the case of what have been termed ‘ill-defined’ problems because there are too many criteria by which they can be measured. Design problems in general can be described as ‘ill-defined’ because the problem structure cannot be clearly and unambiguously described in terms of one type of parameter. Only where this is the case it is possible to find an ‘optimum’ solution. The difficulty with construction problems is that we can measure their success in terms of a basket of criteria that can score optimality in opposing directions, and so therefore ‘satisfaction’ becomes quite clearly a more fitting and appropriate term than ‘optimisation’, although given a particular set of constraints the goal of construction planning is always to develop the least-cost solution, given a particular contract period.

The problems that a construction planner has to deal with are not entirely represented by the design documents but only partly represented by them. The full problem only starts to exist when a complete ‘machine park’ of tradesmen, machinery and equipment (the capacity) is metaphorically set down next to the design from which a selection of units of capacity can be chosen. But even then the complete problem has still not yet been completely described but will begin to take on more form as tradesmen, machinery and equipment are selected to perform various tasks, because with the application of each new unit of capacity a new set of circumstances is created, be it a relatively minor alteration to the present set of circumstances or a very much more major alteration to it. The design itself, of course, creates the most dominant part of the problem, but this is complicated by the fact that capacity itself also brings with it a set of demands for space and supporting activities and equipment that interact with the demands and constraints of the design. It is this interaction of demands and constraints from the two sides that creates the construction planning problem. In solving one problem other problems can be created, and even where this is not the case, once one problem has been solved it will automatically reduce the size of the available solution space for other activities.

1.5 PLANNING TOOLS

There are various planning techniques that are designed to assist the construction planner develop models of the construction process which represent by symbols an aspect of the ‘reality’ of a construction process. They can be useful in helping the construction planner to partially build up a picture of how a process will develop. However, these techniques or ‘planning tools’ can only ever deal with at best a few aspects or a limited part of the construction problem structure. The models that they represent of reality can never therefore be followed without deviation because they cannot deal with the ‘complete picture’. That, of course, has to be done by the human problem solver who being guided by the results of one or more of these abstracted models weighs up their implied effects and ‘interpolates’ between what the models are telling him in a way that his experience guides him, recording of course for others how he believes the construction process realistically and ideally should unfold.

1.6 THE BID TO CAPTURE CONSTRUCTION KNOWLEDGE

For fifteen years or so researchers around the globe have been trying to encapsulate construction planning knowledge in so-called ‘expert systems’ that possess the problem solving capacity of the best practitioners in the field. However, results up until now have in
realism been disappointing, with expert planning systems at best only being capable of dealing with planning problems of a very superficial nature, and where only a very small part of the total construction problem is solved or partly-solved by them. The day when a complex of problem solving systems can be linked together and develop solutions that simultaneously deal with the multi-faceted structure of construction problems seems some way off yet. However, human problem solving capacity does have its limitations and computer systems that would be capable of bridging the hiatus of the human problem solver’s capacity would be welcomed. Perhaps the key to success though in understanding how these models could be made to work would be to fully understand the structure of construction planning problems and the way in which expert construction planners go about dealing with them, a state which many would agree we have not yet reached. (Birrell, 1988; Laufer, Shapira, Cohenca-Zall, & Howell, 1993)

1.7 THE RESEARCH GOAL
The long-range goal of this research is more efficient and effective construction planning. The short-range goal is to improve our knowledge and understanding of how construction experts go about dealing with the structure of construction planning problems, given that construction planning problems can be very complex and given that there are clear limitations to human memory and its information processing power.

The original objective of the research was to develop a ‘design method’ that would assist less-experienced (student) planners deal more effectively and efficiently with construction planning problems.

1.7.1 The Quest for a Design Method for Construction Planners
At the outset of this research the concept ‘design method’ was an unfamiliar one to the author. ‘Design methods’ are certainly not part of the everyday language of the contracting side of the construction industry in the U.K., however, it was a concept that had been researched and taught at the Technical University of Eindhoven. Research into the exact nature of design methods revealed that it was somewhat of an ambiguous concept about which there was a great deal of controversy. It was certainly not a universally-accepted concept that was welcomed by all designers as being something that was logically distinct and useful. What some seemed to consider ‘design methods’ others thought of more simply as useful things to do when faced with particular types of problems. Even if design methods could be maintained as a logically-distinct group it was clear that there were many methods with different spheres of influence and applicability. It was not, for example, as though one design method could guide a complete design process and assist with all manner of different types of problems.

What also became clear as research into design methods continued was that research into design had moved away from putting forward prescriptive models of how design should take place to producing descriptive models of how designers actually design. Therefore, before it would be possible to promote a particular method as being in some way beneficial to a less-experienced construction planner in helping him to deal with a large amount of information so that better choices could be made, it would first of all be necessary to observe how expert construction planners actually went about the task. Only by carrying out such an exercise would it be possible to identify particular paths that experts take in solving problems that might have some benefits to non-experts if they were to follow the same path, for example. A great deal had been read in the literature on architectural design and industrial design about the activities of analysis, synthesis and evaluation and it seemed important that the order in which these activities take place during a construction planning exercise should be properly identified. This lead to the first of the two research questions, namely:

1) What steps and phases go to make up the construction planning process of an individual construction expert?

The second question arose from considering the fact that a construction planning task can often involve dealing with a great deal of information and require that a large number of problems be solved. Given that construction experts cannot deal with all of these problems simultaneously:

2) In what order should the design information be analysed and in what order should problems be dealt with?

1.8 METHOD OF RESEARCH/THE CONTENTS OF CHAPTERS 1 - 7
This thesis is divided into seven chapters.

Chapter Two reports on an investigation into the structure of construction problems. Aspects that are described include the overall objective of construction planning, technical efficiency of units of capacity and the constraints that impinge on construction processes. A wide literature study into the topic of construction planning is also reported. One of the aspects, for example, that clearly came forward in the literature study is that construction planning is not a solo activity but very much a teamwork effort. On certain smaller projects, of course, it is more likely to be a solo activity but on larger projects where a contractor’s skills are divided between different specialisms we find that there are certain ‘key players’ who have a wider-than-average function at particular stages (Laufer et al, 1993). Another finding of that same research is that construction planning is not a one-time activity that takes place before construction activities have started but is very much an ongoing process throughout the life of a project.

Chapter Three looks at the field of problem solving, at human memory, at theories of how we store and structure information and how we deal with certain types of tasks.

It is not possible to directly witness the thought processes that takes place whilst an experienced problem solver of one sort or another deals with a particular type of problem and therefore impossible to know exactly what factors had an influence on any decisions that were made during that process. However, a useful alternative is to indirectly observe these thought processes by asking an expert to verbalise his thoughts while dealing with a particular type of problem. The verbal output that one gains from such an experiment together with notes that are made by the observer of what the expert physically does is known as a ‘protocol’and can be analysed in order to learn more about that individual’s problem solving process; thus the term ‘protocol analysis’. Chapter Four gives a description of a set of protocol analysis experiments that were carried out with three planners who were asked to think aloud whilst dealing with a relatively straightforward construction planning problem. The protocols of the experts were analysed in order to test a model that had been put forward of the construction planning process.
Chapter Five describes possible strategies that might be employed by construction planners during the planning process of complex projects. The factors that may influence the order in which a planner scans information of a new project and the order in which certain types of problems are hypothesised.

Chapter Six describes the second of the two experiments in which expert planners were asked to think aloud whilst planning. This second experiment involved a very much more complex project than the first one so that the extent to which the hypothesised strategies that had been put forward in Chapter Five could be tested. As well as the results of these tests a number of other phenomenon that were observed are described.

Chapter Seven is the concluding chapter and describes the extent to which the research questions have been answered. The method of protocol analysis is discussed and suggestions made for its use in future rounds of construction planning research. To the extent to which a number of steps could be identified in the protocols of the experts a method of analysing the design documents is presented that it is suggested could help less-experienced construction planners go about the task of construction planning.

2. The Nature of Construction Planning

2.1 INTRODUCTION

This chapter lays out the findings of a period of research into the nature of the physical process of construction and into the nature of construction planning. After an initial examination of the overall objective of construction planning this chapter is basically divided into two parts; the first part (2.3-2.6) is concerned with the technical and economical aspects of construction processes on site and the second part (2.7) examines some of the peripheries around the activity of planning itself.

2.2 CONSTRUCTION PLANNING AND ITS OVERALL OBJECTIVE

Construction planning is a problem solving process that takes place in order to deal with the question of how a construction firm can most 'efficiently' employ the resources available to it in order to create the product as described by a set of architectural drawings and specifications. 'Efficient' in this sense meaning that for any given time constraint the cheapest method of production. It is a mainly cognitive process and although some problems can be broken down in such a way that they can be solved mathematically by a computer the overwhelming emphasis of problem solving lies with the human problem solver. And whilst efforts are being made, especially amongst academic institutions, to develop 'expert systems' that can produce better-than-average solutions to particular types of problems their problem-solving prowess at this stage is far from being as powerful or as flexible as that of the human construction-problem-solver. However, with little over fifteen years of development in the field of construction planning problems they should not be written off, but it is undoubtedly true that they have a long way yet to go before one expert system or a bank of expert systems working together will be able to (semi-)independently solve the types of problems that construction experts are capable of dealing with.

The output of the activity of construction planning is a construction plan. Depending on the complexity of the to-be-engaged project and the personal expertise of the individuals involved in the planning process the construction plan can be intangible i.e. 'stored' within the memory of the person that developed it or tangible i.e. committed to paper or some other medium in order to make it more immediately accessible to those who might require information contained within it. However, construction projects being what they are, and human memory being what it is, it is unthinkable that properly thought-up plans would not be brought into a technical document(s) of some description.

Construction plans can be likened to maps that describe routes that show the quickest way to move from one point on the map to another. Although these 'maps' can take on very different forms and can be divided into many different documents they all still serve the same basic purpose i.e. to provide control instruments that can be used to help keep a project 'on course'. For a great many projects, being as large and as complex as they are and demanding the co-ordination and organisation of many individual specialist-contributors as they do, it goes without saying that the quality of construction planning can be of the utmost importance to the successful conclusion of a construction project, in terms of both the client's and the contractor's objectives.
2.3 THE STRUCTURE OF THE CONSTRUCTION PLANNING SOLUTION SPACE

Stockings (1994) described the construction planning solution space by differentiating between (1) The Demands i.e. the description of the to-be-built building, (2) The Capacity or technology that is available at that point in time to carry out the works and (3) The Constraints that impinge on the way in which the technology can be employed. (See Figure 2.01). These three components can be said to form the structure of the construction planning solution space because an architectural design places a certain profile of demands on the available technology and the constraints limit the way in which the technology can be applied in order to meet these demands. The two physical dimensions in which solutions have to be placed are space and time, of course. Construction planning, therefore, can be described as a problem solving activity in which the borders of a solution space first have to be properly established before an ‘optimal’ solution can be chosen that lies within that solution space. But clearly with each type of project and with each type of sub-problem that solution space will shift and change shape.

![Diagram](image)

Figure 2.01 The structure of the ‘construction planning solution space’ showing the relationship between the demands, choices and constraints.

2.4 THE DEMANDS

The demands describe the yet-to-be-built building in its state of completion. The description of the physical artifact is most commonly found in the form of drawings that represent two-dimensional aspects of the building (plans, sections and elevations). Sometimes this collection of two-dimensional information is supplemented with drawings that give particular types of three-dimensional views of the building (isometric, perspective) as well as scaled-down models that also impart valuable three-dimensional information. Together with this collection of drawings architectural information also includes a written specification that adds more detail to what is to be found in the drawings regarding the nature and performance of components that go to make up the building. Other separate types of information might include structural engineering drawings, a soil report and service drawings, depending on the nature of the project and the degree to which the architectural drawings cover these aspects.

Buildings, in general, can be divided into different structural and non-structural elements. The exact division will, of course, depend on the type of building but in general the following elements can be identified:

- Substructure
- Superstructure
- External envelope
- Internal partitions
- Services
- Finishings
- External works

Within each one of these elements many different types of systems, materials and components can be employed. For example, the substructure could be made up of a pile foundation, a strip foundation, pads with beams, or a raft. The superstructure, likewise, could be made of steel, brick, concrete, wood, or a combination of these and other materials. And so it is with all the other elements of a building which means that the types of demands that can be made of the construction industry can vary enormously from small and simple projects such as houses to extremely large and complex ones such as nuclear power stations, with a vast range of projects in between.

For any given project there will be a logical order in which its sub-parts can be assembled. Clearly the foundations will need to be constructed before any other part of the building can be built, followed by the load-bearing frame and then the subsequent layers that are specified in the design information. The strongest determining factor will be whether or not a particular sub-part of the building can be physically ‘carried’. Paint cannot be applied before it can be 'carried' by plaster and plaster cannot be 'carried' before a wall has been placed.

The Demands describe the building-to-be-built in its completed form, but the building in its various stages of completion also throws up constraints that affect the order of construction. For example, those parts of the building that need to be protected from the environment can only be placed once the building is weather tight. And even when a building’s outer shell protects it from the external environment it may still be that the same certain products cannot be incorporated into the building, for example, in a multi-storey building where the wet trades (brick layers, plasterers, screeders and such like) are still working on the upper floors. Where there is a real risk of water or dust contaminating the building lower down then work will not be able to commence on these parts of the building until this risk has been eliminated which in practice will mean that the structure will be built bottom-up, while the finishes will be completed top-down (see Figure 2.02).
2.5 THE CONSTRAINTS THAT IMPINGE ON A CONSTRUCTION PROCESS

There are various types of constraints that impinge on the way a construction process can be carried out. As is true of all problem solving processes the more constraints on a solution there are the greater the degree by which the solution space will be reduced. The degree by which the solution space will be reduced will very much depend on the severity of the constraint as well as the degree to which it can be ignored and/or invalidated. Some constraints can only be ignored at the peril of breaking the law, others will be much ‘softer’ and can possibly be overcome by taking special precautions; others still will be immovable and could, of course, limit the solution-space to such an extent that there remains a minimal range of viable construction alternatives from which to choose.

Stockings (1994) divides the constraints (see Figure 2.01) that govern the way in which a construction process into five areas, namely:

- Legal constraints
- Physical / Chemical constraints
- Environmental constraints
- Market-induced constraints
- Project-specific constraints

Legal constraints are those formally-codified constraints that govern aspects such as working hours, levels of permissible noise pollution, minimum safety standards, employee contractual arrangement, etc. Physical / Chemical constraints are really the ‘Laws of Nature’ and include such aspects as gravity, the rate at which concrete hardens, the way in which soils behave under various conditions, etc. ‘Materials Science’ also is a term that covers part of this set of constraints and clearly has an enormous influence on the way in which part-finished structures should be supported, for example, or the rate at which bricks can be laid; engineering bricks being more difficult to lay than their more porous counterparts house bricks, for example. Environmental constraints are those pertaining to the weather. A large percentage of a building site production takes place ‘out in the open’ therefore allowance has to be made for the possible/likely weather situation. Market-induced constraints are those that pertain to the availability of materials and semi-products that enter the building-site-machine as the input for its various processes. And lastly Project-specific constraints are those which are peculiar to that building site; these include instructions from the client regarding the phasing of project completion, Police-restrictions regarding the timing and point of access of deliveries, the proximity of neighbouring buildings, etc.

In a sense constraints can be likened to the rules of a game. All games have rules, of course, that describe what is permissible and what is not permissible within the context of the game. In terms of a construction process the rules that have to be adhered to are not so black and white as they are in most games. Some of the rules are clear-cut whilst others are very much less so. A fundamental aspect to rules or constraints is their degree of firmness or ‘negotiability’, as Goel & Pirolli (1992) describe them. The Laws of the Natural Sciences are laws that are clearly ‘non-negotiable’, the physical world in which we live in functions according to rules that cannot be violated even to a minimal extent. Man-made laws, on the other hand, can sometimes be violated or even re-negotiated so that they better suit our purposes. For example, where a Local Authority ban exists on Sunday-working it might be possible to negotiate a lifting of the ban for a certain period so that the project could be completed by a particular date.

Another characteristic of constraints is their predictability. Even in the case of the 100% non-negotiable rules of the physical world we cannot say that they are all equally predictable. Gravitational force and its effect on structures (and therefore its control on the order in which something should be built) is 100% predictable. The weather on the other hand is the most obvious and powerful example of a physical situation that is not capable of being predicted beforehand, beyond the shortest period that is.

Different constraints also enjoy different levels of complexity and clarity. The rules concerning Worker Safety ought to be fairly straightforward so that no-one should ever be in doubt about what safety precautions ought to be taken under different sets of circumstances, for example. A construction planning task is principally one concerned with technical efficiency where beliefs and values, for example, play a fairly insignificant role in decision making. However, a construction planner might in some cases have to pay regard to other less-easily defined goals such as public image, for example. Motivation of personnel is a management task but clearly a construction planner has to take into account the welfare and safety of site personnel, but such consideration will be in terms of what safety precautions will need to be taken as well as what facilities will be required by site personnel, and as such will concern tangible measures such as safety rails and on-site shower facilities, for example.

2.6 CAPACITY (TECHNOLOGY)

That which can be picked from in order to construct or help construct what is described by an architectural design is the technological capacity within and at the fringes of the construction industry. In other words the manpower, machinery, equipment and instruments that in some way can be utilised in order to physically produce a building. Manpower and machinery can...
be thought of as a collection of systems that convert energy into a physical activity of one description or another, for example, in cutting, drilling and lifting, the sort of activities that are essential in the direct and indirect processing of the fabric of the building. However, this physical production could not take place without equipment that works in a passive sense, as opposed to an active sense, physically supporting the systems that have to process the components that make up the building, or supporting the part-completed building itself; scaffolding, formwork and sheet piling are three such examples. Instruments are used in the setting-out and measurement of the physical dimensions of the to-be-built building and have a control nature, comparing that which is being built with the criteria by which it had been designed.

These four elements, manpower, machinery, equipment and instruments together form the ‘building-site-machine’, a collection of process, support and control systems that take incoming raw materials, components, etc., and fashion them into a (sub-)building.

Manpower

Looking more closely at two of the elements of this machine manpower can be sub-divided in many ways. For example, through the type of product or component that it processes, through the level of skill associated with the work (physical and/or mental), through its relationship with the type of machinery that it operates and through the degree with which it is involved in the production process i.e. directly involved as an operative, for example, or indirectly involved as a supervisor. But, of course, there are many other criteria by which manpower can be distinguished. Another relevant distinction in the construction industry, for example, is that between directly-employed manpower and sub-contracted manpower, the construction industry being a great mix of firms of different sizes and specialisms that often operate on many different projects at the same time.

Machinery

Machinery can be sub-divided according to its degree of mechanisation. Bright (1958) identified seventeen different levels of mechanisation ranging from level one where a worker uses his hands to produce something, through to level seventeen where a machine guides all aspects of its own production cycle completely independently of human control or input of energy. The two fundamental measures by which the level of mechanisation can be ascertained is (1) the power source that adds kinetic energy to the production activity and (2) the control mechanism that guides the power source. It is appropriate to refer to a process where human muscle power is no longer brought into that process as ‘mechanised’; where machinery is programmed to take over the control function as well this process would be referred to as being ‘automated’.

Whilst the author is unaware of any research that has been conducted in order to compare industries in terms of their levels of mechanisation there can be little doubt that construction, whilst pockets of it are highly mechanised, is far from being a highly automated industry. That, of course, has to do with the nature of the product. Construction produces a fundamentally different type of product to factory production. Buildings are very often large one-offs that are immovable and therefore have to be built at their ‘point of consumption’, whilst the products of factories are often very much smaller and can be produced in large quantities. In the latter situation the opportunity arises to utilise conveyor belt methods of production where operands flow from one value-adding system to another. However, in

construction the ‘operand’ or part-finished product remains static while the ‘value-adding systems’ ‘flow’ around the ‘operand’. In order to control such flows superior visual and tactile skills are necessary, skills that are relatively easily developed in humans but that can only be developed in machines at great expense, if at all. This is why machines that can replace and/or supplement the muscle power of the worker can be utilised in the construction process with great success, but they still need to be controlled by human operators. Some activities, of course, cannot be carried out by machines at all and remain the prowess of skilled workers working with hand tools such as brick layers, carpenters and plasterers.

Performance

One thing that all items of capacity have in common no matter what type they are and no matter what their primary or secondary functions are, they are all only capable of operating within a given performance range whether it be a crane or any other mechanical device, a brick layer engaged in direct work or his supervisor engaged in indirect work, an item of scaffolding required to carry dead loads or an instrument that is needed to measure physical aspects of the building. Some items of capacity have a very specific envelope of capacity (machinery, for example), whilst others have a more statistically-determined capacity-output (brick layers, for example). Even a unit of supervisory labour such as a site manager or a ganger foreman, for example, has a certain performance range within which he or she can best operate. In the case of supervisory labour it is much less straightforward a task to measure the level of work that he or she will be able to perform but clearly there are limits to how much information supervisors will be able to properly process (take planning and checking, for example) and each individual will have an upper limit that they will not be able to exceed without them either suffering from problems of stress and/or performing their work unsatisfactorily.

Each unit of capacity has a particular performance range and a particular cost. The following diagram is an illustration of the development of technology where new states of technology enable outputs to be made in greater numbers at reduced unit costs. The terms “Tech. I”, etc., in the first graph could be replaced with different types of mechanical digger, for example. The point being that different types of machines will be more or less economical per unit of output at different total levels of output. For example, in the case of a small excavation it might be cheapest to simply have a groundworker excavate it by hand. With a slightly larger excavation perhaps it would be cheaper to employ a mini-digger and with a really large excavation perhaps it might be cheapest to employ a drag-line excavator.

Cost per unit Cost per unit

Figure 2.03 The relationship between various states of technology in terms of costs and output.
2.61 The Correlation Between The Demands and Capacity

In reflection of the diversity of the materials and products that are incorporated in modern buildings, construction capacity is divided into a large number of specialist groups of manpower and machinery. Some elements of manpower and machinery are more flexible than others in terms of the numbers of different functions they will be able to perform. The result of this is that where certain types of materials and products are specified in the design documents, then there will be sometimes very little choice as to what types of manpower and machinery will be able to perform the necessary work; in other words, the design itself will select the necessary units of capacity. For example, piling rigs that hammer pre-cast concrete piles into the ground will not be able to place in-situ concrete piles that are formed where a core of sub-soil is first removed. And nor will a shuttering carpenter be skilled in the work of the plasterer. The result being that most elements of the architectural design will be very much tied to specific types of construction capacity, while a minority will be much less product-specific.

The Physical Requirements of Construction Capacity

At the very heart of the construction process are the production units that carry out the activities necessary to produce a building. Irrespective of the nature of the activity the production units perform, whether the production units are men, machines or man/machine combinations, they all require five physical aspects: namely (1) a stable platform (2) sufficient work-space (3) a work-front (4) a supply of materials and (5) time.

Stable Platform

In the case of a tradesman with a typical weight of anywhere between 60 and 100 kg, the platform could be the ground, it could be a scaffold, it could be a ladder; it could even be a basket hanging from a helicopter! Machines on the other hand generally weigh very much more than their human counterparts, particularly machines required to lift heavy weights, and therefore require very much stronger working platforms than humans do. This being the case, most heavy plant and machinery will find their platform on the ground. But clearly where the weight of the machinery exceeds the bearing capacity of the ground suitable measures will have to be taken to spread the load. In the case of mobile machinery, temporary roads may need to be laid, their depth and make-up depending on the nature of the subsoil, the time of year, as well as the type and frequency of use that they will be put to.

Note that the fundamental elements that are necessary for any production process are time, space, energy, materials, and information.

Work-Space

The work-space required will vary little between tradesmen, each tradesman being able to attend articles within an arm's reach of the platform he is working on within arms reach above his head and in front of his body. The required work-space of various items of machinery varies very much more considerably. A 50-ton mobile crane, for example, requires a space of 3 meters wide by 8 meters long by 4 meters high when in transit, requiring a larger platform for its outriggers and body when required to lift weights, but can operate within a space that approximates a half-sphere with a radius of approximately 25 meters. However, in operation it will most likely be confined to a space very much smaller than its maximum operating space due to possible existing obstacles within a particular situation and by the weights it will be required to lift in that situation; the larger the load the smaller its space of operation, of course.

The aspect of safety has to be taken into account in considering the platform on which the production unit stands and the space in which the production unit must work. Clearly, the platform has to allow a tradesman to be able to work within an arm's length of his body and to be suitably strong enough to not only support production units but also any tools and equipment that they might use, as well as the materials that the production units are engaged in processing.

The space in which the production unit is working must also be suitably safe. Where the space is below ground level it has to be made safe from collapsing subsoil and ground water, for example. Whether above ground level or below ground level, the space in which the production unit is working should be made safe from falling objects from activities taking place above the particular space. Where the space is found at some height above ground level, it should be made safe from the danger of falling.

The space in which production units work also sometimes has to be made 'safe' against the effects of the environment, not just in terms of protecting a unit of capacity that is working in a particular space but also in terms of protecting whatever material or element that unit of capacity is introducing to that space i.e. against heat, cold, wind, sunlight, extreme precipitation, etc.

And just as the space itself might have to be made 'safe' in terms of effects coming from outside the space itself, the space might similarly have to be made safe in terms of secondary effects escaping the space itself, for example, from falling debris and water, or from noxious and dangerous substances, but also from noise and light pollution.

Work-Front (m, m², m³ & no.)

The work-front is that part of the part-completed building that is ready to accept the next layer of materials. For any given project there is a particular work-front that grows and spreads during that project's life and shrinks back to nothing at the end of it. To begin with the work-front is relatively small and requires few types of different sorts of capacity, but as the project develops many more different types of work-front will open up to other types of capacity, so that potentially on a particular project a large number of work-fronts will be able to run parallel with one another, each work-front growing and shrinking, and probably fluctuating in size throughout its life.
Some trades, such as brick layers, will in the main create their own work-front, whilst others such as plasterers will need to have it created for them, it depending on the design and how many layers of materials have been specified.

The size of the work-front and the output of a unit of capacity will be major factors in determining the level of capacity that will be assigned to any particular work-front. In the case of a fluctuating work-front it will generally be the endeavour of the construction planner to assign a level of capacity in which there is as little idle time as possible, and preferably none. In the above example it would therefore be advisable to employ the capacity beginning at the second time period rather than the first, because to employ even one unit of capacity in the first time period would mean that there would not be a complete day’s work for that unit. Better therefore to have two units of capacity start on the second day. On the third day three units of capacity could be 100% fully employed and this level could be maintained for approximately seven days.

The advantage of units of capacity with low or zero indirect costs is that where a fluctuating work-front is presented a contractor will not be penalized by fluctuating the levels of capacity in order to meet the fluctuating work-front. However, where large indirect costs are associated with particular types of capacity, for example with large diggers and cranes, then bringing fluctuating levels of capacity onto site will result in a financial penalty for the contractor. (See 2.63)

Figure 2.04 The flow of work-fronts.

Figure 2.05 Fluctuating work-front. This diagram illustrates the notion that an available work-front may fluctuate in size on a daily basis.

The activities that have been listed are transporting, storing, lifting, supporting, and last but not least, processing. The list is not meant to be exhaustive, it is simply meant to give an indication of the types of basic activities that take place at site level. The materials and (sub-...
components first of all have to transported on to the building site where they will either be stored within a particular area on the site or taken up to be immediately processed or ‘incorporated’ into the building. Where this processing takes place at high level the materials or sub-components will first have to be lifted to the point of processing where the systems that carry out this processing are supported by a safe platform. This process continues, of course, until all materials and components have been brought together as described by the architectural drawings. The only activity that is directly involved with the ‘putting together’ of the building is processing. Processing represents all those activities where materials and components are added to what will form the finalised structure and will include pile driving, brick laying, welding, placing, bolting, screwing, concreting, gluing, painting, etc. All of the other activities i.e. transporting, storing, lifting, and supporting can be described as being subordinate to or in service of the activity of processing, and thus ‘indirect’ activities 4. Processing has to take place in a sequential order that is governed by the nomologic that can be gleaned from the design information. Transporting, storing, lifting and supporting can occur in a very much less prescribed manner. If the contractor wished to have a load of bricks driven ten times around the building site and then lifted up and down six times before including it into the works there would probably be no objection raised by architect or client, as long as the handover date and contract sum were not affected.

Construction activities can be overlapped in the sense that once one activity has created a sufficiently large work-front for a second production unit to commence then it will generally make good planning sense to allow this to occur. The reason for this being that the indirect cost centres of site fencing, hutting and supervision, for example, can be minimised with respect the direct cost centres of groundworkers, concreters, etc.

2.63 Efficiency in Construction

Figure 2.08 shows the theoretical relationship in terms of cost and duration of various solutions for a particular construction project that are all 100% efficient. There are basically two reasons why the curve rises much more steeply on the left-side of the cheapest solution than on the right side. The first has to do with the decreasing margin of output where more and more units of capacity are required to work in a given space and the second has to do with the increasing proportion of indirect costs to total costs when more units of capacity are brought onto the construction site.

The reason that the curve rises much more gently to the right of the least-cost solution is that the process is taking longer than it ideally should do whilst certain indirect costs of site

4 A direct activity is one that involves the addition of some material or element to the building fabric, and would include such activities as brick laying and concreting. Indirect activities might be essential in supporting direct activities but the fabric of the completed building does not get the slightest bit heavier as a consequence of them. However, the distinction is not as clear-cut as we might at first believe. For example, if one examines in detail the activities of the brick layer one finds that not all of his actions are concerned with the direct addition of another brick on the wall he is building i.e. on a detailed scale one would not be inclined to detail everything he did as being concerned with ‘processing’. For example, in picking-up a brick we might be more inclined to describe this as ‘transporting’ the brick rather than ‘processing’ the brick. Another problem of classification arises when considering the work of the crane. When lifting materials up onto the scaffold, for example, we would class this as an indirect activity. However, when the same crane was involved in positioning a pre-cast concrete element, for example, adding further to the structure, we would necessarily have to class this as a direct activity. The classification of direct and indirect activities, whilst on one hand adds insight into the understanding of construction processes, is therefore not without its limitations.

Figure 2.08 The relationship between cost and time on a most-efficient construction process.

Figure 2.09 represents total output of an increasing number of units of capacity within a given space. For example, where one carpenter can fix a certain number of units of plasterboard in a room of a particular size it may be found that two carpenters can fix twice as many units of plasterboard in a given period. Put three carpenters in the same room and they will probably fix three times as many units of plasterboard in a given period. Carry on in this way and with each extra carpenter there will be a pro-rata increase in total output. However, there will be a point at which putting extra carpenters in that room will start to have a detrimental effect on the rate at which the other carpenters can work. Instead of the extra carpenter contributing as great an amount to total output as his colleagues he will contribute less. Put yet another carpenter in the room and his colleagues will be interrupted even more. Of course, continuing in this way a point would be reached where production would be so disturbed by the increasing number of carpenters trying to work in the same enclosed space that there would no longer be an increase in total output but a decrease. In other words near the limit of maximum output each extra unit of capacity will bring an increasingly diminishing increase in output and that is why costs will soar while benefit gained in quicker completion will slow markedly.

Figure 2.09 The relationship between units of capacity in a given space and total output.
Figure 2.10 illustrates the effect that an increasing proportion of indirect costs have per unit of capacity on the costs per unit of production for a fixed number of units of materials to be processed. Where there are no indirect costs involved in adding extra units of capacity the unit cost of capacity will remain the same per unit of capacity. However, where there are extra indirect costs that have to be made when employing extra units of capacity the unit cost of processing a given amount of materials will increase. From the graph can be seen that the higher the indirect costs in relation to the direct costs the greater the increase in unit costs will be with each additional unit of capacity employed.

The factors that partly dictate whether or not a fluctuating capacity should be employed to attack a particular work-front are the direct and indirect costs associated with a particular type of capacity together with the general site costs of a particular project. For example, it might be found that the cheapest crane solution of a particular project, in terms of pure crane costs, will be to choose one tower crane but when the reduction in general site costs due to earlier completion is taken into account it may very well be found that three tower cranes could be better employed instead.

The following graph illustrates for a particular fictitious case the cheapest solution for a given profile of indirect and direct costs of a unit of capacity, together with the general site costs of a particular project. In this particular case it can be seen that one tower crane could complete the work in forty weeks at a total cost of 125,000 Euros, two could complete the work at double the speed at a cost of 110,000 Euros but that three tower cranes could complete the job in just under 14 weeks at a cost of 108,000 Euros. While fictitious it nevertheless illustrates the fact that solutions should not just be developed by examining the costs of the major direct activities and seeking the cheapest solution but that potential savings that could be made from reduced site costs should also be taken into account. And so it is found that the higher the general costs of a project the more economically viable it will become to develop a shorter construction programme. These higher general costs could be due to very expensive parking, or due to high rental charges for storage and hutting space, or even due to high security costs, for example. In fact the cheapest total solution will be where the total indirect costs of the units of capacity is or approximates the site costs.

![Diagram of indirect costs](image)

Figure 2.11 The relationship between unit costs and levels of capacity with different proportions of indirect costs (for a given total number of elements).

The following graph illustrates a particular fictitious case the cheapest solution for a given profile of indirect and direct costs of a unit of capacity, together with the general site costs. In this particular case it can be seen that one tower crane could complete the work in forty weeks at a total cost of 125,000 Euros, two could complete the work at double the speed at a cost of 110,000 Euros but that three tower cranes could complete the job in just under 14 weeks at a cost of 108,000 Euros. While fictitious it nevertheless illustrates the fact that solutions should not just be developed by examining the costs of the major direct activities and seeking the cheapest solution but that potential savings that could be made from reduced site costs should also be taken into account. And so it is found that the higher the general costs of a project the more economically viable it will become to develop a shorter construction programme. These higher general costs could be due to very expensive parking, or due to high rental charges for storage and hutting space, or even due to high security costs, for example. In fact the cheapest total solution will be where the total indirect costs of the units of capacity is or approximates the site costs.

Cost (Euros)  

<table>
<thead>
<tr>
<th>Number of Units of Capacity</th>
<th>Unit Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Indirect Costs (No Transport Costs)</td>
<td>100</td>
</tr>
<tr>
<td>Different Capacity Types</td>
<td>200</td>
</tr>
<tr>
<td>High Indirect Costs (Large Transport Costs)</td>
<td>300</td>
</tr>
</tbody>
</table>

Figure 2.11 The relationship between project duration and crane costs for a fictitious project.

Not only will this balance need to be struck in terms of machinery so too will it need to be struck in terms of manpower and equipment. For example, it will be a sub-goal of the construction planner to maximise the learning-curve of personnel and to maximise the re-use of equipment. But clearly where a reduction in the number of man-hours or the reduction in the hire charges of equipment will result in a slower overall construction programme and the subsequent increase in total costs then it would be irrational to maintain these sub-goals as the most important objectives. Clearly therefore in evaluating such situations the total cost implications should be considered rather simply the individual cost centres.

In the same vein, in theory at least, there is a play-off between employing units of capacity as soon as part of the work-front becomes available (i.e. not at 100% efficiency) and being able to compensate losses made on the direct activities side with savings made on reductions in the indirect sphere of the project. But in practice of course it will be very hard to establish what these gains and losses might amount to but, in principle at least, it is an aspect that construction planners might consider when time is of the essence.

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5 Where the indirect cost of setting-up and dismantling one tower crane was taken as 5000 Euros, the direct cost per week at 2000 Euros and the fixed site costs at 1000 Euros.
2.64 The Inhibiting Factors On The Rate Of Production

The following diagram illustrates the notion that there is always a bottleneck factor that limits the rate at which a particular production sub-process can take place. One unit of capacity, being able to operate at 100% efficiency will be able to complete its work in the time-span shown. The volume of that unit of capacity therefore represents the amount of work that it needs to complete. It can also be seen that there is sufficient space in which more units of capacity could operate although, of course, it depends entirely on the nature of the work and the types of capacity involved whether or not they would be able to all work at 100% efficiency. However, assuming that additional units of capacity would not detrimentally affect the efficiency of the units of capacity that were already working in that space (where there was no decreasing marginal rate of efficiency) then there might exist other limits to high performance. One is shown as being the 'materials limit', which might be governed by the time that the material required to harden, for example. The other limiting factor is termed the 'work-front' limit, and is governed by the need to be butt new work up against existing work in a 'wave' out from some starting point. And so whilst in terms of available space it might be physically straightforward to have a large number of workers working within a given space, other limiting factors such as the hardening time and the amount of existing work-front could be the governing factors in terms of how fast that section of work could be carried out. But, of course, under different physical circumstances the governing factors will appear in different orders and at different levels of capacity.

Figure 2.13 The idealised relationship between time, space and output.

Figure 2.14 shows a simple but powerful example of two different physical situations and how the situations determine the rate at which a section of work can be carried out. The bricks in the situation on the left will be laid more than three times faster than those on the right because not only is there enough space for three times the capacity on the left, the right-hand situation will also probably be more sensitive to the rate at which the mortar hardens.

2.65 The Realities of the Construction Market

The danger that accompanies efforts to plan a construction process so that the use of space and time is maximised is the increased inability of that process to deal with disturbances of one form or another. Where a process takes place with a 75% use of available time and space it clearly has a superior ability to deal with unforeseen events and circumstances than a process that is operating at a level of 95% use of available time and space. The latter process...
is therefore more likely to over-run in terms of projected cost and contract period. The sub-objective of flexibility, therefore, will very likely be taken into account by the construction planner in drawing up a construction programme, the degree of which will depend on his perception of unforeseen risks and co-ordination problems. And, of course, in reality a great deal of work is carried out on projects by sub-contractors who will not be at the beck and call of the main contractor but who will probably have operatives working on a number of different projects at the same time. Therefore it will probably be unrealistic to plan for levels of manpower that fluctuate in accordance with the size of the work-front, even where there are no penalties in terms of indirect costs. Much more realistic instead will be the situation where a constant number of workers is taken into account so that they can work for continuous periods.

2.7 CONSTRUCTION PLANNING IN PRACTICE

2.71 The Stages of Construction Planning

Construction planning is a process that begins or should in fact begin during the architectural design phase of a project whether overtly by a construction specialist or covertly by the architect himself as part of the design-consideration of the 'buildability' of the project. However, depending on the type and nature of the contract there are a number of 'pinch points' that divide the process into its highest-abstracted level of stages. In terms of the traditional contract the most-generally identified stages are:

- Pre-tender planning
- Pre-construction planning and
- During-construction planning.

These three levels of planning indicate the scope and depth of their outputs, an idea which is graphically detailed in Figure 2.15. For example, pre-tender planning will cover the entire range of the construction cycle on a particular project but will only do so at a certain depth of detail. Once a contractor or other organisational form has won the tendering procedure a more-detailed level of planning will take place in order to form a clearer picture as to how the project should be carried out but, of course, within the framework of the plan that had been outlined at the pre-tender planning stage. It is therefore very important to ensure that the planning function at the pre-tender planning stage takes place not only at the higher more abstract project level but also at more-detailed levels, especially in 'areas of uncertainty', because it is these areas of uncertainty that can potentially undermine higher-level solutions.

7 In reality it is very difficult to measure the use of space and time in this way. Judgment as to the degree of compactness of a construction process with respect time and space will be relative.

Figure 2.15 The depth and scope of the various planning stages. (Adapted from Neale & Neale, 1989).

During construction very much more detailed shorter-term plans will be produced in order to give even more insight into exactly how sections of the total works can be best carried out. These 'during-construction' plans can range from anything between a three-monthly schedule to an hourly schedule (in extreme circumstances), obviously depending on the needs of site personnel and the difficulty with which its work is co-ordinated.

2.72 The Documents of the Construction Plan

Laufer et al (1993) conducted interviews with personnel from eight leading American construction companies and were able to state:

Nine functional construction plans (areas of planning) were defined in the present study and validated in the first two research phases. They are categorised under four families:

1. Base plan: engineering and method (e.g. main construction technology, systems, and components); and organization and contract (e.g. organizational structure, staffing, contractual strategies, selecting subContractors).
2. Forecast and control: schedule (both short-term action plan and long-term forecasting); and cost and cash flow.
3. Technology: major equipment; site layout and logistics; and work methods.
4. Resources: manpower allocation; and materials allocation.

Vastert (1993) whilst not naming the various sub-plans that go to make up a construction plan detailed the aspects that a complete construction plan must deal with as follows:

<table>
<thead>
<tr>
<th>CONSTRUCTION PLAN</th>
<th>Time</th>
<th>Place</th>
<th>Cost</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant &amp; Equipment</td>
<td>SUB-PLANS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.16 The framework of a construction plan. (Vastert, 1993).
Whilst construction sub-plans have not been named in Vastert's model it would nevertheless be relatively straightforward to fill in the framework with the most appropriate positioning of the list of plans that Laufer et al (1993) suggest. Of course, there would be a certain amount of overlap in the plans because construction plans contain elements of information that integrate them strongly with one another. For example, a simple bar chart programme deals with aspects of time and place, as well as with aspects of labour and plant & equipment. Another document 'Site & Layout' also covers the aspects of plant & equipment and place but conveys its information in a different form. And so whilst one can to a certain degree unravel the different planning documents into logically separate entities there nevertheless remain a great deal of common features of information that integrate these separate construction planning documents into a cohesive whole.

Of course, the names of construction plans are not only influenced by the size and nature of the project they are also clearly influenced by the nature of an indigenous construction industry. More important, therefore, than stating exactly how many planning documents exist and what their names are, is to ensure that a construction plan properly deals with the aspects mentioned in Vastert's model and that the plans clearly and cohesively convey the way in which problems of construction process should be dealt with.

2.73 The Cut-off point in the Development of Plans

As is graphically identified by Neale & Neale (1989) (see Figure 2.17) there is a point at which the cost of continuing to commit planning resources to a planning problem begin to outweigh the potential benefits that can be gained by those planning resources. This is true of planning resources at all levels of planning and is greatly influenced by the degree of uncertainty that casts its shadow over certain aspects of the physical construction process of the project. When a degree of satisfaction has been achieved in the reliability of a developed plan no extra resources will be committed to developing the plan further. Lichtenberg (1974) in his thesis on the subject of reducing uncertainty in planning exercises stated the following:

"The question arises why should we not detail the plans as far as possible?"

At first sight it seem obvious to detail as far as possible. A plan with a low degree of detailing is generally most uncertain and tends to hide the actual problems and difficulties for the planner and others concerned. In short, it is untrustworthy and may even be most unrealistic. These decisive shortcomings are diminished along with an increased degree of detailing which thus offers an advantage.

The above reason is twofold. (1) The above marginal increased advantage fades out at a rather early stage because of individual unavoidable sources of uncertainty, such as the future conditions of weather, price level, etc., and (2) a set of potential disadvantages exists which augments progressively with an increased detailing.

Examples of such disadvantages are (1) the cost and time demand of the planning process itself. This will also tend to prevent the establishing of alternative and possible better solutions, (2) an increased risk of undetected errors, (3) an increased lack of professional knowledge concerned with each particular detail among planners, and (4) practical and psychological problems of current re-planning as well as feedback.

In short, a certain degree of detailing exists above which further detailing would create more disadvantages than advantages. The increased dynamics of modern society and construction industry causes a growing amount of 'inevitable uncertainty'. This, again, tends to reduce the above limit of justified detailing. This is why we should not detail the plan as far as possible."

![Figure 2.17 The relationship between planning costs and total costs.](image)

The aim of any individual engaged in the planning function, no matter what his first function within a firm should aim to direct his efforts so that he stops planning at the x-point on the above graph, the point where direct costs plus planning costs are at their minimum. Of course, in reality, it is impossible to be able to identify what is in fact a theoretically ideal position and one which is far from directly measurable. As Ferguson (1977) states with regard design problems, 'No bell rings when the optimum design comes to mind'. And who is to say, of course, that if a planner had continued to work on a problem that he would not have hit upon a solution to a particular problem or set of problems that would ensure benefits in production efficiency that far outweighed the costs of employed planning resources.

In reality, of course, it is experience that guides firms and individuals as to how great an investment should be made in the planning function associated with a particular type of construction project or an aspect of the total planning problem. In the case of straightforward housing projects the 'saturation' planning point would ordinarily be expected to be at a lower proportion of total project costs than a more unique and complicated hospital complex, for example.

2.74 Construction Planning - Solo or Team Activity?

Laufer et al (1993,1994) conducted a comprehensive research programme that investigated the nature of construction planning. Part of their results graphically show (see Figure 2.18) that construction planning is a team effort and that different members within the team take on differing degrees of responsibility at different stages in the construction planning process.

They stated that programming:

'...as important and as central as it is, is only one of the many construction areas. Our study found that the accumulative effort invested in the preparation of other functional plans was about five times greater than that invested in programming.'

The programme planner who one normally associates with the planning function within construction, as he is charged with producing a time-related schedule, was therefore found in the U.S.A. to be very much less involved in the construction planning process than is commonly believed to be the case. The evidence suggested instead that the production of a
time-related programme is more a book-keeping function where decisions that have been
taken on a higher and more strategic level are simply worked-up.

Schedule (programme)
(A) the pre-tender stage and (B) the pre-construction stage. Source Laufer (1994).

Figure 2.18 The involvement of various construction professionals in the planning function at
(A) the pre-tender stage and (B) the pre-construction stage. Source Laufer (1994).

Laufer et al (1994) showed that meetings are not only important in terms of the management
of construction projects but that they also play a central role in the planning function.

They concluded:
1. Construction Planning is not a one-time activity. While considerable planning effort is invested prior to
   the beginning of construction, its impact being dominant, it is indeed a process, which continues
   throughout the project life.
2. The process of planning during construction is complex and involves many participants. Needed
   information is not found in one place, nor with one functionary. Rather, it rests with all involved parties.
3. Various types of short-term (as well as mid-term) meetings, addressing the entire spectrum of planning
   issues, are the primary mode of planning during construction.

2.75 Construction Planning Tools
A construction planner has at his disposal a number of ‘tools’ that can be applied in order to
help him process information. Each tool has a specific function and is applied in order to
tackle a particular aspect of the construction planning problem. However, having said that
they tackle specific problems the fact remains that they are far from being capable of tackling
comprehensive problems or anything like the full spectrum of problems that a construction
planner has to deal with. But around the globe at various universities researchers are
industriously trying to broaden and deepen the tool-kit base with very much more powerful
instruments. But first the more straightforward tools.

The main tools are the bar chart, the line-of-balance, the linear programme and network analysis. There
are other tools, such as physical models in two and three dimensions, and computer models. Neale &

These techniques fall broadly into the following categories:
(i) Bar or Gantt charts and location-time charts.
(ii) Network analysis - Critical path analysis (CPA)

The above techniques are essentially geared to dealing with the aspects of time, cost and
logical sequence. The relationship between these three being straightforward and lending
itself perfectly, once having been ‘translated’ by a human operator from demand information,
to being solved arithmetically by computer a number of programmes exist that can easily
solve problems of this nature. However, being able to identify the logic of activities in a
construction project, the likely duration of those activities and their cost is only a small part of
the construction planning problem. The fact remains that where a ‘human translator’ makes
mistakes in converting information to be found in contract drawings, etc., into either the logic
of the process or the cost or capacity of technical systems, the computer programme accepts
these mistakes without question like the obedient servant that it is and develops an incorrect
programme.

Computerised programmes are undoubtedly popular in construction generally. A survey
(Aouad & Price, 1993) showed that computerised Critical Path Methods were used by 88 %
and 100 % respectively of construction firms in the UK and US. But, they are not without
their critics:

They have proven effective for certain types of projects. However, these techniques have many
limitations. They are usually carried out in an unstructured form with considerable reliance on the
planner’s judgement, imagination and intuition. They require abstract visualization of the perceived
configurations, characteristics, and spatial relationships among various components of the project.
Because of limitations in the current planning techniques, there is a need for the development of new

This brings us to what might prove to be the ‘tools of the future’!

2.76 Knowledge-Based Planning Systems
An expert system has been described as:

... an intelligent computer program that uses knowledge and inference procedures to solve problems that
are difficult enough to require significant human expertise for their solution. Knowledge necessary to
perform at such a level plus the inference procedures used, can be thought of as a model of the expertise
of the best practitioners in the field. Barr & Feigenbaum (1981)

The knowledge of an expert system consists of facts and heuristics. The ‘facts’ constitute a body of
information that is widely shared, publicly available, and generally agreed upon by experts in a field.
The ‘heuristics’ are mostly private, little-discussed rules of good judgement (rules of plausible
reasoning, rules of good guessing) that characterize expert-level decision making in the field. The
performance level of an expert system is primarily a function of the size and the quality of a knowledge

Knowledge engineers are concerned with identifying the specific knowledge that an expert
uses in solving a problem. Initially, the knowledge engineer studies a human expert and
determines what facts and rules-of-thumb the expert employs. Then the knowledge engineer
determines the inference strategy that the expert uses in an actual problem-solving situation.
Finally, the knowledge engineer develops a system that uses similar knowledge and inference
strategies to simulate the expert’s behaviour.
Since the mid 1980's a tremendous effort has been made to develop expert systems that can deal with various construction planning problems. For example, Gray (1983) developed one that could work out the time and cost implications of different types of superstructures in high-rise buildings, Tommelein (1987) developed one that could update the layout of temporary facilities on construction sites, Gray (1985) developed one that could select possible crane locations together with their size, type and cost, and Brandon (1993) developed one that looked at optimum project durations and profitability. However, despite expert systems having been written about with great enthusiasm in the 1980's their impact on the construction industry, and industry in general, has not been as explosive as was predicted in that period. Clearly therefore expert systems have some way to go yet before we can really classify them as being part of the everyday toolkit of the planner.

2.8 CONCLUSION
A construction planning problem is an entirely logical problem based on, amongst others, the laws of physics, production and economics. Implicit in this statement is the notion that for any particular project there is a single cheapest solution given a particular state of technology and its associated costs. In theory, at least, a construction programme is measured in terms of total cost and total duration, and one construction programme can therefore be compared with another in terms of these two criteria.

In a Utopian situation where all costs were known, where the output of units of capacity could be predicted under all circumstances, where units of capacity were in abundant supply and did not have to be shared between different projects and in which weather conditions could also be accurately predicted, a computer programme could be written that took all the necessary factors into consideration and generated many alternative construction programmes, compared them and established the cheapest and quickest solutions for any particular project. The computer programme would be able to use a large database of information that included such information as the location of all units of capacity, their costs of transport, their associated costs of setting-up on site and dismantling, their energy requirements, weight, spatial requirements, output, and so on, and be able to balance sub-objectives such as maximum learning curve, minimum hire costs, minimum site and supervision costs, etc., and establish the units of capacity that would be required, the order in which they should operate, their duration of operation, etc. In this Utopian world workers would still be able to make learning curve improvements but they would not make mistakes and would not forget anything. In fact in this world everything would be so predictable that plans could be made months in advance stating exactly the task that any particular unit of capacity would be engaged in at any particular time of any working day. It would not necessarily mean that all units of capacity would be working usefully for 100% of the time but it would mean that the cost of non-productive time would have been calculated by the computer programme and set off against cost benefits made at other costs centres so that a minimum total cost would have been arrived at.

Well, of course, we do not live in Utopia and there are certain factors that we cannot predict with total accuracy and there is no giant database in which all relevant knowledge is stored but at the heart of the construction planning problem remains a problem in which technical performances have to be met and which despite the uncertainties of the weather, the building market and the level of human fallibility, units of capacity are still subject to the dynamics that effect the units of capacity in Utopia. In other words units of capacity will have to be employed in a particular order, levels of capacity will have to be chosen that take into account the size of the work-front, available space, the rate at which materials harden, and play-offs will have to be made between maximising learning curve and minimising production time, minimising the indirect costs of units of capacity and minimising the indirect costs of the site as a whole, etc., so that a solution is developed that minimises total cost, regardless of the contract period. Despite the uncertainties therefore the goal of efficient production remains the driving dynamic behind construction planning. And what this means in reality therefore is that it will not be possible to make decisions on the hair-fine basis of Utopia that was perhaps implied in this chapter but that decisions will be made on the basis of very much cruder and coarser units of measurement. Resulting construction programmes will therefore not be optimised solutions but will be solutions in which its devisers will have a certain degree of confidence. A planner cannot plan every last hour and in fact Lichtenberg (1974) clearly stated, "In short, a certain degree of detailing exists above which further detailing would create more disadvantages than advantages". A planner therefore has to develop a framework in which a certain level of detail has been explored but, unfortunately, there is no formula that states how deep the ideal level of detail a plan should be taken to at various stages before or during the construction process. It was also quite clear from the research of Laufer et al (1994) that planning does not stop at some point just before the start of work on site but continues throughout the process and involves the input of many parties. Part of the reason for this of course is that a great deal of the work on site is carried out by sub-contractors and so at the initial planning stage a planner will not concern himself with the fine details of how sub-contractors will carry out their work. Certainly the planner will have had to have considered sub-contractor needs, especially where facilities will have to be shared with other units of capacity, but will be more inclined to consider their work as blocks or windows in the main construction programme in which they themselves will have to ensure that they can carry out their work. The danger in this of course is that once construction is under way the sub-contractor's needs will transpire to be more demanding than was originally planned for. But that danger will not only be confined to the work of sub-contractors of course.

In some senses it seems an almost unsatisfactory conclusion that a construction programme cannot be optimised by some all-encompassing formula or set of formulas, and in other senses quite heartening that human problem solvers continue to be better than computers at dealing with large and complex problems that involve large amounts of uncertainty. But, of course, only time will tell as to how successful knowledge engineers will be in changing that situation!
3. Problems and Problem Solvers

3.1 INTRODUCTION

Problems present themselves in all shapes and sizes, some of which we can solve automatically, others of which we need to consciously grapple with (automatic versus controlled). The question of the order in which a person should put on eleven items of clothing is one that presents that person with a choice of over 39 million different orders, of which only 5000 or so are sensible (De Bono, 1990). Simon (1990) stated:

It is not a trivial detail but a fundamental limit upon computation that human short-term memory can hold only a half dozen chunks, that an act of recognition takes nearly a second, and the simplest human reactions are measured in tens of hundreds of milliseconds rather than microseconds or picoseconds.

Given the fact that there are very real limits to our capacity for solving various types of problems as well as the fact that real-world problems can be extremely computationally complex, this chapter examines some of the aspects that characterise problems, and some of the theories that explain how we solve them.

3.2 WELL AND ILL-STRUCTURED PROBLEMS

Construction planning problems meet four of the six criteria that Simon (1973) listed as characterising well-structured problems (see the following page for details), although Simon expressly stated that a formal definition could not be given to well-structured and ill-structured problems.

Well-structured problems are those types of problems that can be solved by following a sequence of computational steps (an algorithm) and arriving at the single correct answer. Ill-structured problems, on the other hand, are those that can be arrived at by a multitude of different paths, can be measured in terms of multiple objectives which are valued by more than one person, and therefore cannot be categorised in terms of being correct or incorrect but in terms of how well or not they collectively meet the objectives set out for them.

In dealing with problems of an ill-structured nature where the path between problem state and goal state is not known individuals are said to use rules of thumb, or heuristics, that help them develop such paths. Simon (1990) describes heuristics as methods that assist the problem solver in searching the solution space, still requiring the individual to carry out a good deal of search but nevertheless reducing the number of outcomes that need to be examined. The more structured the task domain the stronger the heuristics will be in guiding search to the goal, as in systematic algorithms.

One weak method is satisficing - using experience to construct an expectation of how good a solution we might reasonably achieve, and halting search as soon as a solution is reached that meets the expectation.

…….. Another weak method is means-ends analysis - noting differences between the current situation and the desired goal situation, and retrieving form memory operators that, experience has taught us, remove differences of these kinds. (Simon, 1990)
Construction planning problems display elements of both well and ill-structured problems; for example aspects that characterise them as being well-structured are (1) there are definite criteria for measuring the values of solutions i.e. in terms of time and cost, (3) the initial state and the goal state of a problem, as well as legal moves, can be clearly represented individually (4) knowledge that the problem solver can acquire can be represented in a problem space, and (5) states and operators follow the laws of nature. However, the aspects that characterise construction planning problems as being ill-structured include (2) the initial state, goal state and all intermediate states cannot all be considered at once in trying to develop a solution, and (6) it is questionable that “the basic processes postulated require only practicable amounts of computation”.

Construction planning problems are in fact made up of a great number of mini-problems of different proportions, the precise order in which they can be tackled cannot be determined beforehand, and the information on which decisions are based can never be available in its entirety at the start of the process. Often there is a long period of delay between the moment a decision is taken and the ensuing feedback from that decision (sometimes months), and the output (the construction plan) must be able to function independently of the construction planner. Taken at project level we can consider construction planning an example of an ill-structured problem, but not an extreme example. Taken at a more detailed level where the problems become narrower in scope and timespan they can be found to be more well-structured.

3.3 MEMORY

3.31 Short-Term Memory

When information first enters the human system it is registered in sensory memories. These sensory memories include an iconic memory for visual information and an echoic memory for auditory information. Sensory memories can store a great deal of information but only for brief periods of time. Attention is a very limited mental resource that can be allocated to only a few cognitive processes at a time. The more frequently that processes have been practised the less attention they require. Eventually they can be performed without interfering with other cognitive processes. Short-term memory is categorised by memory structures that are on a high level of activation but of low strength, strength being the function of long-term durability of our memories. In other words we can gain fast access to memories that are in a highly activated state but as their level of activation fades so does the speed with which we can recall them. Anderson (1990) likens the effort made in maintaining information in short-term memory to ‘the circus act that involves spinning plates on a reed’. Just as the circus performer is limited in the number of plates he can keep spinning at any one time because he has to keep going back to re-spin plates that are in danger of dropping off, so too is our short-term memory limited in the number of items that can be maintained in an activated state at any one point in time. Baddeley (1986) suggests that there is an ‘articulatory loop’ in which about one and one-third of a second’s worth of verbal material can be held. And similarly, just as there is an articulatory loop, Baddeley also suggests that there is a ‘visuo-spatial sketchpad’ on which images can be briefly held.

Typically we can hold about seven items (plus or minus two) in our short-term memory, whether it be seven numbers or seven letters or seven ‘chunks’ of information (Miller, 1956); letters, for example can be chunked into words which make it very much easier to remember the letters. Remembering the seven letters ‘h.o.s.t.i.l. e.’ is very much easier than remembering the letters ‘g.x.w.p.b.f.t.’ for example.

3.32 The Structure of Long-Term Memory

We are said to store information in our long term memories in schemas. A schema can be likened to an index system where particular more detailed pieces of information relating to the subject can be found. For example, in the schema ‘house’ could be found items of information such as that ‘it is a dwelling’, that ‘it is probably made of brick or timber’, and that ‘it will have a roof’, ‘windows’, ‘kitchen’, ‘front door’, etc. However, whilst schemas present us with a sort of ‘identikit’ of attributes that belong to a ‘house’ they also allow us to take on board any exceptions to the rule. For example, if a house is to be built underground we can infer that it will have no windows, and if it is to be built at high altitude we can infer that it will need to be well insulated and probably hermetically sealed. Schemas therefore allow us to make inferences and to fill in missing details of information even when large chunks of information might be missing.

Schemas are said to be made up of three types of information, namely linear orderings, propositions and spatial images. A simple example of a linear ordering is the alphabet where it is committed to memory as a particular sequence. Ask someone to recite the alphabet backwards and they will have great difficulty in doing so, having to use a sort of repetition sequence of forwards and backwards searching. Research has shown that the greater the distance between two items in a list the shorter the time it takes a person to recognise which appears first in the list. A proposition is a concept that has been developed in the field of linguistics and logic; it is the smallest unit about which it makes sense to make the judgement that it is true or not. ‘Cows eat grass’ and ‘grass is green’ are two examples of simple propositions, however, most sentences will be complex in that they are made up of a great number of simple propositions, which themselves might rest on a complex of assumptions which can in fact make it very awkward to establish whether or not the sentence is true.

It is not just objects and concepts that can be encoded by schemas, it is also possible to represent events as schemas. Schank & Abelson (1977) refer to these process or event schemas as ‘scripts’. In other words we can encode our knowledge about stereotypic events, such as going to a restaurant, according to the individual phases, i.e. ‘sitting at a table’, ‘ordering a meal’, ‘eating the meal’, ‘paying’, and ‘leaving’. Each of these sub-activities in turn can be divided into its component phases. And just as with object schemas there are hierarchies of scripts. ‘Building an office block’ can be divided into ‘clearing the site’, ‘building the foundations’, ‘building the superstructure’, ‘fitting the services’, and ‘completing the finishings’. Any one of those phases in turn can be divided into a number of different phases. For example, ‘building the foundations’ can be divided into ‘setting out the works’, ‘digging the foundation trenches’, ‘fixing the reinforcement’, ‘pouring the concrete’,

1 The numbering here follows that of Simon 1973.
2 Criteria selected from Goel & Pirolli’s (1989) list of features of the Design Task Environment. However, a construction plan can never become as detailed a document as an architectural design before construction activities take place on site because, as was established by Lauffer, Shapira, Cohenca-Zall & Howell (1993) a great deal of construction planning has to take place on a short term basis in order to deal with constraints that cannot be predicted long in advance.
3 Whilst construction planning problems can be considered to be relatively ill-structured problems they are clearly not as ill-structured as most architectural design problems are, for example. Generally speaking the goal state of the architectural design process is very much less well described than the goal state of a construction planning process.
and so forth. Clearly construction experts will be in possession of a very great number of such
scripts and will be able to recite the order in which a standard house can be built, for example,
as easily as a child can recite the 'a, b, c'\textsuperscript{11}. However, as Brewer and Treyen's research
showed (1981) schemas can sometimes be so dominating that a subject will answer questions
about specific situations according to the more general model of a situation rather than the
situation itself. For example, when subjects were asked to recall where the books could be
found in the office in which they had just been asked to wait, most of them said that they were
on the shelves; in fact there were no books in the office at all!

Models are simplified representations of real or abstract phenomena. We can use them to
describe the underlying relationships and processes of various systems, theories or
phenomena with a view to better understanding, or with a view to solving problems that are
presented in the original setting. In construction planning the two fundamental physical
structures in which solutions must be found are time and space. Solutions where types and
levels of capacity are chosen will need to be developed in one or both of these frameworks;
ultimately in both of them, of course. Because of this, solutions will be dealt with that either
are recorded in terms of time i.e. a simple bar chart or a precedence diagram, or in terms of
space i.e. on a scaled drawing or by utilising a scaled model.

3.4 THE USE OF MODELS IN CONSTRUCTION PLANNING

Models are simplified representations of real or abstract phenomena. We can use them to
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are recorded in terms of time i.e. a simple bar chart or a precedence diagram, or in terms of
space i.e. on a scaled drawing or by utilising a scaled model.

Short-term memory being capable of holding as few chunks of information as it does, and
construction planning problems requiring as many parameters to be considered as they do in
order to solve them, it is a natural consequence that construction planners will make frequent

\textsuperscript{11} It was in fact witnessed in the first round of protocol experiments that a construction expert could write down
all the activities that would need to take place to build the design in question after having spent very little time
examining the design information.
use of external memory, in the form of symbols on paper, or in terms of three-dimensional models. By definition whatever is recorded in external memory will be part of a model where some relationship or process has been transferred to a setting where it can be more conveniently studied and thus can be held stable in short-term memory in an activated state. The jottings of a construction planner in developing a construction plan can be likened to the sketch drawings of an architect in drawing up a detailed design; the acts of jotting and sketching help the construction planner understand and explore the scope of the task environment, enabling him to cross-check newly developed solutions with existing solutions as well as their ability to deal with constraints that had not yet been considered.

The output of a construction planning process is itself a model, just as architectural design information is a model. In the case of the latter the model is of a real-world artefact that does not yet exist, and in the case of the former the model is of real-world activities that have not yet taken place. However, models being abstractions of other situations it necessarily follows that their usefulness is subject to constraints. As has already been stated the two fundamental physical dimensions that give structure to a construction programme are time and space but both aspects cannot be completely represented on paper, for example, in the same model. Models that construction planners use will either be of the spatial variety or the temporal variety with translation from one model to the other being carried out by the planner himself. For example the time aspect of a construction programme can be represented by a simple bar chart in which the description of activities on one axis are accompanied by time bars on the other axis. The model of the construction process can be straightforwardly developed by lengthening or shortening time bars and by adding or cutting-out various activities. Likewise a spatial model of a construction process can be represented by a two or three-dimensional drawing or by a physical model of a particular stage. However, the spatial model will represent a snapshot of the process, a fixed moment in time where the building will be in a particular state of completion. The drawing or the physical model may be very useful in helping to resolve a spatial problem that presents itself at a particular state of completion but cannot at the same time represent other states of completion. In order to do that the model would have to be either added to or deducted from, and then it would represent another snapshot in time.

The only models in which both aspects 'appear' to be seen at the same time would be in animated films of the construction process, whether they be generated by computer or physically filmed one frame at a time like a cartoon. But as models they would be very inflexible and would not allow the problem solver to easily generate alternative solutions. Alternative solutions could only be developed by going back to a particular state of completion and developing an alternative scenario; film being unlike the medium paper, where solutions can be quickly rubbed out and new solutions drawn in, it would take very much longer to simulate alternative solutions. Such a generated film of the process might prove a very useful medium in terms of communicating to others the sequence of operations once all construction problems had been considered, but would be far from a useful and flexible tool that could be used in assisting short-term memory explore alternative construction solutions at intermediate stages of the construction planning process.

Once developed, of course, the construction process model takes on a life of its own as a tool of coordination and a record of decision making. It can be developed into a relatively detailed document, or set of documents, that can be tested by other professionals in terms of their own knowledge and experience. Tests are too numerous to mention but might include, for example, provision for dealing with higher than normal rainfall and limited daylight and its ability to deal with delays in supplies, etc. And, of course, where it is felt necessary the model could be suitably re-adjusted to meet constraints that might not yet have been considered, or were thought of more or less severely by the original developer of the model than by the person or persons testing the model.

Whichever model system is applied, whether it be a simple bar chart, a flow diagram, two-dimensional drawing, physical model or whatever, it will not only be a record of decision-making it will also be an aid to short-term memory in the development of solutions, but it will be an aid with very clear limitations; limitations that can only be overcome by the imagination and intelligence of the construction planner himself.

3.5 VISUAL THINKING

We often think about a particular event in the past or of an object that is not in view and refer to this type of thought as 'seeing with the mind's eye'. In the last 25 years there has been a great deal of research carried out on what is typically referred to as mental imaging, especially the mental processes that can be performed on spatial images. As has already been stated Baddeley (1986) suggests that there is a 'visuospatial sketchpad' on which images can also be briefly held in the same way as the articulatory loop. Shepard & Metzler (1971) found in experiments, for example, that where subjects are required to compare two pictures of three-dimensional shapes to see if they are identical that they rotate the object in the first picture three-dimensionally in their minds. The greater the angle of disparity between the two objects the longer subjects take to complete the rotation, thus indicating that whatever mental process is taking place it appears to be analogous to physical rotation. Moyer (1973) found that when a subject is asked to decide which of a pair of objects is the greater the subject engages in a process similar to that of comparing two physically presented objects, it taking longer for a subject to decide on which is greater the smaller the difference between the two objects.

Visual thinking is not an aspect that was given a great deal of attention in the earlier days of design thinking. However, since those earlier days there are a number who have clearly expressed the importance to which they attach this special form of problem solving ability. Ferguson (1994), for example states 'The gratifying response to my article in Science ('The Mind's Eye: Non-verbal Thought in Technology,' August 26, 1977) convinced me that engineering is founded on non-verbal thought.' Ullman (1993) also states the importance that he attaches to visual thinking but suggests that there can be a large difference in an individual's ability to think visually but that 'the ability to manipulate complex images of mechanical devices can be improved with practice'. When asked in interviews construction experts acknowledged the importance of visual thinking in developing construction solutions (Stockings, 1994). In research carried out by Schaefer (1991) as to the importance of knowledge in construction all respondents spoke of the need to have experienced the construction process a number of times in order to understand which hidden cost factors play a role in the realisation of building projects. One of the respondents spoke of experience as "learning to see the costs". (Italics by Schaefer).

Downs & Stea (1977) have researched extensively an area of visual thinking that they refer to as cognitive mapping and cognitive maps. These are abstractions 'covering those cognitive or mental abilities that enable us to collect, organise, store, recall, and manipulate information about the spatial environment'. These maps are in everyday use helping us to solve such problems as deciding on the best route to take in a number of shopping errands, how we can
best travel from one point to another, and where the most likely whereabouts of a sought-after site is. We can speculate that cognitive mapping of a construction site is an invaluable mental tool that assists construction planners deal with many of the spatial problems of construction processes, because a fundamentally important aspect of construction planning decision making is being aware of how large the work-front is at any particular time, how much space there is available for units of capacity, and knowing what units of machinery, manpower and equipment will already be present in a given unit of space. In fact the ability to mentally simulate the various states of completion is probably the most important mental skill necessary for construction planning because, as Newell & Simon (1972) proposed, in order that a person can solve a problem, that person needs to create a problem space in memory in which the initial state, goal state and the necessary operators that can transform the initial state into the goal state can be held. In a construction process those states of completion are different physical states and the operators that can transform those states are units of capacity, and although it is not possible to directly experience an individual's problem space we can speculate that it is very probably a highly visual one and that an individual will only be able to find a solution to a construction planning problem by its visualisation.

3.6 EXPERTS

Problem solving knowledge can be formalised as a group of production rules that can be applied under particular sets of circumstances. These production rules take on the form “If...then...” or “Condition $\Rightarrow$ Action (C $\Rightarrow$ A)”. A simple example would be, If bricks have been specified by the architect then bricklayers will be required to lay them. Some ‘If...then...’ production rules will be very direct in terms of linking a solution to a set of circumstances while others will be very much more indirect. For example, If a building is high-rise there will need to be some sort of a vertical transport system. However, the fact that the building is high-rise will not link it directly to a particular solution, there being a number of other important criteria upon which such a decision must be made as well. Construction planners who have a great deal of experience in making particular types of decisions will have a command over much more sophisticated rule sets than novices, for example, allowing them to generate more alternative solutions than non-experts (Schaefer, 1991). Simon (1990) stated:

We now know that experts make extensive use of recognition processes, based on stored knowledge, to handle their everyday tasks. This recognition capability, bases (by rough estimate) on 50,000 or more stored cues and associated knowledge, allow them to solve many problems “intuitively” — that is, in a few seconds, and without conscious analysis.

Experts have also been found to enjoy a superior short-term memory function for the field in which they are expert. De Groot (1965) carried out experiments with chess masters who were given five seconds to look at a chess board with the pieces in various combinations. It was found that these experts could reconstruct the positions of up to twenty pieces whilst non-experts could only reconstruct four or five pieces. However, it was found that when pieces were placed in positions that did not comply with the rules of the game the experts were just as unlikely as novices to accurately recall where the various pieces had been placed. Simon (1974) carried out the same experiments with experts and hypothesised that experts can chunk individual positions into mini-groups, experts having been found to pause slightly between each set of chunked pieces when given the task of recalling their original positions. But not only is the memory function of experts different from non-experts, their perception also seems to be better for material within their domain of expertise (De Groot & Gobet, 1996).

3.7 DESIGN METHODS

In order to improve the efficiency with which complex problems were dealt with in the field of design, particularly in architectural design, an attempt was made by practitioners and researchers to develop so-called ‘design methods’ that would allow designers to improve the way in which they dealt with the sometimes chaos-of-information that they were confronted with and therefore allow them to make better decisions. Starting in the 1960’s a tremendous amount of effort was put into the quest for the design method but with very mixed opinions about how successful researchers had been in finding it. Jones (1970), for example, listed thirty-five so-called design methods. These included ‘literature searching’ and ‘interviewing users’, for example, but the question remains the extent to which these methods form a clear and distinctive group. For example, Cross (1984) stated:

It seems that some of the new methods can become over-formalised or can be merely fancy names for old, common-sense techniques. They can also appear to be too systematic to be useful in the rather messy and often unhurried world of the design office. For these kinds of reasons many designers are still mistrustful of the whole idea of ‘design methods’.

However, while it would seem that there is a great deal of agreement that design methods can sometimes help problem solvers in an ill-structured problem solving situation by helping to gather information more effectively and search more systematically for ideas, for example, there are no researchers or practitioners who claim that these design methods allow them to completely solve problems or even make very straightforward decision making processes that are basically very complex. Instead design methods should perhaps be thought of as strategies or tools in a cognitive toolkit that help the problem solver concentrate his efforts in dealing with the complex of problems as rationally as possible, particularly where he is working in a team situation and where the decision making process needs to be as structured, open and as clear as possible, in order to get the most from the team. De Bono’s (1972) six ‘thinking hats’ can also be thought of as cognitive tools because they help the problem solver to concentrate on generating new ideas, for example, without allowing himself to be instantly critical of those ideas and therefore prevent him from cutting off a potential solution before it has been given the opportunity of proper development; later, applying the tools of critical thinking in order to test whether or not the solution can properly satisfy all demands and constraints.

Unlike architectural designers, for example, construction professionals have not developed a toolkit of design methods but clearly some of the methods that are relevant to architectural design such as ‘stating objectives’, ‘brainstorming’ and ‘checklists’ (Jones, 1970), for example, can be equally well used by construction planners as by architects. However, due to the fact that architectural design problems are generally less well-structured than construction planning problems, one would expect more use to be made of these ‘weaker’ methods by architects in tackling design problems than one would by construction planners in tackling

\[12\] Newell (1969) drew a link between the structure of the problem space and the method for solving problems in that space. In well-structured problem spaces stronger methods of search could be applied but in ill-structured problem spaces only ‘weak’ methods could be applied.
planning problems. In construction planning most ‘methods’ are activity-sequence-based (such as critical path networks) and sometimes include various forms of statistical simulation of the duration of activities (such as Monte Carlo simulation).

3.8 CONCLUSION

Taken at project level a construction planning problem can be regarded as a ‘relatively’ ill-structured problem. When divided into smaller and more digestible chunks construction problems become more clearly structured, but construction planning problems are not problems that can be split into totally separate sub-problems; there always remains a web of logic that spreads out with varying degrees of influence from one sub-problem to the next. Decisions regarding certain aspects of the construction process, therefore, can rarely if ever be made without regard for other aspects of the construction process.

A construction site is a three-dimensional working space in which a number of different activities must take place both sequentially and parallel to one another. The three-dimensional ‘landscape’ of a building site changes literally on a daily basis as it moves from one state of completion to the next. It is, of course, impossible to examine any individual’s problem space but we can speculate that where problems of a spatial nature exist an individual will use predominantly his visual thinking capacities. And alternatively, where the spatial aspect of a problem plays a lesser role and the time aspect a more dominant role, problems will lend themselves more easily to be solved in natural language (consider, for example, well rehearsed lists of activities). But only where the spatial dimension is first understood can the time dimension be developed, because the time dimension is dependent on the level and output of capacity that can be applied to a particular state (represented by the size of the work front, presence of equipment and machinery, and available working space). The construction planner therefore needs to have the ability to mentally visualise more or less every aspect of every stage of the construction process in order to test whether or not construction activities can take place alongside one another in a state of harmony and balance. However, construction experts, having very rich memory schemas of past construction processes, it seems likely that they will not have to actually go through the process of visualising all aspects of the total process because they will be able to recognise, by comparison with knowledge stored in long-term memory of past processes, where well-worn ‘chunked’ solutions can be applied, as well as where they will need to develop novel solutions.

Because a construction project goes through a number of part-completed states, and because a construction planner needs to apply operators to transform one state into the next, it is a logical consequence that construction planners will probably tend to deal with the activities that first take place on site. The reason for this being that the planner can only make proper allowance for later states when he is fully aware of the operators that would need to be applied in earlier states, such as temporary works. Only where a planner is confident that he knows what the starting state of a later state will entail will it be efficient to start planning the construction process from a later state, for example, where the structure is familiar to him but where the external envelope and internal finishings present novel problems.

Due to the limited number of elements that can be held in short-term memory at any particular time in an activated state a complex problem will necessarily have to be broken down into manageable chunks and dealt with sequentially. Where there is a great number of decisions to be made in an ill-structured environment there is no simple single order in which those decisions can be made. Construction planning decisions cannot be made, therefore, according to a pre-set linear sequence. Because construction planning is such a complex decision making process a whole host of tentative values based on experience will probably be assumed in order to explore more fully various solutions. With the solution of each sub-problem the construction activities model will become gradually more detailed. As more sub-solutions become developed more insight will be gained into how they mutually interact whereupon it might become necessary to adjust decisions that were made earlier. This cyclical process will continue until a sufficient degree of harmony has been achieved between sub-solutions and satisfaction has been achieved with the construction plan’s overall ability to deal with whichever tests its originator or commentators apply to it.

Due to the limit of short-term memory it can be expected that the use of external memory will take place in the form of drawings, notes and possibly even physical models in order that the temporal and spatial elements of the problem can be more completely examined. So-called ‘design methods’ could play a role in helping the construction planner deal with some of the problems that he is faced with, even if the design method were simply a checklist of aspects that help to remind the construction planner of all aspects that need to be taken into consideration; the objective, of course, would be to make the construction planning process more linear and less circular, in other words to help ensure that critical sub-problems are ‘activated’ at an earlier stage in the process so that they can be properly taken account of and not at a later stage when their discovery might require the adjustment or even abandonment of earlier decisions.

13 Although architectural design problems are dealt with here as though they were ill-structured problems there are a number of practitioners and researchers, such as Akin (1986) and Van Bakel (1992), who believe that design problems are not simply ill-structured problems but that they do in fact form a separate group in themselves.

14 The degree to which the spatial dimension plays a role is partly a function of an individual’s experience. Where an individual has dealt with problems of a similar nature in the past he will ‘understand’ the spatial dimension and thus be able to more automatically choose a level of capacity that can be applied to that space.
4. Protocol Analysis In Construction Planning Research

4.1 INTRODUCTION

Chapter Four describes the protocol analysis experiment that was conducted at an earlier stage in this research in order to learn more about the order in which individual construction planners go about dealing with some of the problems that an architectural design presents them with. Three construction experts were presented with a project that they had never seen before and were asked to ‘think aloud’ while they were dealing with the various problems it posed. Everything that they said was tape-recorded and then typed up so that it could be analysed. As had been well documented in the works of Simon (1974) and Anderson (1990), for example, experts, although expert in particular methods of problem solving, do not always fully appreciate the order in which they tackle problems in their area of expertise and, in fact, are inclined to inaccurately describe their own problem solving methods. It was therefore felt that a more accurate way of determining how experts go about construction planning would be to actually observe them while they were engaged in a planning exercise.

Protocol analysis is a technique that has been developed by cognitive psychologists in order to learn more of the way in which individuals go about solving problems of one type or another. It has been used quite extensively by researchers who have wanted to gain more insight into how, for example, individuals solve mathematical problems, bacteriologists diagnose infectious diseases, students deal with physics problems, and how a chess master calculates his next move (Breuker, Elshout, Van Someren and Wielinga, 1986). It had also been used quite extensively within the field of architectural design and design in general. The technique had never been used in terms of pure construction planning problems, although it has been used indirectly (Aouad, Ford, Kirkham, Brandon, Brown, Child, Cooper, Oxman & Young 1994) where it was utilised to elicit information from teams made up of an architect, quantity surveyor and construction expert during the design phase of a construction project. However, it had never been used with the specific objective of establishing the order of activities within the planning process on the level of an individual construction planner, as was the case in this research. It was therefore felt necessary to first of all carry out an initial experiment with the technique in order to:

1) To judge the suitability of the method for further testing.
2) To test the model that had been developed in order to see how well it represented the activities of construction planning.

This chapter therefore describes the technique of protocol analysis together with a description of the first experiment that was carried out using the technique, as well as a description of how the model that was tested was developed. A number of the results that arose from that experiment are also discussed.

4.2 EXAMINING THOUGHT PROCESSES

We cannot directly observe thought processes. However, whilst not being able to directly observe them we can indirectly observe them by studying the artifact or product that results from them and, of course, we can ask the individual concerned after he has completed the task to describe what went through his mind whilst he was engaged with the task. However, the
problem with introspection, as it is known, is that it is open to the interpretation of the problem solver himself. Mistakes can easily be made in reporting the order in which sub-tasks were carried out, the point at which a sub-task was completed, the way in which creative problem solving occurs, and the reasoning behind various decisions. It is for these reasons that introspection is only used as a casual and reflective tool rather than an intense and analytical tool. Many of these criticisms are overcome through asking the person engaged in solving a particular problem to think aloud whilst dealing with the various aspects that it throws up because thoughts that are 'in focus' are reported as they occur.

A problem solver's verbal output is typed up and forms the basis of a 'protocol'. However, where physical aspects play an important role in the process as well, and can possibly add to our comprehension of how the process is influenced, it is clearly important to make notes of what the problem solver physically did throughout the empirical experiment. A simple and direct means of being able to more fully reproduce the process is to film the problem solver during the experiment with a video camera, for example. In some types of research it is appropriate to further supplement the protocols with information regarding eye movement and heart rate, for example. In the case of an industrial designer who is given the task of designing a bicycle it is clearly an advantage to be able to identify the point at which sketches were developed, further analyzed and reworked, for example. One can, of course, ask the problem solver to name any sources of information that he needs to consult at the time of doing so, but the danger always remains that he may overlook to mention factors that are extremely relevant to the process. Notes about the physical activities of the problem solver can therefore be a worthy supplement to the verbally reported protocol.

4.21 Purpose of Thinking-Aloud Experiments
Thinking-aloud experiments coupled with protocol analysis can be used with basically three goals in mind:
• In order to develop a theory of a problem-solving process.
• In order to test an already-developed theory.
• In order to elicit knowledge that is used during the process.

But, of course, the techniques can also be applied in order to meet a combination of the above reasons, for example, where theory and testing take place in a continuous cycle complementing one another. In this particular research a great deal of theory had been drawn from the 'neighbouring' fields of architectural design research, engineering design research, as well as problem solving research, and construction literature as well, of course. The initial experiments that were conducted in this research were done so with the intention of developing a theory, whilst the initial purpose of the second round of experiments was to test any theories that had been proposed in the first round. However, theory can hardly ever be claimed to be complete and so the use of protocol analysis in this particular research has to be seen in the wider context of the pursuit to gain more knowledge about construction planning in general rather than to present a complete theory.

4.22 Factors Affecting Thinking-Aloud Experiments
Whilst allowing us an as-direct-an-entry as possible into a problem solver's thoughts there still exist a number of aspects that go to limit the effectiveness of thinking aloud experiments coupled with protocol analysis. Breuker et al (1986) list them as follows:

"(a) The ease with which thoughts can be verbalised". Some tasks demand information that cannot easily be translated into language. For example, melodies in music composition, herbs in cookery and mental imagery in spatial problem solving are all aspects that can be perceived in an instant by an individual but which demand large amounts of language in order to reproduce them for another person.

"(b) The nature of the main task". Some tasks take up such a great deal of working memory because of the need to keep a number of parameters activated at the same time that the additional task of having to verbalise what is already in working memory adversely affects the main task.

"(c) The subject's verbal capacity". Research has shown that there are great differences between individuals and that these differences are dependent on the verbal intelligence of an individual. However, experience has also shown that where an individual is given the opportunity to practice in thinking-aloud it becomes more automatic for the individual and therefore places a lesser demand on his or her working memory.

"(d) The subject's capacity in the main task". If an individual is expert in the main task the process of reasoning can take place so quickly that little opportunity arises for the verbalisation of what is in effect happening with a high degree of automation. Real experts often instantaneously 'see' a solution without having to think all combinations through while novices can be so entwined with the problem that they find it very difficult to mobilise the language necessary to be able to describe what they are thinking. As a rule therefore intermediate experts are thought to probably provide the richest protocols.

4.23 Developing Codes from the Theory
Where thinking-aloud experiments are conducted in order to test a theory it goes without saying that a theory first needs to be available before it can be tested.

However, simply having a theory alone does not put us in a position to be able to analyse the protocols. Before we can do this we need to have translated the theory into groups of verbal phrases that reflect the types of statements the theory predicts will take place during the protocol and the order in which they will take place. This is what is known as the 'synthetic protocol'. The synthetic protocol is made up of categories of verbal expressions and activities, with possible alternatives, in the form in which they might actually take place during the thinking-aloud experiment. Each type of verbal phrase is given a code so that a subject's verbalisation of what is in effect happening can be translated into language. For example, melodies in music composition, herbs in cookery and mental imagery in spatial problem solving are all aspects that can be perceived in an instant by an individual but which demand large amounts of language in order to reproduce them for another person.

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4.3 CRITERIA OF THE EXPERIMENT
Clearly the experiment had to meet certain criteria. Of fundamental importance, of course, was that those who were to participate in the experiment were themselves proven planners and not, for example, building students. Further, the experiment had to tax the planners in such a way that solutions could not be developed automatically but had to be thought through. There therefore had to be at least a minimum level of diversity built into the task. On the other hand there had to be an element of realism in what was being asked of them; asking a planner
to prepare a construction programme for a surrealistic project would be to draw him away from his area of expertise. A further consideration that, of course, had to be taken on board was that for the sake of not making the process too great a spaghetti of activities and parameters, etc., because bearing in mind that this was an experiment in itself as much as anything in order to test the suitability of this kind of experiment for this kind of research, the task had to be kept relatively simple. Besides it was a well documented phenomenon that even the most seemingly simple problem solving tasks can bring about great insights into how particular types of problems are tackled as well as cause more than sufficient problems for those endeavouring to analyse the protocols anyway. (See Breuker et al, 1986).

4.31 The Project - A Residential Development

The principal choice of a residential design was decided upon. It had to be such that the solution to the problem would not be too automatic, as might have been the case with other small house designs. An architect was approached in order to see if it would be possible to borrow a set of drawings for the experiment. Understandably this proved to be awkward but the architect did kindly agree to prepare drawings that could be used specifically for the experiment. The result perfectly met the specified criteria, being both relatively straightforward and appropriately different from other house designs. To accompany the drawings a simple specification was prepared, together with information regarding the activities, the required capacity in terms of men and machinery, and key delivery dates. A number of blank programme sheets were given to the individuals with spaces on the left hand side for activity descriptions but where the week numbers from 1 to 25 in 1994 had already been entered along the top of the sheets. As well as any sheets that the experts filled in any other notes or jottings down that they made were also taken to supplement the verbal protocol, together with any notes that the experimenter had made about any relevant physical actions at any particular stage.

4.32 Subject Criteria

Because the chosen project was a relatively straightforward residential-type building it was felt most appropriate to approach smaller Contractors who were engaged on a daily basis with this type of project. Three individuals were found who were willing to take part in the experiment, two of whom ran their own smallish contracting companies, the third of whom worked as a senior planner for a medium-sized Contractor. All three had a great deal of experience with this type of single-dwelling project that the protocol experiment project represented.

4.33 The Exercise Itself

All three participants were informed before the date of the exercise that it would take about one and a half hours to complete and that there would be a number of questions that would be posed afterwards. Before the experiment took place, once the subjects had read the instructions of the experiment, they were each given the opportunity of practising the ‘thinking-aloud’ part of the experiment by describing how they would introduce a new window into the gable of an existing house. A simple drawing was provided showing that the window would have to be placed above a sloping garage roof. Once this simple exercise had been carried out and once the subjects felt quite sure that they understood their task the experiment could begin. The fact that the subjects were to maintain their thinking-aloud throughout the experiment was underlined before the experiment began as well as the fact that should the subjects have any questions regarding construction details, client wishes, etc., they were to answer their own questions themselves, providing of course they stated both question and answer quite clearly.

The output that was required of them was a programme planner with a list of the main activities that would need to take place in order to build the ‘Dream House’, the duration of

4.34 Individual’s Reactions to the Experiment

All three individuals expressed their slight concern before the experiment took place that they were not working in conjunction with a Bill of Quantities from which they could read how many square metres and cubic metres, etc., of various items of work there was. One individual started with the preamble that because his Estimating Department had been so busy recently they had contracted out the work of preparing a budget, and every now and then would refer to a document that was not in his possession. Another individual clearly felt so strongly that a good Bill of Quantities was the basis of a good construction programme that he proceeded to take off quantities involved and spent a fair proportion of the allotted time simply working up quantities. Needless to say that he overran the time limit but nevertheless found himself in a position to be able to produce a well-grounded programme.

4.35 Questions on Completion

Once the individuals were finished and had completed the task to their own satisfaction (time over-runs simply being allowed) a number of questions were put to them. These were formulated in order to ascertain basically how difficult they had found it to think aloud whilst concentrating on the problem at hand and to find out as to whether or not they thought that this type of research could prove helpful in any way in understanding planning and possibly helping to improve the way in which planners go about it.

All three felt that they had sufficiently been able to verbalise their thoughts and one of them said that he did it as a rule anyway, although not when there were ‘strangers’ about. One had felt that it had been a slight handicap to begin with to have to think and verbalise in Dutch as opposed to his more normal dialect and another felt that it had actually prompted him to think about more aspects of the problem. It was clear that as far as the experts themselves were concerned their verbalisations represented a true and accurate record of their thinking and could be relied upon as a record of how they had tackled the task.

When asked about the usefulness of this type of research opinions appeared to be balanced. One felt that it could lay the foundations to improving the planning process, another appeared to be more neutral about the idea and joked that he hoped that the experimenter had learned more from the exercise than he had. The third sceptically observed that there are so many books written on the subject of construction planning that he doubted that further improvements could be made in either education or planning methods. He was of the opinion that beyond a very important educational foundation further training was less important than experience.
4.36 Typed-up Protocols
Having conducted the experiments the verbal statements of the construction planners were typed out. The passage of time was marked by the cassette recorder counter and various words were highlighted in the text indicating literally what the planner had written down. As well as this the numbers of the cassette recorder counter were also highlighted on the various notes and construction programmes that the planners had produced so that again it would be quite a straightforward task at a later date to be able to identify what had been said and done at any point during the experiment.

4.4 THEORIES ON THE PROCESS OF ARCHITECTURAL DESIGN
The question of the order in which the sub-activities of design take place was first considered some forty or so years ago by the early design methodologists and has undergone a great deal of consideration and been the subject of much debate. The earlier writers on the subject were clearly in agreement with one another as Jones (1970, p.63) stated:

One of the simplest and most common observations about designing, and one upon which many writers agree, is that it includes the three essential stages of analysis, synthesis and evaluation. These can be described in simple words as ‘breaking the problem into pieces’, ‘putting the pieces together in some way’ and ‘testing to discover the consequences of putting together in a new way’ and ‘testing to discover the consequences of putting the new arrangement into practice’. Most design theorists agree that it is usual to cycle many times though this sequence and some, (Asimow, 1962, Watts, 1966) suggest that each cycle is progressively less general and more detailed than the one before it.’

4.41 The Basic Elements
Lawson (1994) claimed as questionable the idea that different cognitive operations take place during the architectural design process. He thought it unlikely that a designer can be aware of and in control of any possible mental gear shifting. However, these two statements appear to be in contrast to the findings of the research of Akin, Hamel, and Goel & Pirolli whom all have been able to identify conceptually different types of cognitive activity in the protocols of architects working on architectural problems, and also in contrast with the view of De Bono (1992), a well-known authority in the field of thinking skills, who states (p.53)

Many people ask me if there is an ‘ideal’ type of thinking that can be used for all occasions. The answer is that there is not.

A golfer player has several clubs in the bag. Each club is suited to a particular purpose. You would not use the putter for driving or the driver for putting. A car with a manual gear shift has several gears which are suited to different occasions. Even on an automatic car there are forward and reverse gears. You could not have something which combines the virtues of the forward and reverse gears at the same time.

... Thinking tools and methods may at times seem contradictory. This is because each is designed for a specific purpose. A saw is designed for cutting wood. Glue is designed for sticking pieces together. These are contrary functions - but both are useful in their place.

Lawson (1980 p.26) poked fun at some of the design methodologists citing the ‘Markus/Maver map of the design process’
At a later date in his book ‘Design in Mind’ (1994, p.4) Lawson stated:

‘Such models seemed to have an almost unassailable logic and would probably have appeared quite convincing to those not personally involved in the act of designing. However, while the ‘methodologists’ gathered at conferences to discuss the finer detail of such ideas, designers were quietly ignoring them and getting on with the business of design. While few designers found themselves able to articulate a clear statement about their process, neither did they recognise these over-simplistic models. What cannot be denied is that a designer is unlikely to be successful unless able to generate ideas, that there will be times when analytical thought is appropriate and that a critical and evaluative faculty is essential. What is more questionable is the extent to which these cognitive operations are actually separated into distinct phases, and how the designer controls the necessary shift of mental gears between one and another.’

The view that the process of design could not be somehow encapsulated in a structure was not one that was shared by Akin (1986) and Hamel (1990) who both approached the subject from the field of cognitive psychology. Although neither suggested that architects were necessarily in deliberate control of their cognitive phases Hamel and Akin did put forward descriptive models of the architectural process. Akin, as he stated himself, ‘applied the tools and language of Information Processing Theory (IPT)’ of Newell and Simon (1972) introducing the terms short and long-term memory, schemas, etc. Both Akin and Hamel conducted think-aloud experiments with architects and analysed the ensuing protocols. Through these results both researchers hypothesised that there was indeed structure in the process of the design process and although, in the case of Akin, different terms were used than the more familiar ‘analysis, synthesis and evaluation’ the fact that different terms were used was more indicative of the matter of ‘translation’ rather than a presence of disagreement on there being structure in the process. Hamel maintained the basic terms of the three phase model, also replacing them instead with the terms more in keeping with the language of information processing theorists (p.48).

The above analysis underscores several forms of transformations consistently used to alter problem states during the course of the episode. These correspond to several general categories of operations at least insofar as the investigations in this work have shown. These operations are:

1. Projection of information from existing information through inference, interpolation, or deduction.
2. Acquisition of information from the external environment (slides, drawings, notes) as well as from memory (assumptions about cost, access).
3. Representation of information either after acquisition or after internal processing to assist memory retention and help the other operations.
4. Confirmation of information that is newly acquired or projected to verify its consistency against existing information.
5. Regulation of flow of control from one operation to the next to reduce the search space of the designer as a function of the present state of the problem.

From the results of his protocol analyses Akin concluded that there was a set of legal process transitions from one type of activity to another that could be graphically illustrated as follows.

<table>
<thead>
<tr>
<th></th>
<th>Pr</th>
<th>Pb</th>
<th>Pe</th>
<th>Ps</th>
<th>Pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td></td>
<td>+</td>
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<td>P1</td>
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</tr>
<tr>
<td>P1</td>
<td></td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Where Pr, Pa, Pc, Ps, Pp correspond to representation, acquisition, confirmation, regulation and projection respectively.

Hamel also presented a similar type of matrix detailing legal moves, together with the sub-routines that could or could not be omitted by the architect during the design process.

It was on the basis of the fundamental activities of analysis, synthesis and evaluation, combined with the areas of constraints that I had identified with regard construction planning that I put forward my own initial descriptive model (Stockings,1994) of the construction planning process as a result of the analysis of three protocols that had been taken from construction experts whilst engaged in a construction planning problem. The model that was proposed in that interim report is shown in Figure 4.02.
The basic division of the model was along the lines of analysis, synthesis and evaluation, the three basic activities that all models of design and problem solving tend to be divided amongst. However, these basic elements were further split in order to highlight the different sources of information. For example, the analysis block had been divided according to demands, constraints and capacity, the division that was described in Chapter 2 of the various areas of the rules of construction, and so too was the evaluation block. However, the evaluation block had not been referred to as evaluation as such but as control because of its control nature in checking what has been planned against what is required. (In fact the term evaluation is used in the model to represent utterances of the kind where some sort of humanly judged value is attached that one cannot measure in absolute terms). And likewise the word or activity synthesis has been replaced with the verb plan to more appropriately describe the central activity of construction planning. The terms therefore have simply been chosen in order to better represent the activities peculiar to construction planning rather than to depart fundamentally from the universally accepted terms. However, as we shall see it is by no means straightforward to clearly delineate the meaning of verbs that are very strongly inter-related to one another, a problem in fact that is fundamental to protocol analysis.

4.42 The Left-Hand Side of the Model - Acquiring Information

The first activity that takes place in construction planning is that of analysing the drawings and specifications that represent the demands in the model. This analysis is often followed by a quick evaluation as to whether or not the demands are straightforward, complicated, or whatever. The same also applies for the analysis of constraints and capacity, there being an opportunity in the model for an evaluation to take place of the information that has just been analysed before any other steps occur.

To the right of the three analysis modules is a module titled inferred new information that is divided into four codes in order to be able to make a differentiation between information regarding the demands, the constraints, the capacity and the process. This inferred new information module refers to information that is not directly taken from the drawings or other sources of information but is inferred automatically by the planner from analysed information. For example, the situation drawing showed an existing pathway external to the boundary of the site and although there was no mention in any of the project documents of the fact that the pathway would be required to be protected by the Local Authority planner 2 automatically suggested that this would be the case.

4.43 Planning Stands Central

In the centre of the model the activity plan is to be found. This is divided into the activities plan 1, plan 2 and plan evaluation.

The modules of plan 1 and plan 2 represent primary and secondary planning. By primary planning is meant the first activity descriptions and associated time bars that are drawn on the construction programme. Secondary planning is the planning activity that takes its datum or benchmark form primary information. For example, 'Foundation brickwork...5 days (during week 7)' would be an instance of primary planning and this in turn would act as a source of information for secondary planning, for example, in ordering materials. Primary planning therefore can be seen as taking analysed and inferred information as its source (i.e. drawings, specifications, construction programmes of other projects, etc.) and secondary planning attaches a chain on to a peg, as it were, that primary planning has provided. However, secondary planning is not simply a pure planning activity, it also has an element of control to it, as will be further explained shortly.

Planning evaluation takes account of those remarks that a planner makes which are to do with his reflection on how well or badly the construction programme fits together.
evaluation also accounts for conclusions that can be made as a result of studying globally or specifically the details of the construction programme.

4.44 Control
On the right-hand side of the model is the activity control. It has been divided into three modules in order to reflect the differing nature of the control of demands, constraints and capacity. Control statements reflect checks and tests that a planner applies in order to see how adequately the construction programme deals with aspects that have possibly not yet been considered and should have been considered. These control checks cover the whole range of tests that a construction programme would be expected to be able to endure, and would include such aspects as delivery periods (constraints), available manpower (capacity) and whether complete allowance has been made for all materials (demands).

As was briefly mentioned in 4.43 secondary planning also has an element of control to it. For example, during the secondary planning activity of establishing when various building materials should be ordered the planner has to count back from a time bar that was established in the primary planning phase. In doing so he may well discover that there is insufficient time available to order a particular item due to its long delivery period and still be able to adhere to the construction programme as it had been planned. It can therefore be appreciated that the activity that was intentionally a secondary planning activity results in highlighting a criterion that the construction programme cannot satisfy and thus exhibits, albeit accidentally, its control nature.

4.45 The Manager
The planning process does not occur randomly without guidance. There is clearly management of the process. Most often this management would appear to occur without verbal interpretation, however, sometimes there were utterances that clearly reflected management-type decisions such as, ‘Right the next step is get on with the detailed planning,’ and, ‘Now let us look at the question of how quickly we can build this thing’. Both statements clearly have nothing to do with the analysis of the given architectural information nor do they give an indication that a programme is being pieced together. They simply are statements reflecting that a decision has been made that a foregoing stage has been developed sufficiently to justify commencing work on the next stage. Given that management of the process is a continuous process the module that represents such statements is shown as being the background module on which all other modules rest.

4.5 ANALYSING THE PROTOCOLS
The strength of the developed theory regarding the activities of construction planning can be to an important extent tested by experiment. Where remarks are made that fundamentally cannot be placed within the proposed theoretical framework the integrity of that framework is clearly at stake. One aims, therefore, to develop the theory and the coding thereof as completely as possible before analysis of the protocols takes place. As one might expect, when analysis did take place for the first time of one of the protocols it was found that there were certain types of statements that could not be properly married up to the existing codes. The model therefore had to be slightly modified. (The modified model can be found at 4.7.)

4.6 THE SYNTHETIC PROTOCOL
In order to make the task of analysing the various protocols as transparent as possible, examples are given that typify the different protocol codes that have just been described of the activities of construction planning (4.61 – 4.64). It is necessary to have as good an understanding as possible before analysis of the protocols takes place in order to ensure the highest degree of consistency in coding and the clearest possible division between the different codes. Where there are grey areas, as it were, between code types it is clearly of great benefit to be able to rely on a precedence that has already been set out by example. Having to often consider at depth the meaning of a particular statement is indicative of a synthetic protocol that has not been developed as deeply as it might have been, for example. A good synthetic protocol therefore makes it more straightforward for the experimenter to analyse the protocol and also makes it easier for the coding of a protocol to be independently checked.

4.61 The Codes AD, AC and AM
The term analyse has been used for the taking-up of information purely from the three identified sources of drawings (demands), constraints and capacity. The codes were not used for the taking-up of information from the developed plan, but from project information concerning the building (AD), any particular dates by which it had to be completed and other particular constraints (AC), and information concerning the availability and performance of construction capacity on other sites (AM).

Note that one can distinguish between different levels of abstraction of information in terms of building design but that no distinction of this nature was made in the coding of the protocols. For example, whether the planner was looking at a site layout drawing with a scale of 1:500 or whether he was looking at a detailed cross-section of a single pre-cast concrete beam with a scale of 1:5, all statements of this nature were simply coded AD (Analyse Demands). To have made a distinction in terms of level of abstraction of project information would have been possible but would have made an already difficult task that much more difficult. However, the question of abstraction-level of information and the way in which a planner moves from information on one level to another is clearly an interesting one but it was felt more appropriate not to reflect it in the coding of the protocols.

Likewise all statements concerning the taking-up of information regarding available construction capacity and project constraints were also coded with the same code irrespective of their level of abstraction, although in terms of capacity and constraints it is somewhat more difficult to draw a distinction between different levels of abstraction than it is in terms of a building.

The following are made-up examples of the types of phrases that were thought to represent particular types of planning activity, along with their respective codes.

<table>
<thead>
<tr>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Here we have the south elevation showing how the observatory butts up to the gable end</td>
<td>AD</td>
</tr>
<tr>
<td>The main building is situated centrally on the site</td>
<td>AD</td>
</tr>
<tr>
<td>The two-skin beam supporting the cellar walls is 7m long and 450 mm deep</td>
<td>AD</td>
</tr>
</tbody>
</table>
The project is to be completed by 13th August 1997
AC
Site access will be disturbed by roadworks in week 17
AC
Work on building one is not to commence until building 3 has been handed over
AC
According to this the only crane that can lift 15 tons over that distance is the 55G
AM
Looking at their existing programme the brick layers will not be available until the 7th
AM
Here it says that the 33C can dig a trench 45 cm at that depth at a rate of 5m per hour
AM

4.62 The Codes ED, EC and EM

As has been described the analysis codes were reserved for statements that reflected the
taking-up of information. The evaluation codes ED, EC and EM, however, were reserved for
statements that reflected the quality or the meaning of the information that had just been taken
‘on board’. Thus evaluation comments could basically be of one of two types. The first type of
evaluation comment was in terms of the quality of information that was depicted. The
second type of evaluation comment was in terms of what that information meant in terms of
the production process. For example, a planner could comment on how good or had a certain
drawing was or he could comment on the complexity of the task that was implied by the
information, or he could comment on how good or poor a design he felt it was.

Yes, that is a nice detail. He’s drawn that well
ED
The foundation is quite a complex affair
ED
It is difficult to make out quite what he has hatched there
ED
That completion date will not be easy to meet
EC
Road works in that week should not be a problem
EC
It is going to be very awkward handing over the sub-buildings in that order
EC
Six bricklayers will have no problem with that
EM
Even a 55G will find it difficult to lift those heavier gable elements
EM
But if it should rain trench digging with the 33C will get heavy going
EM

4.63 The Codes P1, P2 and PE

The P codes were reserved for statements of a planning nature. In other words where
synthesis of a construction plan was taking place, where statements did not reflect the taking-on-board of information but the laying-down of a plan of action that would deal with some the problems that had been identified.

Given the nature of the exercise with its emphasis on programme planning it was decided to
make a distinction between statements of plan development that arose from the planner
having directly analysed the project information (P1) and those statements of plan
development that arose from the planner using the already-developed plan (P2). In this way it
was thought possible to differentiate between a primary layer of plan development, as it were,
and secondary layers that were built upon the primary layer.

The code PE was reserved for statements that were made by the planner as to how well he felt
the plan that he had developed would meet the demands and constraints.

First of all we have ‘site clearance’. Should not take more than 3 days
P1
The site hut can be placed in this corner but it’ll have to be kept back as far as possible from the fence
P1
One gang of brick layers for the first lift - 11 days
P1

Looking at the programme scaffolding will be required between weeks 7 and 18
P2
Floor beams are required in week 16. 6 weeks for detailed drawings. Therefore the drawings
will have to be ready by week 10 at the latest
P2
Brick layers will start on the 2nd lift in week 13 / so we’ll have to order them by week 4
(P in this last example the P2 coding starts from the word ‘so’).

The programme as it stands should not present too many problems
PE
It won’t be easy getting all brickwork finished between weeks 3 and 14
PE
Co-ordination of the service sub-contractors in week 7 will not be easy
PE

4.64 The Codes CD, CC and CM

The C codes were reserved for remarks of a control nature i.e. for remarks that were
concerned with the checking of the plan that had been drawn up with aspects concerning the
demands, constraints and capacity that had possibly not yet been considered. In a sense the
activity control is the reverse or opposite to the activity plan. Why? Because the plan is
developed forwards from the project parameters of demands, constraints and capacity while
control is the activity that goes back from the developed plan to check it with other certain
and potential parameters that were not considered for whatever reason at earlier rounds in the
planning cycle. And, where it is found that the developed plan does not properly deal with
some known or potential parameter, then it is quite likely that the planner will adjust the
developed plan so that it can more properly deal with any previously unconsidered real or
potential problems.

4.7 THE PROTOCOL OF PLANNER NO. 2

Apart from making management-type statements, the activity that all three planners first of all
gained themselves in was an analysis of the drawings and specification. This is, of course,
what one would expect because without even a quick glance at the project information a
planner would be able to conclude nothing. Typically then the drawings would be studied first
in order to assess the scope of the works. Having made a rough analysis of the scope of the
task in hand there would follow an evaluation statement as to how straightforward or difficult
the project would be to carry out.

The following excerpts were taken from planner number 2’s protocol. (See also Appendix I –
a table giving an overview of the first 144 assigned codes).

15 And here we have the plans and elevations
AD
16 the front elevation with a car port
AD
17 the side elevation
AD
18 the rear elevation
AD
19 and the left side elevation
AD
20 the foundation is shown
AD
21 the first floor
AD
22 the plan
AD
23 the stairs and the sections
AD
24
25
26 it isn’t such a complicated house
ED

Planner 2 having assessed the scope of the works and the special constraints that would have
to be dealt with proceeded to raise a number of questions that he felt would need to be
answered by either the architect or the client regarding the completeness of the information.
For example, he wanted to know whether or not there was a likelihood of additional works (a bathroom) and whether the client would be performing these additional works himself or whether the Contractor would be required to carry them out. He clearly wished to ascertain whether or not he were in possession of sufficient information regarding the scope of demands before the next stage of planning could begin.

Having made an assessment regarding the fullness of information planner 2 proceeded to establish the ‘time window’ within which the construction programme would have to fit. Although possession of the site could have taken place in the first week of January 1994 this would have been too soon for planner 2’s company as his personnel were all committed to completing other projects first. It was established therefore that the earliest start that could be made on site would be the fourth week in January. Given that the project had to be completed by week 23 this meant that there were 19 weeks in which to complete the project. However, from these 19 weeks 2 weeks would be lost in connection with public holidays.

A quick 2-line programme was then drawn up showing the 19 week period was divided in roughly-equal halves by the 2-week period in which road works would be carried out the by 17 working weeks at 5 days per week.

The observation was made that this 2-week period could well be prolonged for whatever reason and therefore allowance should be made when planning the works.

This drawing up of a first approximate programme was followed by another examination of the specification and drawings. A number of aspects were considered that were identified as having a potential effect on the works on site. For example, the question of parking was considered in the town centre as well as the question of whether or not sufficient notice could be given to the Service Authorities (water, electricity, etc.) who would be required to make the necessary site connections. This analysis having been completed to the planner’s satisfaction he proceeded to the following identifiable stage of filling out a more detailed construction programme. This he did by simply jotting down on a piece of A4 paper a particular work description and drawing in a time bar showing how long he expected it to take to complete. The order in which this was done followed the order in which the house would have to be built. For example, starting with preparation of the site followed by concreting the foundations, etc.

The superstructure was planned in one block i.e. from foundations to roof and the internal finishings were planned in another block i.e. from ground floor screed to painting.

Once this programme had been completed planner 2 went through it to check it against various aspects such as delivery dates in order to see whether or not all building materials that were needed for the project could be delivered on time. Items such as the first floor concrete beams and the insulated roof elements were items with long delivery periods that could delay site production if they were not ordered on time. Another aspect that was checked was the number of men that would be required during the various phases of the construction programme and whether or not they would be available in time from other projects.

The programme having been cross-checked with these and various other aspects the planner made an evaluation as to how well the programme fitted together and the likelihood of the project over-running or being completed ahead of schedule.

Having satisfied himself that the programme that he jotted down withstood a number of tests he proceeded to make a more detailed programme on the blank planning sheet with which he had been provided.
He then proceeded to write down the internal trades such as the plaster, painter, electrician, etc., as well as the little bit of external works to the footpaths and drive. He then concluded that in all the construction programme could soak up four weeks of bad weather without risking a delay of handover.

365 Handover and paving
366 that leaves us with 1, 2, 3, 4 weeks
367 that is the number of weeks that we could lose through frost
368 so it could freeze for 4 weeks

Having completed filling in all the activities that would be taking place as well as the corresponding durations planner 2 proceeded to add more details to the programme. He started by detailing when the various materials deliveries would need to be made followed by detailing when plant and equipment would be required on site and when service connections would have to be made. Allowance was also made for the period when the roadworks would prohibit materials deliveries.

In checking the construction programme against the Estimator’s Bill of Quantities planner 2 found that he had been too generous in the number of hours that he had allowed for various activities. He concluded therefore that the construction programme would have to be critically analysed in order to rectify the situation.

394 final finishings and handover that is altogether 2, 3, 4, 6 man weeks
395 compared to the Bill of Quantities that is too many
396 we will have to reduce the number of men somewhere
397 otherwise we will go over the budget

The completed project gave information as to the order in which the various activities would take place on site, the number of workers that would be required at any particular stage, the dates when service connections would need to be made and the dates by which various materials would need to be ordered and delivered to site.

Having achieved a complete picture of how events would need to unfold on site as well as a pretty full understanding of the ramifications of the chosen programme in terms of the demand that it would place on the workforce, planner 2 concluded that a certain amount of the preparatory work would need to take place in the final week of 1993 and the programme as it stood was sufficiently satisfactory in order to base site production on it.

473 pre-site work will have to take place this year
474
475
476 2 days beforehand for deliveries and then we have still
477 have a bit of time in January for the drawing work
478
479
480 That should deal with it quite nicely

With these words the exercise had reached its conclusion. The planner felt that the programme that he had developed could realistically be carried out and harmonised with the other projects that the company was committed to.

325 the only potential problem in January and February is if it should freeze

334 and then we have a bit of room for manoeuvre here if it should freeze. We can
335 soak up 1 week without any difficulty
336 the 2nd week is also no problem / but we will have to ensure timely deliveries
337 because here the road is being broken out
4.8 THE RESULTS OF THE EXPERIMENT

4.8.1 The Method of Coding the Protocols

Assigning codes to the thoughts that were spoken out loud by planner 2 was in some ways quite straightforward but in other ways quite a demanding task. In general, statements of an analysis nature could be fairly well distinguished from statements of a synthesis nature. However, some more-subtly differentiated statements were more difficult to distinguish from one another. The problem was less to do with the method of protocol analysis itself, because the separation of different types of statements was generally found not to be a problem, but more to do with the definition of the individual codes that were being put forward, there being too great an overlap in the definition of some of the codes.

One code, for example, Control Demands was not observed. The fact that it was not observed did not necessarily mean that it was a redundant code and that it should not have been included in the model. Whilst not having been identified in the protocol of one planner it might very easily have been identified in the protocol of another, for example. However, having been said there was in fact a more fundamental problem with the planning codes and the control codes than simply not having been mentioned. The problem was one of the definition of the activity ‘to plan’ and the extent to which one can logically separate it into activities of a different nature. For example, in the division of the model the activity ‘plan’ had been deliberately reserved for statements of a purely production-like nature, in other words for statements where a solution was being generated. There was also a separate code for statements where the ‘solution’ that had been generated could be tested against other criteria that had not yet been tested; these were the codes of control seemed to be perfectly plausible before any coding of the protocols began to take place. However, when it came to analysing the protocol and assigning the various codes to it, it was sometimes extremely difficult to identify the end of one activity and the start of the next.

The three basic codes that proved to be extremely awkward to distinguish from one another were plan 1, plan 2 and control. An attempt was made to differentiate between what might be described as the first main chain of planning which described the fundamental activities of construction, the second level of planning where shorter chains were added to the fundamental chain, and the activity of checking the first and second chains of plan in order to see if they properly dealt with various other constraints. Fairly straightforward examples had been suggested of the type of statements that would represent such activities. However, when it came to analysing the protocol it was found that statements made by the planner were very much more complex than had been predicted by the codes and that in terms of the meaning given by the codes tended to blend into one another without any obvious lines of separation.

For example, having planned all the main activities from beginning to end (Plan 1) a construction planner might decide to check it in order to see if there would be any problems in terms of delivery periods. Here the code CC (control constraints) would be used because it was clear that the planner was about to check the plan in terms of its ability to accommodate delivery-period constraints. It was at this point that confusion set in as to the correct way in which these statements should be coded. As had been described in the synthetic protocol i.e. the phrases that typified the codes, the going back to add secondary layers of information to the construction programme was initially to be coded Plan 2. Here was an instance of going back to the plan that had been drawn up in order to furnish it with extra information regarding the dates by which certain materials should be ordered. But where it was found that a certain building element could not be ordered on time to meet the date by which it would be needed on site the planner would have to re-analyse the programme and develop a solution that would allow for the later arrival of a particular element but still allow the demanded completion date to be honoured. In other words in terms of the coding the planner had decided to check the plan for completion dates (CC), had written on the programme the latest dates by which certain key materials would have to be ordered (P2) had subsequently discovered that a key element could not be ordered on time to meet the date by which it had been planned for on site, and therefore had gone on to alter other aspects of the programme (P1). However, what had been coded as three different activities was realised to be in fact the same conglomerate activity but being born of slightly different intentions. Because whether the planner had deliberately searched for inconsistencies in the plan or whether he had accidentally found inconsistencies in it, it really made little difference, the problem still required to be dealt with and the subsequent activity that he engaged himself in was none other than the central activity of ‘planning’. It was felt that what had been described as three different activities were, logically speaking, so tightly bound to one another in the same conglomerate activity that there was little to be gained in trying to make a distinction between them. At best the codes could be used as markers in the protocols to mark the point at which the planner had signalled his intention to add secondary layers of information to the already-developed programme, or to mark the point at which he intended to check the construction programme against various constraints but the codes could not be used as continuous codes. They could only be used to mark an intention; following the intention the activity in which the planners engaged themselves could not logically be classified as anything other than planning (P1).

Another, but very much smaller problem than the one that had been found relating to the codes of planning concerned the information codes (H1, H2 and H3). These codes were applied whenever the planner found that there was insufficient information regarding some aspect of the construction project. The 3 areas in which there could possibly be a shortcoming in information regarding the demands, constraints and capacity. The codes allowed for documents to be consulted, for a third person to be consulted or for the planner to assign a value himself. However, while these codes nevertheless served to add information about the source that would need to be consulted they said nothing about the nature of the missing information. This could have been easily rectified, for example, by adding the letters d, c and m (demands, constraints and manpower/machinery). And so had the planner stated that he needed to ask the client about a completion date, for example, the code He could have been used. However, this would have been a minor addition to the coding system as opposed to a major alteration.

4.8.2 The ‘Dream House’ Assignment

The task set the construction planners was the development of a construction programme detailing the order and duration in which construction capacity would be required. As such the bulk of the efforts made by the planner was in terms of dealing with the order in which the various tradesmen would need to be employed, and how many would need to be employed. The project was really quite straightforward and did not present any particularly awkward problems. As such the planners were able to concentrate on the time scheduling aspects of the project and did not have to deal with any particularly awkward problems such as a site that was highly constrained in terms of space, for example. Because the planning exercise concentrated on the time scheduling aspects of planning it was decided that for the following round of think-aloud experiments a much more complex project ought to be used so that the influence of project-complexity could be examined on the planning process.
4.9 CONCLUSION

Despite its relative simplicity the Dream House Project had provided an abundance of data. The technique of protocol analysis had shown that a great deal could be learned from even a relatively straightforward project, but it had also shown that the task of splitting the protocol into phrases that represented fundamentally different types of activity was far from straightforward. The suggested types of activities, of course, had already been put forward in the model but it was clear that there were some deep problems that could not be easily resolved. Passages could be easily found in the protocols where initial planning decisions had been made, where subsequent layers of decisions had been built upon initial decisions, and where discoveries had been made of real and potential criteria that might upset the construction plan as it had been laid out up until that point, but the task of categorizing these phases into fundamentally different activities was beyond the scope of this research. It had been found that too great a degree of subtlety had been sought in the sub-division of the activities and that the model should be simplified in order to allow a wider variety of phrases to be coded under more broadly-defined activities. The problem being that the more finely the sub-activities were differentiated the more difficult it became to make a clear and logical distinction between those sub-activities, particularly when faced with the task of identifying those activities in the midst of the idiom of a particular expert’s protocol.

A possible explanation as to why it is difficult to assign codes to the verbalisations is that, as Newell & Simon suggest, in order to solve a problem an individual must create a problem space in memory in which the initial state, goal state and operators that can transform the initial state to the goal state can be held. And so while the entrance into that problem space, as reported in language in a protocol, might be through the activity of planning or checking (controlling), the fact remains that other features, that may not be verbally reported, have to be present in the problem space in order for a decision to be made. Decisions cannot be made where just demands are in focus or where just constraints are in focus. Decisions can only be made where both demands and constraints are in focus whether the concentration of focus be more on the demands or more on the constraints of the problem. And it is probably for this reason that codification is such a problem because the problem space has to be made up of different types of features and the coding aims at concentrating on one aspect of these features, which in reality is an unjust over-simplification of what has to be taking place in memory.

However, the degree with which one could be confident that analysis-type statements had been properly separated from synthesis-type statements was much greater than the confidence that could be had in the more-detailed coding of the protocols and therefore it could be said with a greater degree of certainty that the construction plan had been developed in cycles between analysis of the demands/constraints and the synthesis of a solution. The activities of analysis, synthesis and evaluation were found to be entwined with one another in a continuously developing cycle where demands and constraints were analysed, a (partial) solution put forward, other constraints and demands examined, a part of the solution found to be inadequate, the solution re-adjusted, and so on until a general level of satisfaction had been achieved. Synthesis was found to first occur shortly after the initial analysis had taken place, it being clear that it does not necessarily have to be an activity that can only take place once a great deal of information has been analysed. A planner can clearly develop a portion of the plan, examine more of the project information, develop another portion, and so on, sometimes refining what he has already planned, thus broadening and deepening the plan as he goes along. In fact the construction programme was drawn up in three distinctive phases. The first plan was a simple two-line programme in which the major phases of the project were divided.

The second one listed all the major activities and their durations. The third one was based on the second one but was used to carry more information such as the dates by which the materials would have to be ordered and the number of personnel that would be required.

From the protocol it was clear that the task of generating a construction programme, even for a relatively straightforward project such as the Dream House Project, is made up of a large conglomeration of mini-problems. There are many aspects that a construction planner has to take into account and it is clear that he cannot take all of these aspects into account and solve them in one step. He has to tackle them piecemeal, by building up a solution, exposing the solution to various tests, and further developing the solution until he is confident that the plan has reached the general level of robustness required of it.
5. Theory: The Process of Construction Planning

5.1 INTRODUCTION

Expert construction planners do not randomly sift through project information and neither do they randomly develop a construction plan. They carry out the process guided by a number of principles, some of which are described in this chapter. Because the principles that are described in this chapter were strictly speaking hypothetical tests needed to be carried out in order to gauge the extent to which they could be supported. This was done by means of protocol analysis, the results of which can be found in Chapter Six.

5.2 ANALYSIS

There are different levels and types of intensity of analysis but clearly the first type of analysis will be a more general one. In the case of construction planning the goal state is represented by the information relating to a particular construction project i.e. the description of the artifact to be built. Without even the briefest of details of the goal state a construction expert will clearly not be able to go any further in solving the process problems that it presents. The first part of this analysis will therefore be an orientation in order to establish two things 1) What information is available? and 2) What type of a project is it?

Wishing to know more about the type and scope of the works the construction planner will probably maintain a simple strategy of analysing information that will fill the construction expert in on the ‘big picture’ as opposed to the detailed version. Drawings of high detail will be initially of less interest than ones showing site layout, main elevations and the nature of the frame, for example. (Principle one - In terms of detail of information this is a ‘top down’ strategy).

The most powerful guiding principle will be to search the documents according to the order in which the building must logically be built. (Principle Two - In terms of that part of the building that the information describes this is a ‘bottom up’ strategy). First he will wish to know more about the ground conditions and the design of the foundation system. Then he will wish to get to grips with the load-bearing structure of the building together with the likely positioning of major plant and equipment. Aspects such as internal finishings, mechanical services, and landscape gardening are likely to be considered of lower immediate priority, that is until more insight has been gained in terms of the major overall framework of the construction process.

Of course, it is always possible to think of circumstances where this guiding principle might be ignored, for example, where the construction of the load-bearing frame is a matter of well-known routine but where the internal finishings present a very much more complex coordination problem. Were this the case the construction planner may very well feel that the limited resource of his time would be better spent dealing initially with the more complex aspects of the problem. (Principle Three).

A planner might analyse the problem at hand on the basis of routine i.e. that he always begins to analyse a new project by reading the specification, or because the drawings have been presented to him in a particular order. However, these ‘non-strategies’ are likely to be quite time consuming as they will probably make the task of developing a mental model of the
project that much more awkward. Firstly the planner will not have an accurate overall concept of the project and so will not be able to embed new information into it and secondly the chances are great that sub-parts will be analysed that do not necessarily relate to one another and therefore the task of connecting these pieces of information into an overall conception will be made unnecessarily difficult. In other words, in theory at least, the absence of an information-gathering strategy would lead to inefficient analysis of a new project. However, caution must accompany the notion that it might be a waste of the planner's time to initially abandon the frame drawings. He might consider investigating the nature of the services and concrete frame which leads the planner to ponder the nature of the void and thus temporarily abandon a particular line of analysis and follow another one (Principle Four). One can imagine a situation where the construction planner analyses elements of the frame, for example, and discovers a void in the concrete frame which leads the planner to ponder the nature of the void and thus temporarily abandon the frame drawings. He might consider investigating the nature of the services and might subsequently discover that a large piece of mechanical services equipment will have to be placed in the building before other parts of the structure can be completed. Having satisfied himself that he is fully aware of the nature of the mechanical services constraint on the order in which the frame can be built he could then go back to completing the task of analysing the frame drawings.

5.21 The Product of Initial Analysis

As has already been touched upon, during initial analysis, two things will be occurring. Firstly the expert will be building up his mental model, his understanding of the project. He will be committing information to memory. He will be converting the two-dimensional information that is before him into a three-dimensional understanding of the building. As well as building up a spatial model of the building he will also be committing verbal information to memory. For example, he might store verbal facts about the length and breadth of the building, the number of storerooms, the nature of the frame, etc. But, of course, the construction planner's understanding of the project will not just stop at the building itself; he will also have built up an understanding of the relationship between the building(s) and the site itself, as well as the relationship between the site and the immediate surroundings of the site.

The second and somewhat inevitable product of analysis is a level of (automatic) inference-making that will take place. This inference-making will be in terms of different aspects of the problem and will go to different depths. Some inferences will be automatic, others will require more deliberate thinking. However, especially in the earlier phases of analysis, inference-making will be more restricted to a general overview rather than an immediate focusing on particular problems. The more concentrated shining of attention will come later when the construction expert has satisfied himself that he has a good enough grasp of the general problem. But even where no direct or vague inferences have been made certain memory structures will have been activated and primed for use in future analysis and problem solving rounds. In cognitive psychological terms the construction planner's problem space (his understanding of the project) will likely be connected with relevant features in his long-term memory and therefore the problems the project present will have become more structured.

The result therefore of general analysis will be a fairly rich memory structure of what is required as output, together with ensuing sets of inferences that relate to the sort of capacity that will need to be employed on the project and the constraints that will impose on the way in which the capacity can be employed. Some inferences will throw up direct answers, others will result in vague as opposed to direct associations taking place, and others still will require that more detailed analysis and problem structuring take place.

The simpler the project and the more it resembles a previously-carried-out project the more will be known about how the project can best be tackled. Seeing a relatively straightforward project an experienced construction expert will quickly be able to draw up a realistic construction programme with details and levels of manpower, machinery, equipment, etc. In the case of a very much more complex project, the type of which is unfamiliar to a particular expert, it is thought probable that that construction expert would be able to form an opinion as to the project's complexity and be able to make some sort of judgement as to its likely demand of physical resources, as well as be able to identify any particular areas of construction planning that might require special attention. However, without having a relevant frame of reference to compare a new project with, a construction expert who examines an unfamiliar type of project is more likely to make errors in his appraisal of that project.

5.3 SYNTHESIS

Synthesis, in construction planning terms, is the linking together of chains of activities by specifying levels of capacity (men, machinery and equipment) in the time and spatial frameworks.

At the start of the process of synthesis the important aspect will be the major spatial framework of the construction plan. The construction expert will wish to establish where the site entrance(s) should be, how the site will need to be divided between transport routes, storage space, site hut location, major plant and equipment, etc. Clearly the position of these will be dominated by the way in which the building interacts with the site and its surroundings, but so too will the way in which the major capacity can respond to the demands.
of the design have an influence on the way in which the site can be divided. The construction planner will attempt to pick and choose items of capacity so that production takes place at as high a level of efficiency as can be sensibly expected. Knowing the degree of uncertainty that accompanies a construction process it cannot be seriously expected that all elements of capacity will be fully utilised without idle time, but where idle time can be expected to occur the construction expert will attempt to isolate it to the less expensive elements of capacity. Often therefore the most expensive item of construction equipment will form the starting point of the development of the construction programme, setting the tempo at which the rest of the construction capacity must be fine-tuned to. Piecing together a construction programme starts therefore with the bigger items of equipment with the largest indirect costs and works its way down scale, filling in the details within the frameworks that have been created by the major items of equipment (Principle Five). Of course, earlier decisions on larger pieces of equipment can always be reviewed in the light of information that is generated by lower level planning. For example, if it becomes evident at the detailed planning stage that a single tower crane will be insufficient to meet production at a particular rate then perhaps this will force the decision to be made that two tower cranes will be needed. But to ensure a minimum of tower crane idle time extra gangs would, of course, have to be employed.

And so the process of construction planning will continue, with decisions that have been made at major framework level being subsequently filled in with the detail of the more minor systems, allowing for the fact that possible inconsistencies will be found between frame and detail therefore requiring the framework to be 're-jigged'. Each planning sub-framework has to fit in to and harmonise with the existing sub-frames of the overall planning framework. Of course, once a project reaches a certain maturity it will be possible to consider certain blocks and spaces of the building as separate entities, or at least partially separate entities that can be dealt with by different persons or teams of persons.

The majority of construction planning will be carried out 'from the beginning', by choosing a level of capacity to carry out the first section of work and continuing to plan subsequent sections of work until 'completion' has been reached. This is 'forward chaining', in other words where the start-date is known, but where the completion date has not yet been worked out. However, this might not always be the most sensible approach to planning, particularly where the construction period is highly constrained; in which case it might be advantageous to chain-back from the date by which a particular section of work must be completed, dividing the time between the various activities in a balanced way and then establishing levels of capacity that can meet the dictated work-tempo. This would be 'backward chaining' and would be employed where the time dimension took precedence over spatial efficiency (Principle Six).

5.4 EVALUATION
The activity itself has up until this point not been mentioned. But clearly it will have been present throughout the synthesis phase in the background, as it were, monitoring plan development. Evaluation is the measurement of the criteria by which decisions are made. It is carried out for a number of related objectives, namely: 1) to expose the weaker aspects of a plan (for example, demands and constraints that had not yet been considered), 2) to expose aspects of the plan that are in conflict with one another, and 3) for the purposes of comparing one potential solution with another.

Evaluation can take place on different levels and with different degrees of formality. It can be conducted by the planner himself at the time of solution generation, or it can occur at a later stage in a very much more formal manner where it is carried out by more than just the plan creator himself. In terms of the Akin model it is the test activity in the 'generate and test' heuristic.

Evaluation is the last phase of the planning cycle, because once a level of satisfaction has been achieved, it then remains for the plan to be brought out of its abstract form and put into effect. Once this takes place planning will continue but should do so within the framework that has been provided at the pre-construction stage, providing, of course, that the project develops "according to plan".

5.5 CONCLUSION
The process of construction planning starts with analysis and ends with evaluation. Project information is made up of a great number of two-dimensional drawings from which the construction planner can build up a three-dimensional understanding of the to-be-built building. As has been stated the order in which the drawings will be analysed will not be random but according to reasoned principle. Synthesis of a solution will not suddenly occur at the end of the analysis of all drawings but will start to take place when sufficient aspects are known of a particular sub-problem. Evaluation will take place of the solution that has been developed to check it for (1) internal harmony and (2) to check it for its compliance with other demands and constraints. The first type of evaluation will be more confined to checks within the construction plan itself, whereas the second type of evaluation will also contain an element of analysis. This is because the starting focal point of this second type of evaluation will be the construction plan but will widen to encompass design information so as to check the plan's ability to deal with the demands and constraints, and indirectly to ensure that all demands and constraints have been taken into account. Any as-yet-unconsidered-constraints might even be generated by the construction planner himself.

The construction planning process will continue with the activities analysis, synthesis and evaluation running in close proximity to one another where project information is analysed, a (part-) solution put forward, and checked for 'internal' and 'external' harmony in continual cycles of different lengths until an overall level of satisfaction has been achieved; a complex example of 'generate and test'. The order in which the generation and testing of solutions will take place will be guided by certain principles; six strategies that arise from these principles are described below. Although the strategies have been divided between strategies of analysis and synthesis, some of them will in fact be equally applicable to both. They can be summarised as follows:

17 The question of what constitutes a "major" aspect needs to be briefly considered. Clearly it is not something that can be defined absolutely but instead has to be defined relatively. A major aspect will be one that occupies a large proportion of the available space, or takes place over a large proportion of the construction period, or has an important role in terms of the structure of the construction project. A major aspect need not necessarily only be involved in a direct activity it might also be part of an indirect activity such as a special scaffold, for example, that is needed to support the new structure or existing structures. A major aspect could also be one where high indirect costs were involved in the transportation and setting-up of a particular unit of capacity in relation to its direct operating costs. A major aspect might also be a long delivery period for a particular element or a particularly awkward time window.
1. **Look at the 'big picture'. (ANALYSIS)**

Look at the information of the project as a whole, especially the drawings showing elevations and site layout. Appreciate the scope of the works as opposed to the detail. ‘Big picture’ drawings will have a scale in the range of 1:100-500 as opposed to 1:1-20, for example.

2) **Follow the load-bearing structure (ANALYSIS/SYNTHESIS).**

(This is possibly the most important strategy).

Start by looking at the point where all weight will be carried i.e. at ground conditions. From the structure in the ground follow the line of load-bearing up through the frame. Finishings are the last elements to be attached to the frame and therefore the last aspect to be tackled.

3) **Examine the ‘complex and unknown’ before the ‘straightforward and familiar’. (ANALYSIS/SYNTHESIS).**

Where the load-bearing frame, for example, is of a type with which the construction planner is familiar and which in itself presents no particular difficulties, it is very likely that the construction planner will skip over structural information and go on to look at other ‘problem’ areas, the services, for example.

4) **Deal temporarily with the unforeseen before continuing with the planned. (ANALYSIS/SYNTHESIS).**

Whilst a construction planner might attempt to deal with the problems that a particular design presents him with in a particular order it should also be recognised that there will be times when the construction planner might be diverted from that order. Where a previously unforeseen problem is highlighted, or where a particular piece of information is required, the planner may wish to temporarily abandon the hitherto ‘main line of investigation’ in order to deal with the missing information/problem that has been highlighted. This deviation from strategy should also be distinguished, not as a strategy as such, but as a response to previously unforeseen problems. Once the unforeseen problem had been dealt with it would be expected that the planner would then return to his previous course of planning.

5) **Build the construction programme around the major plant and equipment. (‘BIG PICTURE’ SYNTHE~SIS)**

The major plant and equipment with the highest indirect costs will have a dominating factor on the tempo of a construction programme as well as the major spatial division of the site. Because it will be a primary objective to employ major units of capacity as economically as possible a construction planner will try to build the rest of the construction programme around them. Minor systems will therefore be planned so as to comply within the frameworks created by the major systems, and transport routes and storage areas will only be resolved once the major system(s) has been chosen.

Note however, that where it is subsequently found that a major framework cannot accommodate the necessary number of minor frameworks then the major framework will have to be reviewed.

6) **Chain backwards as well as forwards. (SYNTHE~SIS).**

Where a project is perceived to be very tightly constrained in terms of the contract period the construction planner might elect to plan the works backwards instead of forwards; he would start with the date that the project must be completed by and, working his way backwards, would choose points in time by which certain activities would have to be completed. At this initial stage he would probably pay less attention to any particular technical difficulties that might arise as a result of having to carry out the works at the required tempo because he would simply be more concerned with dividing the available time into balanced blocks. The consideration of the technical difficulties of the demanded tempo would then take place at the following stage.

It should be noted that the above strategies are not mutually exclusive; it will be possible for them to be combined at times, for example one analysis strategy with another and one synthesis strategy with another. In fact during any one construction planning process all strategies might be encountered in different measures. But while we can expect certain principles to dominate the construction expert’s approach to the analysis and problem solving of construction planning problems there might very likely be periods in which a strategy as such is not plainly evident. Instead the planner might respond to currently-activated information in a more spur-of-the-moment vein. However, even in the absence of a clear strategy it seems unlikely that such a spur-of-the-moment planning process would be purely chaotic i.e. where the construction planner examined and dealt with one totally unrelated subject after another.
6. Protocol Experiment II: Testing The Strategies

6.1 INTRODUCTION
This chapter describes how the search and solution strategies that were proposed in Chapter 5 were tested, as well as describes a number of other phenomenon that were observed during the analysis of the protocols.

Testing of the proposed strategies took place by examining the protocols of three construction experts who had taken part in think-aloud experiments. Each construction expert (C.E.) was assigned the task of dealing with a number of planning problems for an out-of-the-ordinary construction project. The first part of this chapter describes how the experiment was set up.

6.2 THE ‘X PROJECT’
At the time that a suitable project was being sought the Construction Technology Department at the Technical University of Eindhoven acquired a fairly complete set of architectural drawings together with a reasonable number of structural drawings for a very interesting construction project. The fact that it was far from being a typical office development was considered important because one of the criteria that we had for the experiment was that any assigned task should be sufficiently taxing for an expert. The ‘X Project’ was a five-storey office development for a large insurance company that required specialist office space. The building was made up of two long parallel wings that were connected by gangways that ran through an atrium. The atrium was covered by a curved glass roof that ran from ground level to the fifth floor and back down to ground level. The entrance building was somewhat of an eye catcher, being what one can only describe as UFO-shape. Its structure was part-concrete and part-steel and was enveloped in lightweight pre-cast concrete panels. The main building was made up of very much heavier pre-cast concrete wall and floor elements. The mechanical and electrical services were also out-of-the-ordinary and were required to maintain a very clean internal climate, particularly in the basement where a large mainframe computer was to be housed.

6.21 The ‘Scenario’
All three planners were given a single sheet of instructions with a preamble in which the scenario was created of a client wishing to be speedily given information regarding some of the most important construction aspects of a particular project. This information was to include the order in which various sections of the structure should be built, the way in which the site should be laid out and a suitable system of craneage. As well as these aspects attention was also to be directed towards safety.

The experiments were to be video-recorded as well as tape-recorded. This was to act as a back-up in terms of the audio side of the experiment as well as to allow the opportunity to exactly follow which drawings were being studied at any particular time. With the previous round of think-aloud experiments (the ‘Dream House’) there had been very much less design information and therefore it was very much more straightforward to make notes as to which one of the drawings was being used at any particular point throughout the protocols, but the
fact that for the X Project there were more than one hundred drawings it seemed only sensible to video record the experiment as well.

In order to keep the experiment business-like and ensure a concentrated effort on the part of the construction experts the experts were asked to complete the task within an approximate time-limit of one-and-a-half hours.

6.22 Project Information
Available were fifty-six architectural drawings, forty-eight engineer’s drawings, thirty-three mechanical and electrical service drawings and twenty-eight service drawings. A complete drawing list was provided, typed out on three sheets of A4 paper.

It had been decided by the experimenter not to include the specifications of the contract as well as the drawings as it was felt that this would probably cause the experts to be overburdened with too much information. However, the fact that all three experts remarked on the importance, at more or less identical phases in their planning processes, of various items of information that were not present in the drawings and that could have been found in the specification had it been available, illustrated the fact that, in order to be able to properly assess the problems a construction project presents, certain items of information need to be taken on board in a particular order. This together with the fact that one of the drawings on the drawing list could not be found at the time of the experiments, and which was clearly felt by the experts to contain vital information, further underlined the point that for any particular decision to be made various parameters have to be established. It also underlined the fact that written and graphical information can be just as important as drawn information to a construction planner. And so whilst somewhat irksome at the time of the experiments for the experts to have to dig about for information, in terms of the nature of the research, it was quite a fortunate accident. Of course, no mention was made to the experts beforehand of the fact that a particular drawing was missing nor that they would not have access to the specification, it being felt more appropriate that they discover and deal with these problems themselves.

6.3 THE STRATEGIES TESTED

6.31 Strategy Number One - The ‘Big Picture’
Two of the experts began their analysis of the project by looking at the three-page drawing list. C.E.3 looked at the drawing list in some depth and established that the project was made up of two buildings, one of which was six-storeys high. He noted the extent of drawings that were present but made no further comment as to what were and were not of particular interest.

C.E.1 examined the drawing list and made the comment that the mechanical and electrical service drawings as well as the bundle of service cable plans would not be of immediate interest and physically placed those drawings to one side. C.E.2, who did not examine the drawing list until he had examined the site layout drawing, also physically put the bundles of service drawings to one side.

The first drawing that all three experts examined was the site location plan (scale 1:500).

C.E.1 “So this is the layout. It can be approached from both sides. There are main roads nearby, so transport to and from the site shouldn’t be a problem.....I can’t see if the client has any particular demands in terms of the space around here. Perhaps he’ll say, “Yes, this is my current office and I need this area for parking”.

C.E.2 “I think that I’ll start by looking for the site layout drawing to see how the project is set. Here is the site layout drawing. From the drawing I can see where the West Ring Road is located. My immediate impression is that I can’t see any strange things but on the other hand I don’t know to what extent this is the new layout or the existing layout. So I would want to know more about the site as it stands”.

C.E.3 “Now we have finally found drawing B5001. (He had to look for six minutes before he could find it as the drawings had not been properly sorted beforehand). What I see straight away is that the project that we have got to build, a main office, is apparently on the edge of a built-up area. Access, so to see, has already partly been taken care of by the West Ring Road. I take it that this area is accessible. The building site is reasonably generous in terms of being able to carry out building activities, that is if everything shown is part of the site... site boundary, property boundary, if this is all correct? I think that I’ll use this space at the back and on the right side for parking. And to begin with that should give us enough space for site hutting and storage.”

All three planners questioned the reliability of the information detailed on the site location plan, wanting to know whether or not what was shown on the drawing would be available to them for construction purposes. One of them felt that a site visit would be necessary to resolve the matter, another wanted to know whether the site would be made available in its entirety by the client or whether it would be made available in phases.

Having examined the site location plan the following drawing that all three experts sought to examine was the plan (scale 1:200) which detailed the division of the site itself in more detail. C.E.1 looked at it for no more than 13 seconds deciding that it was “very nice” but that “it did not give much more information that the previous drawing”.

C.E.2 “Let’s have a look at the next drawing. That is B5051 (site layout and parking) in order to get some insight into the building. Yes, the floor of the ground floor is 16.84m above sea level. There is no further reference to ground level. That says nothing. Ground level is given here 14.9m, 13m above sea level. So there is a reasonable difference in height”.

It had been suggested that as part of the ‘big-picture-approach’ elevation drawings of the building would also be of interest to the experts in order to give them a rapid appreciation of the scope of the works, particularly its three-dimensional nature. However, not one of the three experts proceeded to look for any elevation drawings. And in fact only one of the three experts even looked at an elevation drawing throughout the whole experiment, and that was only after more than thirty minutes of having looked at various other drawings.

Conclusion: Understanding the to-be-built-building in the context of the site is the highest initial priority that the planners who took part in the experiment had. The factors that the planners were particularly trying to establish were the amount of space that would be available for construction activities, the size of the building-to-be-built and the points and ease of access to the site. Once they had analysed this information they could make judgements on how straightforward or otherwise they thought it would be to carry out
activities on the site, one of the three planners deciding at this early stage where the hutting could be placed, as well as specifying which areas of space that could be used for parking.

'Big picture' analysis remained in terms of the 2-dimensional plan of the site and did not include a 3-dimensional appreciation of the site. In fact, only one of the three planners commented on any vertical information making the note that there was a reasonable difference in ground levels on the site.

6.32 'Follow The Structure'

The next drawing that two of the three planners proceeded to look for was the basement drawing. Unfortunately the basement plan was the one drawing that was missing. C.E.1, having established that he could not find the basement drawing went on to look at the ground floor plan. However, he soon realised that the ground floor plan gave him too little insight into the basement, stating:

"I was intrigued as to the size of the basement. Does it form a small part of the building or a large part? Because that determines a great deal eh! If you've got the basement drawing then you can see how big it is. Then by looking at the soil report and the bore-hole data you can determine the way in which the soil behaves. Do you need to pile, or don’t you need to pile? If you do need to drive piles what type of piles do you need? The type of pile has a great deal of influence on how you tackle this sort of job".

C.E.2, having spent over two-and-a-half minutes looking for the basement drawing stated:

"I take it that there are no problems then with the basement. The information is missing and I simply do not have enough insight into the basement to be able to say what it entails. I can have a look at a section, that’ll give a bit more information at least. That should be section C-C then, drawing B5031. Section A-A, section B-B. Yup, it seems that there is a basement, if I look at this drawing, then we can see that it is larger than the superstructure and if I look at this I can see that the underside of the floor construction is 3.68 m below ground level. And one of my first questions is, "What are the ground conditions like and what about ground water?" There is nothing to find so I have no idea about ground water drainage or sheet piling."

The third planner did not at this stage look for the basement drawing specifically but stated, "What I’ll do now is to look for a structural drawing". Having found the structural drawings he stated:

"I am just going to open these drawings one after the other. The foundation. By the way I can’t see the specification." (Experimenter - "It is not available"). "I would like to know more about the ground level, ground water, the nature of the sub-soil, the bore report, that type of thing. I have to assume that I know the site and that I know what type of conditions I can expect if I go into the ground. It can be of great importance. I’ll have to go without that information then".

At more or less identical stages in their analysis of the project all three construction experts wanted to acquire information regarding the ground conditions and clearly felt that the nature of the sub-soil was of fundamental importance to the way in which the construction project could be tackled.

Two of the construction experts used the architectural drawings to gain information regarding the structure, the third tried to use the engineering drawings which in some respects, unfortunately, were not as complete as the architectural drawings. Having looked at the ground floor plans the first two experts went on to look at a drawing that detailed sections of the building in its length and breadth. Having done this, including switching backwards and forwards a few times between plan and section the first two experts proceeded to look in fairly quick succession at the remaining floor plans of the building, working from the ground up to the fifth floor The third expert, however, did not look at any drawings beyond the second floor stating:

"Now that is clear to me. The structural section drawings are missing. That is a pity. But at least I now have an idea as to the structural set-up of the building".

Conclusion: It was found that the order in which a building is to be built has a major impact on the order in which information is sought. It had been speculated that the experts would wish to develop a 3-dimensional understanding of the building as part of the very first analysis of the project but this was found not to be the case. However, the experts that took part in the experiment did develop their 3-dimensional understanding of the building as part of their investigation into the structure of the building. In this way they could combine two objectives. The external envelope of the building together with information regarding internal partitions and finishings, for example, was clearly considered initially to be of very much less importance than the structural elements of the building. However, in this particular project an appreciation of the façade could be gained from the structural engineer's detail drawings because the outer walls were made up of pre-cast concrete panels like the main structure.

What had not been anticipated before the experiment took place was the desire of the construction experts to gain structural information would be given such a high priority that the analysis of structural engineer's drawings would take clear precedence over the analysis of architectural drawings. It had not been appreciated that although structural information could be gleaned from the architectural drawings it is much more efficient to analyse structural engineering drawings in order to gain good insight into the elements that make up the structure of the building. This clearly demonstrated that the three experts that took place in this experiment did not wish to carry out an all-encompassing analysis of the new project but preferred instead to investigate the structure of the new project as part of the first step and then investigate other work-intensive items that could be gleaned from the architectural drawings or the service drawings as later steps.

6.33 The 'Complex and Unknown' Before The 'Straightforward and Familiar'

In fact the experiment that was carried out with the expert construction planners was not suitable for testing this particular hypothesis because what is 'complex and unknown' and what is 'straightforward and familiar' is partly a function of personal experience and partly a function of more objectively-measured criteria. Due to the fact that none of the experts construction experience was quantified in any way and because only one experiment was carried out with each expert it is not possible to make a judgement as to whether or not a
planner does in fact deal with complex and unknown problems before straightforward and familiar problems.

Conclusion: In order to properly test the hypothesis it would first be necessary to set up a number of experiments where a construction expert was asked to develop a construction programme for a number of similar designs that included familiar and unfamiliar problems as well as straightforward and complex ones, and then to observe how these newly presented problems influenced the planner's planning process. Only then could the above hypothesis be properly tested.

6.34 Develop the Construction Programme Around the Major Plant and Equipment.
As part of the experiment two of the three construction experts were specifically asked to:

1. Indicate the order in which the prefabricated concrete section, the steel section and the glass roof should be built.
2. Choose a system of craneage.
3. Specify how the site should be divided.

Of these three aspects of the construction plan the second one was probably the most dominant because although the structure was made up of prefabricated concrete sections as well as steel sections, there was really little other 'sensible' option, for reasons of structural stability, than to build each floor completely before proceeding on to the next floor. None of the experts suggested, for example, that the steel frame of the lift houses should be first erected followed by the concrete frame of the main structure. The steel-framed structures were clearly felt to pose a much lesser problem than the pre-cast concrete side of the structure because although two of the experts did seek detailed drawings of the steel structure, two to be precise, their examination was only cursory.

The site layout was also a relatively straightforward problem because the points of exit and entry were non-negotiable, the site was quite generous in terms of space for hutting, etc., and there were no peculiar spatial constraints that had to be dealt with. As has already been stated the question of site layout did not present any untoward problems and that construction planners was efficient production, in other words, to create the conditions where an extremely powerful crane would be powerful enough to lift the very heavy concrete elements the distances that were being demanded.

However, the craneage problem presented a somewhat more complicated task because the building was elongated and the complete structure was made up of a range of very heavy pre-fabricated elements. In fact all three construction experts spent a relatively large amount of time studying the drawings in order to establish the weights of the various pre-cast concrete panels. In fact six out of a total number of twenty-five drawings that C.E.1 examined, 5 out a total number of twenty-one drawings that C.E.2 examined, and 7 out of a total of eighteen drawings that C.E.3 examined were pre-cast concrete element drawings16. It was clearly felt by the construction experts that knowledge of the weight and location of the pre-cast concrete panels was of fundamental importance to the crane decision making process which itself would seem to indicate that the crane problem itself was considered to be a relatively major problem.

Note, however, that the division of the site did not take place once the question of the crane had been settled but that the crane question was resolved in conjunction with the question of temporary roads. Also as a result of dealing with the crane question the order in which the buildings to the front and rear of the main building should be built was also established, the decision being made by the planners, for example, to build the single-storey building at the rear once the main building had been built. This allowed some sort of mobile crane (be it on rails or otherwise) to be placed as near to the main building as possible.

Conclusion: As a result of the experiment it was clear that the question of resolving the major plant (the system of craneage) did have a large impact on the way in which the experts went about planning. It was not only observed that the question of major plant had an impact on how the building site should be divided but also had an impact on the order in which the main building and sub-buildings could be built. It was clear that the sequence of construction activities was first and foremost dictated by the design but that the order of construction was adjusted, in as far as the design could accommodate adjustment, so as to create the conditions in which a major item of capacity could more easily operate. Clearly the goal of the construction planners was efficient production, in other words, to create the conditions, within the scope that was available to them, to allow the minimalist unit of capacities to operate. However, in the case of the X project it was not so much a question of manipulating the spatial environment so that the lightest crane could be used but of creating the conditions in which a major item of capacity could more easily operate. Clearly the goal of the construction planners was efficient production, in other words, to create the conditions, within the scope that was available to them, to allow the minimalist unit of capacities to operate. However, in the case of the X project it was not so much a question of manipulating the spatial environment so that the lightest crane could be used but of creating the conditions in which a major item of capacity could more easily operate. Clearly the goal of the construction planners was efficient production, in other words, to create the conditions, within the scope that was available to them, to allow the minimalist unit of capacities to operate. However, in the case of the X project it was not so much a question of manipulating the spatial environment so that the lightest crane could be used but of creating the conditions in which a major item of capacity could more easily operate.

However, on balance, taking into account the fact that two of the planners were specifically directed to deal with the crane problem by the experimenter undermines to a certain extent the claim that the major plant and equipment will have a significant bearing on the way in which a construction planner goes about planning. That regrettably was a consequence of the nature of the experiment, particularly the fact that the thinking aloud sessions were limited to about 2 hours and during that period some sort of a solution had to be put together. It had been found namely that the first expert whilst having carried out a thorough analysis of the project did not actually move on to the stage of synthesis; he did not begin the process of putting a construction programme together, and this was in fact a vital requirement of the experiment. Therefore it was decided to direct the second two planners towards solving certain aspects of the construction programme with three specific instructions. However, that having been said the analysis of the project by C.E.1 was remarkably similar to those of C.E.2 and C.E.3, and C.E.1 did remark on a number of occasions how important the crane aspect was and what measures he would take personally and what measures he would delegate to others in order that the question be resolved.

However, in the case of the X project it was not so much a question of manipulating the spatial environment so that the lightest crane could be used but of creating the conditions in which a major item of capacity could more easily operate. Clearly the goal of the construction planners was efficiency and therefore making sure that the most expensive items of plant and

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16 All pre-cast concrete panel drawings had a scale of 1:50.
equipment can work efficiently is the logical starting point for developing such an efficient process.

6.35 Chaining Backwards As Well As Forwards

‘Chaining backwards’ as a so-called strategy is exclusively a solution strategy as opposed to a search strategy. The simple reason for this is because it is to do with time, an aspect that does not directly exist in the project information.

No evidence was found of ‘backward chaining’ as it has been described in this research in any of the three protocols of the experts that examined the X Project. However, the focus of the experiments in the X Project was not to develop a time programme but to look at a number of physical aspects independent of the time aspect. That having been said though, one of the three construction experts (C.E.3) did ask some fifteen minutes after the start of the experiment if the contract period for the project was known. Without thinking about it too deeply the experimenter replied, "18 months". This caused the expert to later on in the experiment develop a construction programme in which the project could be completed in 17 months. However, it was not developed backwards but forwards simply with a larger crane capacity than the other experts had chosen. For example, C.E. 2 chose to use one mobile crane that would first work from one long side of the main building and then move round to the other long side of it but did not go as far as work out how long the frame would take to construct this way. However, C.E.3, 'intuitively' aware that working with one crane alone on the main building would not be sufficient to maintain a production tempo that would allow completion within 18 months, chose to operate four cranes: two tower cranes on rails for each of the two long flanks, a rough terrain mobile crane for the heavier elements that the tower cranes would not be able to deal with and a single, much smaller tower crane for the entrance building. On the basis of this seemingly 'ad hoc' decision to work with so many cranes he was able to forward chain a time programme with production rates that met, almost as though by accident, the time criterion for the project. Presumably had the contract period worked out to have been longer than the 18 months specified he would have either explored the possibility of increasing the rate at which the cranes would work or he would have sought another solution with more cranes. However, as has already been stated neither of these two options was necessary because the solution that he had 'plucked out of the air' could be shown to work. And because it could be shown to work no other solution combination was considered.

In the first round of think aloud experiments with a very much more straightforward project (The 'Dream House') the emphasis was much more clearly placed on the time aspect of the project. And although, once again, there were no examples of solutions being worked out 'backwards' there was an example of a construction programme being worked out forwards from which order dates were established by counting back the number of weeks that were necessary for detailed drawings to be checked, etc. In doing so it was found that because a particular building component could not be delivered on time work on site could not commence as soon as had been anticipated, whereupon subsequent capacity levels had to be increased in order to meet the handover date. And so again whilst clearly not a 'pure' example of backward chaining it did nevertheless contain an element of the strategy.

Conclusion: No evidence was found that supported the hypothesis that construction experts 'chain backwards'. However, the nature of the task, it principally not being one of time planning, coupled together with the fact that no time constraint was set for the project created the conditions in which the strategy would clearly not be of use. To properly test the hypothesis a different type of experiment would have to be organised.

6.36 Deal Temporarily With The Unforeseen Before Continuing With The Planned

Of course, having to deal temporarily with the unforeseen before continuing with the planned is as equally applicable in terms of information gathering as it is in terms of solution development. And, as has already been stated, it should really be thought of as less of a 'strategy' and more as a 'response' to unforeseen and unexpected pieces of information. Clearly in order to be able to identify whether or not a line of investigation has been 'strayed from' or 'temporarily abandoned' it is first necessary to establish what information is immediately relevant to a particular problem and what information is not relevant to a particular problem. Unfortunately it was not a simple task to find definitions for what were relevant and what was non-relevant factors, however, armed with a necessarily pragmatic and personal definition of these factors, the protocols of the three experts were analysed for such phenomena.

Nowhere in the protocols could it be seen that an established line of investigation was either temporarily or permanently abandoned for a quite different line of investigation. There were points during the experiment where the construction experts stopped looking at a floor plan, for example, in order to hunt out a detail drawing showing a cross-section, for example, but these were cases of associated investigation. This, of course, is what one would expect because the greatest majority of drawings are made from a two-dimensional perspective and for a construction expert to be able to gain a three-dimensional appreciation of a particular sub-section of the building he has to refer to other drawings as well.

Whilst it cannot be said that different lines of investigation were suddenly carried out during an already-established line of investigation there were clearly points in the experiments where information was 'unexpectedly discovered' that the construction experts had 'question marks' about. For example, C.E.1 had analysed various architectural plans and on studying the architectural sections stated that he thought it very strange that the vertical elements of the frame were detailed as being pre-cast concrete while the horizontal sections were hatched as being in-situ concrete. He explained why this would lead to all sorts of organisational and technical problems and said that if he were in the shoes of the engineer he would never advise such a solution. Five minutes later, having started to examine the engineer's drawings he discovered that the horizontal sections were also to be built in prefab.

“No, they are hollow concrete floor slabs after all, do you see? I thought that it was a bit strange that he hadn't detailed that. That's why I said that you really need the structural drawings as well because it was not logical. Look, this is how he achieves structural stability. Look, and now it's clear to me. Yep, fixed with Demu anchors and everything in the structural reinforced concrete topping. Nice. Very good.”

Conclusion: The phenomenon of dealing with unexpected sub-problems and then returning to the main previous problem was not observed. Of course, had the experiments taken place over a longer period than two hours and had the planners had the opportunity of being able to more fully develop a construction programme for this rather complicated construction project then perhaps the phenomenon would have been encountered.
6.37 Drawing Used by The Construction Experts

Looking at the pattern of crosses that mark which drawings were used by the three construction planners it can be seen that there is a remarkable degree of commonality between chosen drawings. All three experts chose to study the drawings that describe the space and within the building site itself. All three experts sought floor plans for the basement, ground floor and first floors, and all three experts studied drawings that detailed the pre-cast concrete elements. C.E. 3 avoided, however, the architectural drawings in preference for the engineer’s drawings. In the light of the poor hatching that C.E.1 discovered which caused him to believe for a short while that the vertical elements of the frame were to be prefabricated whilst the horizontal elements of the frame were to be cast in-situ, C.E.3 was probably quite right to have a higher regard for the engineer’s drawings than the architect’s drawings. However, because C.E.3 had not seen any architectural elevations or sections he was unaware of the curved glass roof that ran between the two long wings of the main building and was later to make the mistake of believing that the glass roof was to be found in the entrance building. However, this was a minor detail in comparison to the main task but does nevertheless illustrate the point that there can always be some undiscovered item of information in a drawing or elsewhere that potentially might have a material influence on planning decisions but for reasons of ignorance are not taken into account.

ARCHITECTURAL

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<tr>
<th>B5 001</th>
<th>Site location</th>
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<td>Acoustic measures glass roof en balustrade bridge</td>
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6.4 OBSERVATIONS AS A RESULT OF THE EXPERIMENT

Although the protocol analysis experiments were conducted chiefly in order to find out more about the strategies involved in searching through the design documents and putting forward a construction programme, a great deal more could, in fact, be gleaned from them. Some of these findings have been divided into six groups and are summarised as 1) initial evaluation based on spatial criteria & the non-reported logic of decisions 2) visual thinking 3) negotiating the problem space, 4) solution proposal and development, 5) personally bound preferences and 6) the priming of memory structures.
6.41 Initial Evaluation Based on Spatial Criteria & The Non-reported Logic of Decisions

As was described in Chapter 2 space is the ultimate bottleneck that cannot be overcome and therefore the medium that a planner has to understand and properly deal with when a construction process is pushed to the limit. There are many features about the way in which the construction planners conducted their analysis of the design documents that indicate that consciously or not the construction planners were more focused on the spatial limitations pertaining to sub-solutions than to the temporal limitations, although they clearly were concerned at times about temporal features as well. However, most of the problems were dealt with were spatial problems where the aspect of time did not even come into consideration. For example, only one of the three planners asked if there was a projected contract period whereas all three planners wanted to know whether or not all the space that was shown on the site location drawing would be available for construction activities.

In examining the protocols of the three planners during their analysis of the design it is quite straightforward to judge which construction activities the planners considered to represent the more awkward problems and which activities they felt could be carried out relatively straightforwardly. For example, the foundation was not considered to be of any great difficulty and indeed it was not particularly awkward when compared to other problems. Little of the planners’ time was spent analyzing the foundation drawings and little of their time was spent stating how they would have it built. One planner (C.E.2), at a later stage in his planning process, said that he would “pump the concrete of the foundation raft” and that he would “not place the concrete using a crane”. Unlike many other decisions this particular decision was not preceded or followed by any explanation or reasoning as to why he had chosen such a solution. In fact given the number of cubic meters of concrete and the distance that the concrete would have to be transported it was the most sensible decision, but the point is that there was no verbal reporting of why that decision had been made. And this is where it is clear that expert construction planners know under which types of circumstances certain units of capacity should be employed. Where the analysed conditions coincide with the idealized conditions for a particular unit of capacity then a planner will have little difficulty in ‘recognising’ which unit of capacity should be employed. Likewise for example the in-situ concrete walls in the basement were also considered to be a very straightforward problem requiring little consideration. Presumably this was because there was a great deal of free space between the walls, the walls were simple in form and they met at right angles. No mention was made by even one of the planners that shuttering would be required to support the wet concrete and that the shuttering would have to be maintained in a true vertical position by props; to the planners it was all-too-obvious as to how the in-situ concrete walls would be built - the problem was almost synonymous with the solution and therefore unnecessary to mention how they should be built.

In Chapter 4 the concept of “problem space” was described i.e. that part of memory in which the initial state, goal state and operators are held that can potentially transform the initial state into the goal state. In analyzing the design information a construction planner may find that some evaluations can be made very easily and quickly because some transformations can only be carried out by one type of operator and therefore the planner need not engage himself in any process of choosing between operators. However, even in such instances, of course, the design information will still have to be first of all analysed so that a decision can be made; this analysis will then activate the selection of a particular operator. And while it is impossible to examine an individual’s problem space it can be surmised that a subsequent judgement will take place as to whether or not the particular operator can be comfortably accommodated in the space that is available. Where the unit of capacity does not comfortably fit into the space or where some other aspect also needs to be considered then there will exist a problem that will require further analysis.

From the following statement it is quite clear that the spatial aspect of this particular sub-problem was given clear priority over the temporal aspect and that, because the problem was spatially quite straightforward, as a whole it was considered to present very little difficulty. C.E.2 stated:

“I can put down enough of a temporary road at the front part, so I can place the steel structure without a problem and I don’t see any difficulties as far the entrance building is concerned. I shan’t spend much time looking at that. It can only be a question of time; in terms of building method it won’t be a problem to erect that there”.

6.42 Visual Thinking

While it is not possible to directly inspect an expert’s “problem space”, judging from how important experts have stated visual thinking to be (Stockings, 1994) and given the overriding spatial aspect of construction problems, it seems very likely that such a “problem space” will be a highly visual one. It is speculated that as each sub-part of the building is analysed, that part of the building will be understood in terms of the construction capacity that can build that part of the building. It is speculated that the planner will “see” the unit of capacity in the newly analysed situation whereupon a judgement can be made as to whether or not the unit of capacity can operate comfortably in the space that is available. Newell and Simon (1972, p.801) state that the “STM should be defined, not as an internal memory, but as the combination of (1) the internal STM and (2) the part of the visual display that is in the subject’s foveal view”. It is speculated that as a planner examines the basement in-situ walls, for example, he will automatically “activate” the types of equipment necessary to build those walls and see them on the drawing in front of him. On the basis of this superimposed vision of the units of capacity he will be able to make an evaluation as to whether or not the demands and the capacity are in or out of congruence. Of course, it cannot be directly proven that this imaging takes place but it can be argued that logically a planner can only make a judgement about a particular situation when he has analysed the building demands, recognizes the units of capacity that are necessary to construct that sub-part and makes a comparison of the two. A similar phenomenon was reported by Moyer (1973) who was interested in the speed at which people could recall from memory which of a pair of animals was greater; many people reporting that they experienced images of the two objects and seemed to compare the size of the objects in their image.

The mental “superimposing” of units of capacity on to the design information can be said to have been indirectly witnessed where a construction planner was considering the crane question and the siting of the necessary temporary roads and sketched their location on the site layout drawing. This was not done randomly but after some careful consideration, in other words, the planner will have had to have considered the location of the temporary roads on his visuospatial skethpad in memory before he will have resolved certain aspects and found a particular solution. In fact it can be argued that the whole act of sketching will not occur without aforethought, everything that a planner draws will most likely have to have first been considered and “seen” in memory before it is set down on paper.
Even in the instances where statements were made that effectively said that there was “no problem” certain steps logically have to have taken place; the demand situation and the corresponding units of capacity would have had to have been held in an activated state in short term memory in order that a judgement about them could be made, even though in some instances they were not verbally reported. It is thought highly unlikely that a decision could be made without some sort of ‘comparing’ mechanism being engaged whether it be a visual one, a verbal one or possibly even a combination of the two. Evaluation simply cannot take place without there being some sort of comparison between the newly analysed situation and situations stored in memory.

6.43 Negotiating the Problem Space

It was quite evident that the planners held as an important objective the manipulation of conditions so that the capacity could operate as easily as possible. For example, all three planners, having ascertained that the pre-cast concrete elements were very heavy (ranging between 8 and 22 tons) investigated whether it would be possible to erect the building behind the main building at a later stage so that crane access could be improved; the test of whether or not the lower building could be built later being whether or not there were any particularly time consuming activities in that building. The two planners who developed a plan both decided to do this in fact.

Another example of attempting to make the problem easier was where C.E.3 said that he would consult the structural engineer to see if some of the heavier elements could be divided into smaller elements. Another planner (C.E.1), because he concentrated more on the analysis of the drawings than the other two planners, and therefore was able to look into the project at more depth, suggested that the in-situ concrete pads on the roof for the mechanical window cleaning system could be better replaced with prefabricated ones because then they could be placed once the roof had been laid, allowing the building to be made wind and weather tight at an earlier stage.

As had been stated in Chapter 2 the two dimensions in which construction solutions have to be placed and harmonised are the time and spatial dimensions and it was clear that the experts wished to seek out the major constraints that would have an influence on the way in which activities could be placed within these two frameworks. And although there was not sufficient time for the construction experts to draw up detailed programmes for the project it was clear that particular production constraints were of particular interest to them, constraints that act as “stop” or “go” signals for other construction activities. For example, the point at which the building could be made wind and weather tight was the point at which work on the internal finishes could proceed, but protection from the weather could not be achieved before the external envelope had been laid, which itself could not be completed before all concrete work at high level had been completed due to the risk of spoiling high quality prefab panels from falling wet concrete. Another time constraint that was clearly considered of being importance to all three planners was the long lead-in time that would be needed for the pre-cast concrete elements and the fact that if an early start was expected on site there would probably come a lull in production once the relatively straightforward groundworks and substructure had been completed. One planner (C.E.1) spoke in this respect of “losing time” because there were no foundation piles.

The problem space as it has been used in this sense is not the problem space that Newell & Simon (1972) wrote of i.e. the mental representation of a problem, but the physical problem space as set in the spatial and temporal dimensions in which a demand from the design requires a certain performance from a unit of capacity. The planners were clearly conscious of the boundaries of these dimensions particularly where strenuous demands were present and attempted to ease the boundaries and demands so that the lightest units of capacity could be used. It was quite clear that they would attempt to influence the design so that the demands could be reduced in order to make the building production friendlier. Design aspects were not just taken as non-negotiable inputs but as being very much negotiable particularly where the design would not be detracted from and where construction could in some way be assisted.

6.44 Solution Proposal and Development

The way in which the solutions that the two experts developed went along the lines of proposal and development. Solutions were put forward at various stages during the analysis of the drawings. Analysis of the drawings would continue, new information would be discovered and the solutions developed. In the case of C.E.2, for example, he made an analysis of the structural engineer’s plans, stated that he now had a good idea as to the structural set-up of the building and said that he had not worked out the weights of the elements but that it was clear that a moveable crane as opposed to a stationary one would be needed. He then stated that he would need to look at access and decided that as the building was symmetrical he would have the crane positioned on the rear side of the building. At later points in the experiment he reiterated a further two times that a mobile crane of some description could be placed at the rear of the building. He then went on to examine the detailed drawings of the pre-cast concrete units to work out their weights. He realized that some of them were “gigantic” – up to “22 tons”. He spent five minutes working out the weights of various elements and cross-referenced them with their positions on the plans. Having completed that exercise he stated that “a very heavy crane would be necessary” and that “he would want to get as close as possible to the front of the building” with the crane. He then decided that he would not only need a temporary road at the back of the building, he would also need one at the front of the building as well. And much later on he was to decide that he would link up the temporary road at the back with the one at the front so that he had the opportunity to drive all the way around the building and not box himself in.

It was clear that, although he had taken on board quite a lot of information when he stated that he now had a good idea as to the structural set-up of the building, he still in fact had not yet uncovered enough information to enable him to make a proper decision. His first decision was to be altered and the second one concerning the temporary roads was to be added to.

Decisions were not only “developed” but could often be described as “loose-fit”. In other words they were rather vague and clearly rested on knowledge of construction practice that was not being explicitly stated. For example, (C.E.2 10:31:30) stated, “That is the basement. I'll pour that in-situ and that shouldn't be a problem". But he was not to say at this stage whether he thought that three hundred men should run back and forth with wheelbarrows, or whether the concrete should be transported by crane or whether a concrete pump should be employed. At a much later stage in the planning when he had approximately settled the

20 The first expert who took part in the experiment made a thorough analysis of the project but did not develop any solutions.
question of how the pre-cast panels should be lifted he stated that he would use a pump for the basement and that he would not use a crane.

These examples illustrate two characteristics of the way in which expert construction planners develop solutions. Firstly that tentative solutions are put forward and then developed and secondly that some earlier decisions encompass a range of possibilities rather than one particular solution. This would seem to reflect the nature of the problem and the fact that it is not well-structured because one system can have a large spread of influence over other systems and only by gradual proposal and adjustment can the systems be brought into harmony with one another. So too does the fact that a construction planner needs to trawl a great deal of information in order to bring a construction plan into harmony, information that even at a late stage of discovery might have a profound effect on how a construction process should be carried out. The lesson therefore would appear to be to delay decisions for as long as sensibly possible in the analysis of new projects. But on the other hand by making decisions and subsequently discovering that there is a problem with that decision is probably also a valuable part of exploring the problem space that can only take place once a decision has been made. In other words it seems that in dealing with an ill-structured problem a tension will always exist between delaying decision making until the problem has been better analysed and making a decision and exploring the problem space more deeply through the discovery of secondary problems.

6.45 Personally-Bound Preferences

The protocols also demonstrated that initial decision making at least is based on personally-bound beliefs as opposed to objectively-measured criteria. For instance, one planner chose to use a mobile crawler crane to lift the pre-cast concrete panels while the other chose to use two tower cranes on rails. The fact that they had chosen different solutions also meant that they were faced with different secondary problems. For example, the planner who chose to use two tower cranes said that it could not be avoided the fact that a 600 kVA electric cable would probably be required which he clearly considered to be a substantial demand, whereas a mobile crane, being diesel driven, would require no such electric cable. The first planner stated quite clearly that he would not use tower cranes even on rails, and that he would use a mobile crane on a crawler underbody because in relation to a road-going mobile crane of the same capacity it could handle a lot more weight. When the planner who had chosen the tower crane solution came to check the capacity of the crane that he had suggested he found that it simply could not handle the weights over the distances that were involved. He then decided that for ‘incidentally heavy’ panels he would use a mobile crane as well.

6.46 The Priming of Memory Structures

It is believed that when a construction planner analyses the design information he goes through a process of priming memory structures so that a particular sub-part of the building might be understood in terms of a small selection of possible solutions without one solution being necessarily explicitly chosen. At some later stage in the process, when a decision has been made about some other aspect of the construction process or where a relevant new piece of design information has been analysed, can the values that emanated from the earlier analysis be combined with the value of the newly-made decision, so that a decision can be made about the earlier analysis. Such an example was witnessed in the protocols.

The protocol of C.E.2 started at 10:14 am. At 10:20 am he analysed the foundation drawing for the first time.

(10:20 am) “Now, let’s have a look here at the drawings – level 1 foundation. Those are two drawings .... walls from the front and back sections – quite an extensive thing. I would have preferred to have a drawing with a smaller scale then I could have laid everything on the table. There’s a great deal of information here. There is more information than would be on a smaller drawing. Anyway, I can see that the basement has an in-situ floor with walls and columns. And in the cellar the walls and columns are – the cellar walls and most of the columns are in-situ (concrete). And then it carries on in prefab (concrete) and in the front building I can see that the walls and columns are mainly in-situ. And then a floor higher it is mainly pre-fab apart from a few walls. I’ll have a look a bit higher”.

C.E.2 had established six minutes after he began analysing the drawings that the basement floor was “in-situ”. Exactly how the concrete should be placed was certainly not mentioned, although much later in the protocol at 10:52 am he was to state that he would use a concrete pump and not the crane, so it seems safe to assume that at this early stage he had considered both methods or at least ‘recognised’ that two solutions existed for the problem. And, judging from the matter-of-fact way that he reported that the basement floor was in-situ and the way in which he continued his analysis without further remarks about the basement, he presumably felt that there was nothing particularly difficult or untoward about the basement.

The planner was to look at the same foundation drawing four more times but not once was the basement floor specifically mentioned. For example, at 10:31 am he used the drawing to indicate that he would run the crane along the back of the building and at 10:33 am he used the drawing to establish the approximate size of the pre-cast concrete elements to the lift house. It was not until 10:52 am that he, verbally at least, made the decision to use a concrete pump for the basement floor, although he was not actually looking at the basement floor drawing when he did so but the site layout plan.

(10:51 am) “... and that means that I’ll make a new entrance because it is very difficult to get round the corner there (10:52 am), to get in there. Then I will assume that I have kept enough ground temporarily at least to get to this point where we can set up the crane. I’ll place this prefabrication here from this point. I’ll put down a temporary road here so that later on I can place the prefabrication from here and the rest of the prefabrication at the top end and then on the basis of that I can determine what type of mobile crane I’ll need. The real order will be basement. The floor I am just going to pump. I don’t use the crane for that. That means that I am going to excavate, (10:53 am) build the basement floor with the pads that go with it ....”

But it was clear from what he said that he had at least considered using the main crane of the site for pouring the concrete to the basement floor as well. He had analysed in detail the weights of the various pre-cast elements, their positions and where temporary transport routes should be built. And having established that a very powerful crane would be required for the elements he presumably felt that it would not be economical to have the same crane brought earlier to site so that it could assist in placing the steel reinforcement and the concrete. Judging from what he said it was clear that this would sometimes be thought appropriate. However, at the time when C.E.2 examined the basement floor drawing for the first time he had not yet established what sort of main crane would be used for the job and therefore could not yet sensibly decide whether he would use the main crane to place the basement floor concrete or not. Thus certain possibilities had been ‘primed’ but a choice could not yet ideally be made.
6.5 CONCLUSION

Of the six strategies that were put forward four could be shown to be supported by evidence. The other two could not. The fact that two could not be supported does not necessarily mean that they could not at times be appropriate strategies to follow but that they were not observed during the three 2-hour experiments that were conducted with construction experts. Had the experiments lasted longer and had the tasks and problems been different then they may well have been observed. The only way to resolve the matter would be to conduct more protocol analysis experiments, of course.

The fact that two strategies were not observed and the fact that they might otherwise be observed is indicative that strategies are not universally applicable at all stages of the construction planning process, but that their use will be based on certain criteria. For example, the so-called “Big Picture” is an action that will take place right at the beginning of the analysis stage of the design drawings and takes place in order that the planner can get to grips with the project in its setting. The strategies “Follow the Structure” and “Major Plant & Equipment” on the other hand are strategies that are of longer duration, but once the structure of the building had been analysed and the major methods of construction had been chosen might no longer be of applicability. And so the question of whether strategies will be applied is governed by at least two aspects i.e. 1) the point in the process at which the strategy could be applied and 2) the type of (dominant) problems that need to be solved at that point. In which case it is possible that there will exist a hierarchy of strategies and a degree of applicability to various scenarios, rather like design methods that will be more or less appropriate under particular sets of circumstances. Of the strategies that were observed the dominant analysis one was “Follow the Structure” and the dominant synthesis strategy was “Major Plant & Equipment”, although due to the time limit planning did not get beyond the skeletal phase. And because the task was not programme orientated, for example, the strategy of “chaining backwards” was not likely to be observed anyway.

But whilst certain strategies may describe the way in which construction planners will go about looking for information or developing a solution it is the information itself and what that information means to the construction planner that guides the planner on a particular course. In the experiment that was conducted it was the crane problem that was the dominant problem for the planners. However, it is quite plausible to imagine the situation where a planner had dealt with a similar project very recently and would be able to ‘recognise’ the crane problem very quickly and be able to state what type of crane would be needed, where it should be positioned, how long it would take to construct each floor, etc., etc., and then be able to move on and deal with other problems. The question of personally bound experience can therefore play a large part in how an individual goes about planning. Each construction expert will read the information contained in the design information as though it contained signboards directing him on to follow a particular path of analysis and to solve different types of problems because each construction planner will be sensitive to different problems. But, despite the large number of drawings that were available and the fact that the three planners worked for different companies and therefore had different experiences of experience, there was in fact a great deal of commonality in terms of the drawings that the three construction experts examined as well as the order in which they examined them. This would appear to confirm two things: firstly that there is a definite structure in a construction planning problem that is made up of the logic of technology, materials science, etc., and secondly that experienced planners can identify a hierarchy of problems within that structure.

Construction planning is the assignment of units of capacity to temporal and spatial frameworks so that construction outputs can be realised. Construction planners clearly occupy themselves with how these frameworks can be organised so that available units of capacity can operate as easily as the design and various constraints allow. In order to be able to do this planners need to know the size of these various frameworks as well as the magnitude of the performance that has to be achieved within any particular framework. From the way in which the planners analysed the design information and their continual commentary on their own processes it was clear as to which problems they considered fitted comfortably within a particular frame and which did not. Where there were problems of large demands on the capacity within a given frame the planners would attempt to find ways of reducing the size of the demand or increasing the size of the frame so as to make the problem less constrained.

Judging from the way in which the planners analysed the design information they first of all sought to understand the size and makeup of the various frames, analysing the largest first. This analysis started with the inspection of the site layout drawing which gave insight into the size of the site, the size of the building to be built in relation to the site, information regarding location and site entry. This was followed by a search into the size and make-up of the physical framework of the building (the substructure and the superstructure). This having been done the planners clearly felt that they had enough insight into the project as a whole to be able to start the process of drawing together a construction programme. Generally speaking the planners were more concerned with the spatial frameworks than the temporal frameworks, although certain temporal constraints were mentioned by all three planners. The fact that a construction programme should be drawn up was something that was mentioned by all three planners but to begin with at least they were more concerned with understanding the technical demands of the project and their comparative sizes rather than how long it would take to build a particular section of the building. Of course, the duration of an activity can only be established once the size of the demands has been established and corresponding units of capacity have been chosen, then it is more or less a simple long division problem in order to arrive at how long those units of capacity would take to build a particular sub-element of the building. All three planners measured the dimensions of the building and all three worked out how heavy the pre-cast concrete elements of the frame were. The structure was clearly the largest ‘frame’ problem in the literal and metaphorical sense and therefore the way in which the pre-cast concrete elements that made up the frame would be placed was the single largest frame-problem that the planners had to deal with. When viewed in terms of the criteria that were set out in Chapter 5 (footnote 4) it was clear that the crane problem was a major problem because the crane would need to operate in a large area of space, it would be instrumental in the way in which the structure would be put together, it would take place over a large proportion of the total construction period and it would very likely involve large indirect costs (transport to site), as well.

The over-riding strategy of the planners was to understand the load-bearing structure of the building. Load-bearing information also included the nature of the subsoil but unfortunately the soil report in which this information could be found was not available to them. The load-bearing structure and its make-up were clearly of the greatest importance in determining where transport routes and major equipment should be sited, and the greater part of the initial analysis of the design information was clearly orientated towards the goal of better understanding of the structure. However, very much later on in the planning exercise when

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27 Different experience within the context of experience within one country as opposed to different experience between say the European and Asian building industries.
the planners had a good grasp of the scope of the total problem, the examination of design information would become less goal-orientated and more opportunistic. For example, one planner started to look at the drawings which detailed where the electric and gas cables were situated and was 'prompted' to think about whether or not the central heating for the site building should be based on a gas-burning or an oil-burning system. He decided that because running a gas cable around to the back of the site would likely be very expensive it would be cheaper to have an oil-based central heating system. From the protocols therefore it was quite clear that a planner will mostly follow a strategy in searching through design information but will clearly at times also examine information on a more casual "as-it-comes" basis. Even looking at the "wrong" drawing at any particular moment in time might not be a completely wasted effort if some of the information in that drawing can be retained by the construction planner and used at some later stage in the planning process, or if through the examination of the information in that drawing the planner is somehow 'prompted' to think of some important aspect of the process that he had not yet considered. However, in the main the planners were clearly goal-orientated in searching through the design information and did not leave the process to chance. One of the planners even consulted a checklist every now and then in order to make sure that he had considered all the relevant facets.

The evidence of the protocols appears to support the notion that the question of choice regarding major plant and equipment will play a dominant role in construction planning strategy; it also appears to support the notion that complex problems should be dealt with before straightforward aspects. Logically it makes sense, of course, that the question of major plant and equipment should be resolved first because major plant and equipment can have such a large influence on the rate at which the overall construction programme can be carried out, as well as have a big impact on the way in which the site will have to be spatially divided. And clearly where there is a hierarchy of problems, where one problem has to be resolved before another problem can be tackled, the dominant questions will have to be resolved before the less dominant ones can be dealt with. In other words where one problem that can be chosen quite easily from a generous solution space is impacted upon by a more complex problem that exists within a more constrained solution space, it would seem to make more sense to make the more complex decision before the straightforward one because the more straightforward one can yield more easily to the more complex one than the other way round. A construction planning process is about fitting units of capacity into time and spatial frameworks - a bit like a packing problem where objects of various shapes and sizes have to packed into the smallest box possible with a minimum of non-utilised space - it being more sensible to start considering how large the box needs to be to accommodate the larger items rather than the smaller items.

7. Conclusions

7.1 OBJECTIVES AND RESULTS OF THE RESEARCH

The initial motive for carrying out this research was to develop a so-called design method that would assist construction planners with the planning of large and complex projects, especially less experienced and student construction planners. The goal, of course, was more efficient construction. The exact form of the necessary design method was not clear, that would only transpire as the research continued.

The whole concept of design methods was not one that originated from the construction side of industry but from the design side, from the architectural and industrial design community in general and, in a sense, from Christopher Jones in particular. The subject of design methods played an important role at the Faculty of Architecture (Eindhoven University of Technology) at the start of this research (1991), and it was against this background that the Department of Construction Technology took as its goal the development of a design method for construction planning. At that time there were no researchers in the field of construction technology who were pursuing such a goal. The topics that were of interest to the construction side of industry were more related to the various forms of construction management and artificial intelligence; the latter being the pursuit of ways in which computers could partly replace or support human decision making in construction planning. No researchers considered as a specific goal how an individual might be able to plan more efficiently and effectively as an individual processor of information; presumably as it was felt that beyond education and experience there was little more that could be done to improve an individual's ability. With regard design problems some industrial designers and architects were of a different opinion, although designers clearly have to deal with much less well-structured problems than construction planners do. Some designers and architects were of the opinion that methods needed to be developed that could help them deal with a sometimes chaos of information. The result therefore was that there was a great deal of literature on the subject of methodical design from industrial and architectural designers and nothing that resembled 'methodical planning' from writers on construction. The nearest that any of the literature came in construction planning to advice on method was the type that came from Neale (1989), for example, who recommended that a planner should be allowed to work in peace and quiet, that he should not be disturbed by colleagues or the telephone and that he should have plenty of wall and desk space.

As more of the literature was consulted more dissenting opinions on the whole question of design methods would be found, some of them very passionate, among them was Broadbent who at the start of the movement was very much a proponent of methodical design but came to want nothing more to do with it claiming that people were looking for a formula, and that they were trying to promote good and sensible ideas as 'methods'. In the Eindhoven University press there would also appear articles by researchers and practitioners such as "The method does not exist" (Bakel, 1993). But research into design methods had slowly changed from prescriptive modelling into descriptive modelling. No longer were researchers proposing formulas of how the process should be carried out, but instead they turned their attention to describing what designers actually did whilst designing. Newell and Simon (1972) the originators of the Human Information Processing Theory had considered the task of the architect and had conducted protocol analysis experiments with them. This lead to a number of other researchers carrying out similar experiments with architects and their putting
forward certain theories about the nature of design problems and the way in which human problem solvers deal with them.

It had become clear that if were to be possible to develop a design method for construction planners it could only be done so by first of all having properly described the construction planning process. Hamel's thesis (1990) was particularly inspiring in this respect because he had conducted think-aloud experiments with architects who had been tasked with the question of designing a school. The method of protocol analysis seemed a potentially very appropriate process. This seemed an appropriate question to ask because if a design method were to work then it was hoped the question of what steps and phases go to make up the planning process. Hamel's thesis was particularly inspiring in this respect because he had conducted think-aloud experiments with architects who had been given the task of planning a process. It was therefore decided that there were no particular benefits to be gained by being excessively detailed in dividing the verbalisations of the planners. But it was logical it seems very difficult to accept that an evaluation can be made unless some sort of comparing mechanism is engaged. In terms of the evaluation of the foundation the question was that, was the comparison of the examined project with an instance of a past project in memory where it was known that there were no untoward problems i.e. where no specific consideration of units of capacity was made at that point? Or did the evaluation take place only once potential units of capacity had been associated with the particular part of the building and some sort of judgement made about sufficiency of space and the ease of use of that type of capacity in that space? Or was there a combination of these two types of comparison? But these were issues that were far removed from the intention of the research, although it had become clear that they were certainly relevant to the nature of the research. Of course such issues are fundamental to the nature of human problem solving and are not just peculiar to construction planning. It was therefore decided that there were no particular benefits to be gained by being excessively detailed in dividing the verbalisations of the planners. But it was clear that the activities analysis, synthesis and evaluation would take place in larger and smaller cycles in such a way that information from the design drawings and from the planner's memory could be said to be 'knitted' together. But no sensible prediction could be made about the order and timing of these cycles.

The second question that this research attempted to answer was, "What strategies do construction planners apply in dealing with construction planning problems?" The protocols lent themselves more obligingly to this question because it was more straightforward to identify what information was being analysed and what solutions were being put forward. It short it could be concluded that the question of whether or not the strategies that were suggested during the research could be supported or not was relatively straightforward; the results of which are described in more detail at 7.3.

7.2 THE METHOD OF PROTOCOL ANALYSIS

The data of this research was acquired using the technique of protocol analysis. Expert construction planners were presented with design information and asked to think aloud whilst considering how the construction problems could be solved that the design presented. As has already been described there were two ways in which the results in this research were used. On the one hand an attempt was made to differentiate the phases within the process and on the other hand the data was used in order to trace the order in which information was analysed and the various problems solved. The method was therefore applied with two different objectives, one, which for reasons that have already been described, could be more satisfactorily achieved than the other. The aspect which enabled a great deal to be learned from the protocols was the traceability of information in terms of problem analysis and problem solution. While clearly not all knowledge regarding the development of a solution mentioned, after some other question had been settled. There was a clear example in one protocol of the planner deciding to use a concrete pump for the foundation but he only mentioned this towards the end of the exercise whereas right at the beginning of the exercise he had examined the foundation drawings and had stated that the foundation did not present a particular problem. The question was whether they realised at the initial analysis of the foundation drawing that it was a task for a concrete pump and because there was lots of space the foundation did not present any untoward difficulties, or had he made the same evaluation without specifically thinking in terms of a concrete pump and indeed only thought of a concrete pump at the point in the exercise when he mentioned it? (It was in fact felt that he had thought of using a concrete pump much earlier, but this could not be proven).
was verbally reported, particularly for those problems that can be described as recognition problems, a certain amount of production knowledge was verbally reported. And this would appear to be an area in which protocol analysis could be used to great effect in construction research, more specifically, in helping to capture the knowledge that differentiates an expert from a non-expert.

In the first think-aloud experiment that was carried out using the more complex design the task that was put to the construction expert was apparently not clear enough because he actually solved very few problems. What he did do though, being particularly interested in details where elements of the structure joined together, was to make a thorough analysis of the drawings and suggest a number of ways in which the design could be improved to facilitate construction. He also described what he thought were the more critical construction aspects of the project and how they should be further dealt with. Whilst it was unfortunate that he did not put together a construction programme or look at the question of site layout for example, he did describe a great deal of the rationale behind various types of decisions. For example, there was no ground report available with the design information and he explained in great detail why it would be important to know about the nature of the sub-soil, level of ground water, etc., and how various combinations of circumstances would have different consequences for the way in which foundation piles would be driven and the site arranged, for example.

The think-aloud experiments that were conducted in this research were carried out with the objective of disturbing the experts as little as possible, of avoiding any forms of communication except in circumstances where the participant could not make any further progress for whatever reason. This was done in order that the construction planning process could take place as naturally as possible so that any claims to a particular structure in the process would not be undermined. But, where the goal would be to elicit production knowledge from an expert, the nature of the think-aloud experiment could take on more the form of an interview where questions could be asked of the expert at various points in the process as well.

The think-aloud experiments could take on different forms and involve different types of projects. In fact there is a great potential for the method not only in terms of acquiring information from experts but also in testing students, for example. It would be a very interesting exercise to set experts and non-experts alike an identical task and then to compare their results. Such exercises could be of great benefit to students in helping them develop their planning skills and would give lecturers the opportunity to identify any areas that might require improvement from the teaching perspective.

Setting experienced planners of different nationalities the same task might also lead to some interesting insights into different construction methods. Think-aloud experiments could also be conducted with specialist sub-contractors, for example, if it were felt that particular production information needed to be gained and that there were problems of integration between the main contractor’s work and that of the subcontractor, for example. Planners could also be asked to give their thoughts on how buildable a design was considered to be, as well as any suggestions that they may have as to how that aspect could be improved.

The purpose of such experiments would be to gain production knowledge that is typically only ever gained through experience and to codify that knowledge in some standard way. It would be important to have a standard method of coding information both on the design document side and on the solution side. In this way it would be easier to compare the processes of different planners especially in terms of what information was used to support various decisions and the order in which those decisions were made, and to build up a better picture of what factors play a more dominant role in decision making. And, where it could be shown that there was a great deal of commonality in terms of the data that different experts examined, checklists could be compiled that would help ensure that all relevant aspects to a decision were considered.

The question of the duration of the think-aloud experiments is an important one. The think-aloud experiments that were conducted in this research each lasted about two hours. On one hand the longer that an experiment lasts the more that can be potentially learned. However, it should not be underestimated how much data is gained from such an exercise nor should the task of typing up the verbalisations be underestimated; typically it takes several days just to type up one experiment, particularly where the participant does not speak very clearly and passages of verbalisations have to be replayed a number of times. On the other hand it is better that such an exercise is kept short because it is rather mentally demanding of the participant, and clearly it is better that he or she is mentally fresh and alert than tired and forgetful. And of course it should not be forgotten that some experts can be persuaded to give up their time at no cost, or the firms they work for agree to allow their employees to take part in such experiments at no cost, but if experiments of longer duration are planned, say for example over a few days, funds would probably be required for remuneration of services.

As has already been stated experts do sometimes report decisions without any hints as to why they have made a particular decision. Therefore, once a protocol has been analysed and as many rules codified as it were felt possible to codify, it might very well be a useful exercise to interview the expert once again and show him relevant passages on the videotape so that he could explain why particular choices had been made.

7.3 THE MAIN FINDINGS OF THE RESEARCH - THE STRATEGIES

As was earlier described, during the course of the research the question arose of the order in which an expert would examine and deal with the problems that a design presented, where the design information was made up of many drawings. Reflection on this question lead to a number of hypotheses being put forward which were subsequently tested by analysing the data from the protocols. Of the six strategies that were put forward four could be shown to be supported by evidence; two could not, but as was pointed out in Ch.6 the fact that two strategies could not be supported did not necessarily mean that they might not be observed under different circumstances. The fact that other strategies might be used suggests that the use of strategies might be governed by two aspects, namely 1) the point in the process at which the strategy could be applied (reflecting the knowledge state of the planner at that point) and 2) the type of dominant problems that need to be solved at that point. However, that having been said on reflection over the whole findings of the research there is in fact one dominating analysis strategy that emerges as well as one dominating synthesis strategy; although they are really just opposite sides of the same strategy. The strategy is quite simply to follow the work-front. The work-front starts in the ground, passes up through the foundations into the superstructure and into the façade, the internal partitions, the electrical and mechanical services and into the finishings; the exact order of course depending on the nature of the design.
The structure of the building was clearly regarded as being of the highest initial importance. Drawings regarding the electrical and mechanical services, as well as drawings detailing the location of the various service cables were put clearly to one side and were hardly ever looked at throughout the experiment by the three planners. The structural engineer's drawings were clearly preferred to the architectural drawings. One planner specifically stated that it would take him a lot longer to get a structural impression of the project if he only had architectural drawings and no engineer's drawings.

One of the hypotheses that had been put forward was that the planners would probably wish to gain a three-dimensional impression of the design by analysing the architectural elevation drawings. This the planners did not do. Instead they sought a three-dimensional impression of the project through the structural drawings. From these drawings the overall dimensions could be gleaned, the number of floors, the height of the building but with direct information regarding the structural make-up of vertical and horizontal elements of the building starting with the foundations. It could be seen directly whether the elements were made up of in-situ concrete, pre-cast concrete, steel, timber or whatever, and the sizes and positions of the various elements could be seen. In fact it would appear that, to an expert construction planner, the structure forms the first problem solving question in a construction planning exercise in which information regarding the presence and routing of electrical and mechanical services and the types of internal partitions and finishes, and even the façade to a certain extent, do not even enter their decision making processes. It was evident that to the planners who took part in the exercise, the first and foremost priority was the question of how the structure should be assembled, and to make that decision certain types of information could be clearly left to one side. The three planners' approach to the analysis of the project was remarkably similar. Presumably they had found from experience that analysing the structural information first was the most economical way to analyse a project and to deal primarily with the problems that the structure presents. Of course, had the planners regularly found that having decided on how the structure of the project should be tackled and how the site should be divided that those decisions were materially affected by factors that arose form the subsequent analysis of the mechanical and electrical service drawings, for example, then presumably they would also have analysed those drawings as well before making decisions about how the structure should be assembled and where temporary roads should be sited, but they did not. One planner hardly ever looked at any architectural drawings. All of which very clearly suggests that there are hierarchies of problems, at least two in any respect i.e. the structure and the rest, and that the structure takes clear precedence. Theoretically it is always possible that on subsequent analysis of other types of information slight adjustments would have to be made to the question of how the structure should be tackled but judging from the behaviour of the three planners who took part in the experiment that will occur seldom to never. Their clear priority was structure first.

The construction planner who wished to more or less examine the engineer's drawings exclusively did however inspect the architectural drawings in order to gauge whether the buildings at the back and front of the main building could be built later or whether they would have to be built at the same time as the main building. He did this in order to establish how near to the main building the route of the crane could be positioned. He concluded that the building at the back (a concrete bicycle shed) could be built later but that the building at the front would need to be built at the outset because there were clearly more time-consuming activities in the front building (it had a complex form and included a great deal of service equipment). But the question of the nature of these sub-buildings had arisen out of the planner wanting to settle the question of how the main building could be built. In order to gather that information the planner did not have to inspect all the architectural, electrical and mechanical service drawings instead he could be much more goal-orientated in his search.

It would appear that there is a good psychological reason why the planners should wish to examine the structural engineer's drawing first; simply that it is far more straightforward to form a mental picture or gain an understanding of something when information is presented in a random and unrelated way. By information being presented in a related way the subject matter can in a sense be "glued" together. By analysing the structural engineer's drawings the very framework of the project can be assembled mentally so that the total scope of the project can be understood and then later filled in with the details of the façade, the internal partitions, the mechanical and electrical services, etc. When there is nothing that links two pieces of information those pieces of information may remain in limbo and unconnected until the missing links have been discovered. Planners, having experience of many projects will probably have stereotypical schemas in which such items of as-yet-unconnected pieces of information will be able to be stored until a more positive status in memory can be given to them. But clearly trying to work out how a piece of information probably relates to other pieces of information will be much more time-consuming than knowing almost immediately how the last piece of analytical information connects up to foregoing information.

As a plan development strategy it also makes sense that just essential or the most immediate information is analysed because then short-term memory and working memory need not hold information in an activated state that has no bearing on the central problem. Rather than search through all sources of information for possible factors that might not even be activated as factors that affect the decision anyway by the time that the decision comes to be made, it is probably more efficient to make decisions based on the most immediate factors and then adjust them later when other types of design information are analysed. Planning decisions that have been made can be subsequently reversed or adjusted; it is not as though once made they are impossible to overturn. And this type of planning behaviour was observed during the experiments; decisions were made and subsequently adjusted in the light of new information. Planners did not wait until they had analysed all the design information before they started the process of putting a plan together.

7.31 THE HIERARCHY OF COMPLEX AND STRAIGHTFORWARD PROBLEMS

An aspect that came out clearly of the protocols is that not all planning is problem solving. A proportion of planning can be fairly mechanistic. Newell & Simon (1972, p.821) stated:

In common sense terms we might not refer to [somebody who was asked to multiply 1492 x 1762] as solving a problem at all, but simply as following "mechanically"a well-learned algorithm for multiplication".

In the same sense we would not say that a planner had solved a problem because he were able to state, upon seeing a brick wall hatched on a drawing, that brick layers would be required to lay the bricks and that a scaffold would be needed for work above a particular height.

The in-situ concrete walls in the basement were also such a case. All three planners analysed the basement drawings, mentioned the fact that the basement walls were in-situ concrete walls
and carried on their analysis without considering them any further; the in-situ walls were clearly a "non-problem" as far as they were concerned. The word "formwork" did not even need to be mentioned because it was all-too-obvious that where in-situ concrete was detailed formwork would be required. To an expert a great deal of the elements of the building will often be dealt with by the same mechanistic reasoning so that any new project that they evaluate will very likely present a mixture of many recognised problems together with a degree of new problems.

Just as it is possible for an expert to make a very quick evaluation as to whether or not a particular aspect of the design presents a straightforward problem, so too must an expert be able to judge whether or not the demands that a design places on the units of capacity go just slightly further or very much further outside the ordinary scope of the capacity or not. Newell & Simon (1972, p.814) stated, "The recognition process is a powerful selective accessing mechanism to the internal memory". In a sense information stored in long term memory that is activated through recognition will act as a sort of mirror in which a comparison can take place between the analysed situation and the situation in memory. It is on the basis of this mirroring in which rapid evaluations can be made allowing a construction planner to identify the aspects of a project that represent standard types of problems for which standard types of solutions can be applied, as well as being able to recognise the non-standard types of problems for which reasonably or substantially novel solutions will have to be drawn up; the latter being more in keeping with what we would ordinarily term 'problem solving'.

7.32 NEGOTIATING THE SOLUTION SPACE

A construction planner will analyse the design drawings in order to gauge the size of the various problems that that design presents. As has already been described some problems will be considered 'non-problems' for which standard types of solutions can be applied. These will be easily recognised by the expert. On the other hand aspects that present non-standard solutions will need to be examined in more detail and the planner will attempt step-by-step to find the right combination and set of circumstances under which units of capacity can deal with these particular problems.

From the protocols it was clear that the experts would attempt to negotiate the solution space in which a particular performance was required. Negotiation would take the form of either trying to reduce the size of the performance that was required, or of trying to increase the size of the solution space in which the performance had to be carried out. For example, one construction expert discovered that the pre-cast concrete elements of the structure were extremely heavy (up to 22 tons); he realised that this presented a non-standard crane solution because even the most powerful tower crane would not be able to handle such weights over the distances that were required. He considered two ways in which this problem could be eased; his first suggestion was that he would consult with the structural engineer within his firm to establish whether or not the elements could be divided into smaller units. After a short reflection on this he decided that it would probably not be feasible. He then considered how the distance over which the elements would need to be lifted could be reduced. He carried out an analysis of the architectural drawings and decided that the building at the back of the main building could be built once the main building had been completed, allowing the crane to be positioned as close to the main building as was possible.

The first planner who carried out an analysis of the more complex project gave another insight into how construction experts attempt to negotiate the solution space. What he did was to examine the drawings in great detail and was, for example, able to suggest that the in-situ concrete pads that that were needed on the roof to support the window cleaning system that they could be better replaced with prefabricated steel ones. The reason that he gave for this was that the roof could then be made watertight at an earlier stage so that work could be carried out sooner on the internal elements of the building that were more susceptible to the effects of the weather.

Here were three instances in which it was clear that planners not only engage themselves in how various problems can be solved but also in how conditions under which the units of capacity must work can be improved. Of the suggestions that were put forward two were in terms of altering an element of the design in some way so that in the first instance a lighter unit of capacity could be used and in the second instance so that other construction activities could take place sooner. And in the third instance, no material alteration was suggested in terms of the detailed design, the suggestion was that a part of the design be constructed at a later phase in the construction process so as to once again enable the use of a lighter unit of capacity elsewhere in the process.

It was quite clear that the design, at least as far as two of the three experts was concerned, did not represent a package of non-negotiable demands but that it was quite legitimate to negotiate certain details of the design so as to make it production-friendlier.

7.4 TOWARDS METHODICAL CONSTRUCTION PLANNING

The three experts that tackled the second more complex project showed great similarity in the way in which they sought information regarding that project. It was clear that the experts were not only very knowledgeable about the way in which problems on site could be dealt with, they were also quite clearly expert in efficiently going about seeking the information they needed on which they could build the structure of their construction programmes. As has been stated architectural drawings were considered, initially at least, to be of second importance to engineer's drawings which detail purely the load-bearing structure of a project. All three experts first of all examined the site layout which gave information regarding the size of the building in relation to the site itself, as well as the interaction of the site with its surroundings. After this information was sought regarding the ground conditions and then the structure. They wanted to know about the make-up of the subsoil, its load-bearing capacity, the level of groundwater, the slope of the terrain, and such like. Then they proceeded to examine the plans from the basement upwards together with the sections. The fact that all three experienced planners were very keen to gain insight into the same structural information and would put other types of information to one side is indicative of the fact that experience has taught the experts that structural information presents a planner with the major problems of a construction process, and therefore that major aspects should be dealt with before minor aspects.

1. Clearly, if one were to recommend a particular strategy of examination of the drawings, then this is what it would be i.e. deal first of all with the load-bearing structure, (including the nature of the subsoil), in order to thoroughly understand what demands it makes upon the major backbone of construction capacity.
2. When it is felt that sufficient information has been analysed regarding a particular aspect of how the structure should be tackled, a potential solution should be put forward (major aspects taking precedence over minor aspects). Construction planning problems can be large and complex and the only way in which way humans can be solve them is to start the process with an assumption, whether or not that initial assumption be later found to be entirely correct or not. If the assumption is found to be a proper one then it will mean that no time has been wasted in having to alter the solution, but where it is later found that the assumption was either partly or wholly incorrect that piece of information will at least help guide the planner towards a better solution. Of course a plan cannot be put forward as being the most superior plan unless it is compared with other solutions. By definition therefore alternatives have to be put forward in order that they can be compared and a choice between them made. Even a computer could not develop the ‘best solution’ without it having made comparisons with other solutions. Therefore the examination of alternative solutions is a necessary part of the process and allows the solution space to be better explored.

3. Where solutions lie in marginal territory i.e. where it is not really altogether obvious whether one solution is superior or inferior to another, an effort should be made to investigate the quality of the solutions on an objective basis rather than a subjective basis. Closing down a potential solution line because of incorrect judgment is clearly undesirable because at worst it means that the potentially most efficient solution will not be developed and at best will mean that time is wasted in having to discover that the first chosen solution is not entirely satisfactory. (This is the ‘down side’ of point ‘2’ i.e. you have to make a decision before you can move on, but where it is a major decision investigate the alternatives first objectively).

4. Assumptions regarding the un-checked areas of the design should be kept to a minimum. Examination of detail should be given high priority because potential danger for a construction plan can lurk there. Harmonious, well-balanced and efficient construction programmes can only be developed where feedback takes place of information from the later phases of the programme into the earlier phases. Such feedback helps to steer a construction programme towards ultimate efficiency and means that at an absolute minimum the whole process has to be planned at least once from beginning to end. (The planner has to ensure that there is no stress between what is planned at the framework level and what has to fit into that framework on a more detailed level).

5. Having examined all the relevant structural information and having gone on to examine the rest of the design information the ‘navigational system’ of the planner himself has to be relied upon to guide the planner further down the construction planning path. The construction process is a complex of cycles within cycles that are governed and effected by values that originate both from without and within the process itself that it is not possible to lay down further guidelines as to how they should be best tackled, beyond general guidelines that is22. What is fundamental to the process of construction planning is production knowledge. Without this even the most methodical and clear-cut method of approaching planning problems will not help an individual produce superior construction programmes; detailed production knowledge remains the corner-stone to superior construction planning because discovering information alone is not enough, it is understanding the implications of that information and taking subsequent rational action that counts. Only by having a large reserve of knowledge will a planner be able to recognize potential problems.

All construction planning problems are in a sense one of whether or not an activity can be made to fit within an appropriate framework. However, those frameworks are not determined by the construction planner alone but by others as well, including sub-contractors, local authorities, suppliers and utility companies, for example. Persuading those bodies to fall in line with a particular plan is part of the practical side of construction management which demands different skills and knowledge once again.

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22 Of course the experiment did not go beyond the main structural phase anyway and therefore it is beyond the scope of this research to be able to make more recommendations regarding later phases.
Appendix I: The first 144 allotted codes of ‘Planner No. 2’.

The following is an example of how the allotted codes can be represented. It shows very clearly how the activities of analysis, synthesis and evaluation take place in mini-cycles; not unlike Zeisel’s forward looping spiral (see page 51).

|   | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| M |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AD |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AC |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AM |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| IC |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| EVAL | | | | | | | | | | | | | | | | |
| P1 | | | | | | | | | | | | | | | | |

|   | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
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| AM |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| IC |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| EVAL | | | | | | | | | | | | | | | | |
| P1 | | | | | | | | | | | | | | | | |

|   | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
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| AC |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AM |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| IC |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| EVAL | | | | | | | | | | | | | | | | |
| P1 | | | | | | | | | | | | | | | | |

|   | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| M |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AD |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
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| IC |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| EVAL | | | | | | | | | | | | | | | | |
| P1 | | | | | | | | | | | | | | | | |
Appendix II: The drawings that were used by ‘Construction Expert 3’ during the first ten minutes of the exercise.

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<thead>
<tr>
<th>C.E.3</th>
<th>10:15am</th>
<th>10:16am</th>
<th>10:17am</th>
<th>10:18am</th>
<th>10:19am</th>
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<td>BS-011</td>
<td>Site location</td>
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<tr>
<td>BS-021</td>
<td>Site layout &amp; car park</td>
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<td>BS-022</td>
<td>Building 1 Basement plan</td>
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<td>BS-023</td>
<td>Building 1 ground floor plan</td>
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<td>BS-024</td>
<td>Building 1 1st floor plan</td>
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<td>BS-025</td>
<td>Building 1 2nd floor plan</td>
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<td>BS-026</td>
<td>Building 1 3rd floor plan</td>
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<td>BS-027</td>
<td>Building 1 4th floor &amp; flat roof plan</td>
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<td>BS-028</td>
<td>Building 1 5th floor &amp; roof plan</td>
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<td>BS-029</td>
<td>Building 1 6th floor plan</td>
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<td>BS-030</td>
<td>North and west elevations</td>
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<td>BS-031</td>
<td>West elevation</td>
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<td>Building 1 sections A-A, B-B, C-C</td>
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<td>BS-033</td>
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<tr>
<td>BS-034</td>
<td>Building 1 sections E-E, F-F, G-G, H-H</td>
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<td><strong>STRUCTURAL DRAWINGS</strong></td>
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<td>Excavation profiles</td>
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<td>Level 0 foundation main building</td>
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<td>Level 0 foundation entrance building</td>
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<td>Level 0 main building</td>
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<td>BC-015</td>
<td>Level 0 entrance building</td>
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<td>BC-016</td>
<td>Level 1 main building</td>
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<td>BC-017</td>
<td>Level 1 entrance building</td>
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<td>BC-019</td>
<td>Level 2 entrance building</td>
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<td>Level 3 main building</td>
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<td>BC-021</td>
<td>Level 3 entrance building</td>
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<td>BC-022</td>
<td>Level 4 main building</td>
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<td>BC-023</td>
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<td>BC-024</td>
<td>PRE-CAST ELEMENTS</td>
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<td>BC-026</td>
<td>Standard facade element</td>
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<td>BC-027</td>
<td>Standard balustrade element</td>
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<td>BC-033</td>
<td>Side wall at D level 4</td>
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<td>Telecommunications network</td>
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References / Bibliography


Summary
The Process Of Construction Planning
William Henry Stockings

This research arose from Professor G.J. Maas' (Construction Technology, Technical University of Eindhoven) question of whether or not it would be possible to develop a design method that would assist construction planners during the process of construction planning. A great deal of the relevant literature on general and architectural design methods was studied including Ronald Hamel's thesis 'On Designing By Architects: A Cognitive Psychological Description Of The Design Process'. In order to be able to answer the question of whether or not it would be possible to develop such a method it had become clear that it would first of all be necessary to examine the way in which expert construction planners went about the task of construction planning. It was decided to carry out a number of experiments using the technique that Hamel had used, the so-called technique of 'protocol analysis' whereby experts think aloud while dealing with a particular problem. It was felt that this would allow as direct a method as was possible of finding out what an expert actually does when dealing with a construction planning task. A number of interviews had been conducted with experts about the way in which they went about planning but these give in a sense 'interpreted' accounts of what an expert does. Two sets of experiments were therefore conducted, each with three construction experts who were asked to think aloud whilst dealing with the problems that an architectural design presented them with. The first set of experiments was conducted with a fairly straightforward dwelling-type of building whilst the second set of experiments was carried out with a very much more complex office project.

In order to be able to put forward any hypotheses about how construction planning problems are tackled it is first necessary to have as clear a picture as possible of the structure of construction planning problems. A literature search was carried out, certain own theories were developed and the major factors that form the logic behind any construction process identified. The aspect 'work front' is explored, something which receives very little attention in the literature on construction problems, and the way in which understanding the size of the work front at any particular stage in the construction process is fundamental in selecting the type and number of units of capacity that can be employed at any particular sub-state of the completed building. For any given project there is a theoretically most efficient way of carrying out that project given a particular state of technology with corresponding costs. The influence of the direct and indirect costs of individual units of capacity coupled with the indirect costs of the site are discussed and it is demonstrated that a most-efficient process is not one necessarily where unit costs are minimized but where the right balance is found between direct and indirect costs. The closer the indirect costs of major units of capacity to the indirect costs of the site (hutting and supervision, for example) the more efficient the process. The two fundamental structures in which construction planning problems have to be developed are space and time and in a sense construction planning problems can be thought of as 'packing problems' where the units of capacity have to be fitted into these dimensions as harmoniously and efficiently as possible.

A literature search was also conducted into the field of cognitive psychology and such aspects as short and long term memory, visual thinking, schemas, and cognitive mapping explored. Construction planning problems can be described as large web problems, the aspects of which can not all be ‘activated’ in memory at once by the construction planner. In order to overcome
this inability to deal with all problems at once experts necessarily have to break the problems down into manageable chunks. Construction planners make use of models in order to overcome the limitations of short term memory but these models can only ever simulate one outcome of the two dimensions in which a solution must be developed. For example, critical path networks only deal with the order and length of activities, and drawings and scaled-models only represent one sub-state of the completed building. Simulation where spatial and temporal aspects are both taken into account is a translation that has to be carried out in human memory.

The strategies that the planners would adopt in approaching the potentially complex task of construction planning were hypothesized, and using the think aloud protocols tested. Six analysis and synthesis strategies were put forward, of which four could be supported. One result that came forward very clearly was the importance construction experts place on structural engineering drawings. These were considered to be of fundamental importance in making decisions regarding the division of space on site, the choice of major equipment as well as vertical and horizontal transport routes; these aspects were found to be the starting point of the expert’s solutions. The protocols also demonstrated that the experts sought similar information at particular points in the process and that they apparently preferred to take on board information in a particular order. The protocols also demonstrated that experts can and do make mistakes and that making adjustments to already-made decisions is the natural result of only being able to deal with a limited number of aspects at once, and thus a normal part of the process. The protocols also demonstrated that experts have preferences for particular types of solutions that are subjectively evaluated rather than objectively evaluated.

In conclusion a number of steps are put forward that might assist less experienced planners develop construction programmes. However, the fact that extensive construction knowledge is required in order to make decisions is underlined as well as the fact that good construction plans are not simply the result of a particular method. The method of protocol analysis is also discussed in terms of its benefits and limitations and a number of suggestions made as to how the method could be used to further increase our understanding of how planning decisions are made as well as how it could be used in helping students develop their skills in construction planning.

Samenvatting

Het proces van het ontwerpen van de uitvoering

William Henry Stockings

Dit onderzoek begon met de vraag van professor G.J. Maas (Uitvoeringstechniek, Technische Universiteit Eindhoven) of het mogelijk zou zijn om een ontwerpmethode te ontwikkelen voor degenen die een planning moeten maken voor bouwprojecten. Begonnen werd met een literatuuronderzoek naar methodisch ontwerpen in het algemeen en specifiek op het gebied van architectonisch ontwerpen. Het proefschrift van Ronald Hamel Over het denken van architecten; een cognitief psychologische beschrijving van het ontwerpproces bij architecten maakte hier onder andere deel van uit.

Uit de literatuurstudie werd duidelijk dat, voorafgaande aan het ontwikkelen van een ontwerpmethode voor degenen die een planning moeten maken, het nodig zou zijn om eerst te kijken naar uitvoeringsdeskundigen terwijl ze bezig waren met een planningsopdracht. Er werd besloten om de techniek te gebruiken die Hamel had gebruikt, namelijk ‘protocol analyse’, waarbij iemand hardop denkt terwijl hij bezig is met een bepaald probleem. Op deze wijze zou het mogelijk zijn een expert te volgen bij het oplossen van een planningsprobleem.

Met uitvoeringsdeskundigen werd een aantal interviews gehouden over hoe ze een planning maken. Dit waren in zekere zin ‘geinterpreteerde’ verklaringen van wat ze deden. Daarom werd besloten om twee experimenten uit te voeren, elk met drie uitvoeringsdeskundigen, waarbij ze gevraagd werden om de uitvoeringsproblemen die een bepaald architectonisch ontwerp creëert, op te lossen. Het eerste experiment werd gedaan met een vrij eenvoudig, woningachtig gebouw, terwijl het tweede experiment werd gedaan met een veel complexer kantoorgebouw.

Voordat hypotheses geformuleerd kunnen worden over hoe een uitvoeringsprobleem aangepakt moet worden, is het nodig eerst een zo duidelijk mogelijk beeld te hebben van de structuur van uitvoeringsproblemen. Een literatuuronderzoek werd gedaan, bepaalde eigen theorieën werden ontwikkeld, en de voornaamste factoren bij de bepaling van de logica van een uitvoeringsproces werden geïdentificeerd. Het aspect ‘werkfront’ werd onderzocht, iets wat heel weinig belangstelling krijgt in de literatuur over uitvoeringsproblemen. Het is van fundamenteel belang om te weten hoe groot het werkfront is in alle fasen van een uitvoeringsproces, zodat keuzes gemaakt kunnen worden in verband met het aantal en type capaciteitseenheden. Voor elk willekeurig bouwproject is er een meest efficiënte manier om het uit te voeren, gelet op de technologische mogelijkheden met de daarbij behorende kosten. De invloed van directe en indirecte kosten van individuele eenheidscapaciteiten, gekoppeld aan de indirecte kosten van de bouwplaats wordt uitgezet. Er wordt duidelijk gemaakt dat een meest efficiënt bouwproces niet noodzakelijkerwijs datgene is waar alle eenheidskosten zijn geminimaliseerd, maar juist datgene waar een goede balans wordt gevonden tussen directe en indirecte kosten. Hoe dichter de indirecte kosten van de meest belangrijke capaciteitseenheden de indirecte kosten van de bouwplaats benaderen (bijvoorbeeld voor de keten en supervisie), hoe efficienter het proces.
De twee fundamentele dimensies waarin uitvoeringsproblemen opgelost moeten worden, zijn *tijd* en *ruimte*; in zekere zin kan een uitvoeringsprobleem omschreven worden als een 'inpakprobleem' waar de capaciteitseenheden moeten worden ingepakt in de twee dimensies, en wel zo harmonieus en zo efficient mogelijk.

Een literatuuronderzoek werd ook gedaan op het gebied van cognitieve psychologie en er werden aspecten zoals lange- en kortetermijn geheugen, visueel denken, schema's en cognitieve kaarten onderzocht. Uitvoeringsproblemen kunnen omschreven worden als een groot web van problemen, waarvan de aspecten niet allemaal tegelijk geactiveerd kunnen worden in het geheugen van een uitvoeringsdeskundige. Om dit probleem te kunnen overbruggen dient een uitvoeringsdeskundige de problemen in kleinere stukken op te delen. Uitvoeringsdeskundigen maken daartoe gebruik van modellen om de beperkingen van hun geheugen te boven te komen. Deze modellen kunnen echter enkel een van de twee fundamentele dimensies vertegenwoordigen. Bijvoorbeeld, kritieke pad modellen behandelen alleen maar de volgorde en lengte van activiteiten, terwijl tekeningen en schaalmodellen alleen maar een ruimtelijke stand van een bouwwerk vertegenwoordigen. Simulaties waarin gelijktijdig met ruimtelijke en temporale aspecten rekening wordt gehouden zijn een vertaalslag welke alleen maar in het menselijke geheugen plaats kan vinden.

De strategieën die een uitvoeringsdeskundige eventueel zou gebruiken bij het benaderen van een potentiële complex uitvoeringsprobleem werden als hypotheses opgesteld. Zes synthese en analyse strategieën werden voorgesteld, waarvan vier onderbouwd konden worden. Een resultaat dat duidelijk naar voren kwam was het belang dat uitvoeringsdeskundigen stellen aan constructie gegevens. Deze werden beschouwd als van fundamentele belang bij beslissingen in verband met de indeling van de ruimte van de bouwplaats, de keuze van het groot materieel en de locatie van verticale en horizontale transportwegen. Deze aspecten vormden het startpunt voor de oplossingen van de deskundigen. De protocollen demonstreerden dat de experts op bepaalde tijdstippen tijdens het proces dezelfde informatie zochten, en behoefte hadden om informatie in een bepaalde volgorde te vergaren. De protocollen liepen ook een te zien hoe experts fouten kunnen maken en hoe het bijzaken van reeds genomen beslissingen een normaal onderdeel van het proces is. De protocollen demonstreerden tevens dat experts een duidelijke voorkeur hebben voor oplossingen die berusten op subjectieve maatstaven, eerder dan op objectieve maatstaven.

Ter conclusie worden een aantal stappen voorgesteld welke minder ervaren planners eventueel kunnen helpen bij het ontwikkelen van een uitvoeringsplanning. Het gegeven echter dat uitgebreide uitvoeringskennis nodig is om uitvoeringsbeslissingen te kunnen nemen ondersteunt tevens het feit dat goed plannen van de uitvoering niet alleen maar het resultaat is van een bepaalde methode. De voor- en nadelen van protocol analyse worden besproken en daarnaast worden een aantal suggesties gedaan over de manier waarop onze kennis om uitvoeringsproblemen aan te pakken kan worden vergroot, en hoe de methode gebruikt kan worden bij het ontwikkelen van vaardigheden bij studenten in het maken van planningen voor de uitvoering.

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**Curriculum Vitae**

William Henry Stockings was born in Hemel Hempstead, England on 26th October 1962. In 1982, having completed A-levels at secondary school, he commenced a study at the Hertfordshire College of Building for a Higher National Diploma in Building. In 1985 he joined a property developer of luxury homes, first acting as a surveyor and later as a projects coordinator. In 1986 he passed the membership examinations for the Chartered Institute of Building. In 1988 he went to London University where he gained a Masters Degree in Construction Economics and Finance. 1989 he joined a London based management contractor as a planner working on commercial properties. Towards the end of 1989 he moved to Holland. After a period of doing administrative work outside the building industry he gained some work experience on a large project in Eindhoven after which he joined the Technical University of Eindhoven in 1991 as a research assistant to professor ir. G.J.Maas of the group Construction Technology (Uitvoeringstechniek). In 1995 he commenced work for a Dutch contractor working on commercial projects as an estimator. In 2000 he returned to the his research period. He is currently employed by a practice of architects working on health clubs in Holland for an English client.
Theses

The Process of Construction Planning

1) From the cognitive point of view of taking up information efficiently it would appear to be advisable for a construction expert to initially ignore the architectural drawings and study the construction drawings instead, thereby gaining fast insight into the backbone and scope of a building upon which subsequent layers of information can be carried.

2) Creativity in construction planning is negotiating the solution space so that circumstances in which units of capacity must operate become as production-friendly as the design will allow. Negotiating that space includes negotiating the boundaries of the design as well.

3) Progress in understanding and dealing with different types of problems is hampered by the fact that there is no international definition for the sub-division of different types of problems. In chemistry elements are divided into a ‘periodic table’. In the field of problem solving there is as yet no such fundamental system of classification. Instead researchers have to use nouns and verbs that are applied in general language with all the consequences of ‘interpretation’ and lack of clear definition that follows.

4) If a planner cannot mentally visualise a construction problem he will not be able to solve it.

5) De Bono’s theory that the brain is a self-organising system in which an idea is a circular connection of activated neurons has a great deal of credibility. In conducting this research it was often felt that the exploration of unchartered territory went hand in hand with neuron-firing that reached out in all directions without being able to find that circularity. This attempt to find circularity can take months and can be extremely frustrating and mentally fatiguing but once it does take place is the reward that a researcher is motivated by.

6) The extent to which the building industry and its suppliers would benefit from more efficient planning is questionable. As an industry the increase in turnover due to lack of proper management and planning probably creates just as much extra wealth for the industry as a whole as would more efficient practices. National governments therefore probably have more to gain from efficient construction than the construction industries themselves.

7) Working hard in some repetetive way is easier than looking for an idea without inspiration.

8) A true expert will always be able to describe a complex system to a non-expert in straightforward language.

9) The Dutch Building Regulations (Bouwbesluit) are full of formulae that ensure high standards in terms of use of energy, the entry of daylight, safety in terms of fire prevention and escape, etc. However, one formula is missing from that sophisticated package of formulae, namely one that would make the development of long soulless lines of identical houses a thing of the past.

10) Knowing how refreshed a person can feel after a ten minute snooze it seems appropriate that Holland, a country at the forefront in social and technical experimentation, should test whether or not an obligatory afternoon nap would improve the quality of research in its universities.

William Henry Stockings