Analytical Design Planning Technique (ADePT): Programming the Building Design Process

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1. Introduction

The construction process is traditionally planned either directly with bar charts, or with network analysis techniques forming the basis of the bar charts. The success of these approaches in construction planning over the years has led to their extensive use in the planning of design. Network analysis techniques and bar charts were developed specifically to plan production processes, such as construction, that have an easily definable logic and are sequential in nature. Design, however, is an iterative processes requiring assumptions and estimates of information to be made and work to be redone until a satisfactory solution is developed. Network analysis is not therefore an appropriate basis for planning design. They cannot account for this iterative nature, they monitor progress based upon the completion of drawing work and other design deliverables and are inappropriate for monitoring the availability of key pieces of information.

The Analytical Design Planning Technique (ADePT), shown schematically in figure 1, offers an approach to planning design that accounts for the necessity to undertake work in an iterative manner, enables work to be monitored on the basis of the production of information, and allows design to be fully integrated with the overall construction process[1]. The first stage of the ADePT methodology is a model of the detailed stage of the building design process, representing design activities and their information requirements. The data in this model is linked via a dependency table to a Dependency Structure Matrix (DSM) analysis tool[2] which is used in the second stage to identify iteration within the design process and arrange the activities with the objective of optimising the task order. The third stage of the methodology produces design programmes based on the optimised process sequence. The technique requires some iteration between the DSM and programming stages. The authors have developed computer tools to enable each stage to be undertaken in an efficient manner and thus, facilitate more effective planning and management of building design[3].

This paper reviews current problems in design planning within the construction industry and the use of a Dependency Structure Matrix tool to order the detailed design process. It then describes in detail the representation of the optimal design sequence within a programme and the integration of the optimised design programme with procurement and construction programmes.

2. Problems in design planning

Management of design is influenced by things such as contract procurement, management of the client and supervision of the design team, and encompasses factors such as information exchange management and quality management. However, the fundamental activity in the management of design is the planning and control of work. In current practice, design is planned using the same techniques that are widely employed to plan construction processes, such as network analysis. These techniques are well founded[4], and although they were developed to schedule construction, their use in design planning has been in existence for many years[5]. However, because network analysis techniques and tools are designed to represent sequential processes, they cannot easily account for a process containing iteration, such as design[1]. Over recent years, network analysis techniques have come in for much criticism on the grounds that the techniques are cumbersome and laborious to use, and are unable to properly deal with the dynamic nature of a construction project[5,6]. This results in the omission of logic or information links between activities in complex processes. This problem is particularly prevalent in building design when considering information exchanged between design disciplines because of the disparate manner in which they undertake their work and the planning of that work. A further problem is that it generally takes a low priority in the overall planning of a construction project, the design being programmed to suit the timing of work on site. This has been deemed acceptable in the past on the grounds that construction accounts for the majority of the project costs. However, there is now an increasing understanding that construction efficiency and costs are heavily dependent on the quality of the design solution and information, as shown by various surveys that have found that a significant proportion of problems on site are design related[7,8]. A recently published brief introduction to ADePT[9] has generated interest from designers and managers from a range of backgrounds (including consultants, clients and contractors, totalling some 70 companies) and reflects the industry's need for improved design planning.

3. Ordering design with a Dependency Structure Matrix (DSM) tool

The Analytical Design Planning Technique (ADePT) has been devised to overcome the problems evident in current design planning practice. Design activities and their information dependencies are represented in the process model that forms the first stage of ADePT. The model has been built using a modified version of the IDEF0 methodology and represents the detailed design process **(RIBA Plan of Work stage E)** broken down into five main disciplines (architecture, civil engineering, structural engineering, mechanical engineering and electrical engineering), building elements and systems, and finally, individual design tasks. It consists of some 150 diagrams showing 700 design tasks and 4000 information requirements across the five disciplines. **Models of the earlier stages of the design process that incorporate cost and risk analysis are being compiled through associated research[10]**. A detailed description of the model's creation and features is given elsewhere[11].

The second stage of the ADePT methodology is the ordering of design activities on the basis of their information requirements, which is achieved with a Dependency Structure Matrix (DSM) tool. This is outlined here in more detail than the process model of stage one, because it is crucial to understanding the programming stage and the latter involves iterations between the matrix and design programmes. A full discussion of the DSM component of ADePT is presented elsewhere[12]. DSM analysis is a system whereby complex problems containing interrelationships can be represented by the interactions between variables in the form of a matrix[2]. DSM theory has been developed over the last twenty-five years to examine a range of problems.

Austin *et al.*[13] identified that DSM analysis is a suitable technique to schedule design activities in a construction project because it:

- identifies design tasks that are in iterative loops;
- orders the tasks to minimise design iteration;
- identifies the natural groupings of tasks that require close co-ordination
- allows the effects of changing the order of design to be analysed and explained; and
- can act as a step towards producing a design programme.

Figure 2(a) shows a matrix for a very simple design problem containing 20 activities, which are listed arbitrarily down the left hand side of the matrix and mirrored across the top of the matrix. An assumption is made that the activities are undertaken in the order listed within the matrix, starting from the top left corner and finishing in the bottom right corner. Each mark in the matrix indicates that the activity on the left hand side is dependent upon the activity at the top of the matrix. This means that in the assumed order of activities, a mark below the diagonal shows that an activity is dependent on information which has been produced by a previous activity whereas a mark above the diagonal indicates that an activity is dependent on information that has yet to be produced. This can be overcome by estimating the information that is as yet unavailable and then verifying the estimate once the information generating activity has been undertaken.

It is desirable to reduce the need for estimates and therefore iteration within the process. This is achieved using an algorithm to reorder the activities within the matrix so that the marks are below the diagonal or as close to it as possible thus producing the optimal sequence of activities. The process of reordering the matrix is called partitioning. Figure 2(b) shows the partitioned matrix which highlights iterative loops of tasks.

Our process model in indicates that there are approximately 350 to 450 activities and 2400 to 3000 dependencies in the detailed stage of building design. The resulting matrix can be clarified by accounting for different levels of information importance and therefore strengths of dependency. This is done by classifying the dependencies within the matrix and using a partitioning algorithm that can prioritise the sequencing of activities on the basis of these classifications.

4. Representing the design process on a programme

In the third stage of ADePT, the partitioned matrix is linked to a proprietary planning tool to reveal a programme for the design activities. A number of issues require consideration which are described below.

4.1 Planning iterative design work

The use of ADePT to date has indicated that the typical contents of an iterative loop, such as those highlighted in figure 2(b), relate to co-ordination issues to be dealt with during the design, such as ceiling, underground services and perimeter structure co-ordination. Conventional programming techniques represent only sequential processes and consequently fail to take them into account. The output from a partitioned DSM can be represented on a programme in a manner that incorporates the iteration within the process, while still allowing the programming tool to function. This is done by grouping tasks that form a loop under a 'rolled up' activity and removing interrelationships from the loop. While the loop's relationship with previous and subsequent tasks is not affected, within the loop, tasks can be programmed to occur concurrently. **This means that tasks in the loop can be scheduled in a way that achieves design and co-ordination in parallel. Assessments of each task's duration and the number of iterations to achieve a satisfactory design solution are not required, simply an estimate of the overall duration of the loop.** Table 1 indicates alternative methods for representing tasks in an iterative loop with different implications for the way programming and design is undertaken. For example, ensuring that all tasks begin simultaneously (options A and B) means that co-ordination between tasks in the loop can be sought from the very beginning of that element of design. Alternatively, programming tasks in a loop to finish concurrently (options A and C) means that final co-ordination of the design should be easier to achieve. In each of these cases, levels of resource allocation may need to be heavy to deal with the number of tasks being undertaken in parallel.

Investigation of the design issues highlighted by loops with our industrial collaborators revealed that no single option is appropriate as the sole means of programming iterative work. Each loop needs to be considered in its own right and programmed in such a way that both initial and final co-ordination can be achieved, resources are allocated in a way that suits their availability, and the overall project duration is achieved. **The scheduling of tasks in a loop also has implications for the way designers undertake their work: ongoing design and construction suggests a close relationship between designers who have a constant appreciation of each others work.**

The output from the matrix in figure 3 can also be used by the design manager to ensure that as the design of the relevant element is undertaken, information is exchanged between members of the design team at the appropriate moment in time. The exact nature of the information and its exchange is established prior to the start of the design, as is the timings of these exchanges within the loop. This represents a management activity which is not represented in the DSM and must be added to the programme following the establishment of the design sequence.

4.2 Planning the design's management

In scheduling the building design process, the DSM tool only considers activities that are related purely to the development of the design. This means that activities such as design review meetings and approval exercises are not scheduled. The DSM is capable of dealing with these issues but the philosophy adopted by ADePT is that they are management activities that are best programmed following the establishment of the optimal design sequence. For example, it is beneficial to programme a design review meeting following the completion of a loop of iterative design so that all relevant co-ordination issues can be reviewed, the element of design can be fixed, and the need for any client approval can be established. In current practice, a design tends to be reviewed periodically with no consideration for whether it is necessary or which elements of the design require special attention.

The detailed building design process model in the first stage of ADePT identifies information that is required by the design from external sources such as regulating bodies, local authorities and the client. The optimal design programme assumes that this information is available when required, but in practice there is often a delay in obtaining this type of information. A schedule of the information required from external sources and its effect on the programme can be produced with ADePT and is a further example of planning the management of design.

Towards the completion of the design it is necessary to plan on the basis of release of information to contractors. This means the addition of tender dates, tender periods and other exchanges with contractors to the programme. This is part of the process of integrating the optimal design programme with the procurement and construction programmes.

4.3 Integrating design and construction programmes

In current practice, design is usually programmed to achieve the required timings of information release to contractors. This is because the scheduling of a construction project starts with the programming of the construction work, followed by the preceding procurement periods, and finally the design. This approach to planning a project has the effect of compromising the design process which can affect the quality of design information available during construction. In order that it can be used to manage a project, the optimal design programme produced with ADePT must be integrated with a procurement and construction programme. This is done by determining the procurement work package that each design task contributes information to, and assigning a work package (WP) reference to the tasks. Having established the tender dates of each WP on the procurement programme, the design programme can be rescheduled to ensure that these dates are met, a process that means reducing the duration of some WP designs. This rescheduling can be achieved by either changing the duration of some tasks, with corresponding allocation of resources, or by changing the sequence of tasks through the omission of some relationships. The latter has the effect of reducing the project duration, but means that some information must now be estimated. We already know from the classification of information dependencies during the DSM analysis that links shown on the programme cannot easily be estimated and so particular care must be taken over these estimates. Figure 4 shows the example matrix on which design task T has been promoted so that the design and procurement programmes can be integrated. The matrix clearly indicates an estimate that must be given special consideration and incorporate an appropriate margin of error so that it need not be revised during the later stages of the design. This demonstrates the need for iteration between the matrix and programming stages of ADePT. Such proposed changes to the optimal design programme can be reviewed to establish the ease with which task duration and resources can be reallocated, and the most suitable pieces of information to estimate. Also, the additional cost incurred through over-designing some elements of the building can be compared to the costs of extending the duration of the corresponding work packages.

5. Implications of planning with ADePT

The adoption of ADePT as a design planning tool, requires not only the consideration of a number of programming issues, but also changes to current planning practice.

5.1 Production of an ADePT programme

Procedures to produce an effective design programme using ADePT have been developed. Through the application of ADePT to a range of projects under construction including a pharmaceutical research laboratory, a railway terminal building and an office development. The procedures cover all three stages of ADePT, the programming stage involving the following steps:

- Indicate the work package(s) of each design task on the programme.
- Group tasks under 'rolled-up' headed names where possible. Some of these are in iterative loops which are grouped under headings for those loops, while others are grouped as building 'systems' or 'sub-systems'.
- Omit links from iterative loops so that the programming software can calculate the overall project duration.
- Establish the most appropriate method of undertaking the design of loops and programme tasks accordingly.

- Include 'tender issue', 'tender period' and 'construction issue' dates to the programme as necessary.
- Assign durations and resources to the tasks.
- Examine the resource graphs for the project. Using these and a knowledge of the design organisation, determine the maximum number of each resource that will be available throughout the project. Enter this information in the programming tool and level resources on the project.
- Examine the design milestone dates and compare them to the dates required to suit procurement and construction. Amend the programme as required, identifying information that must be estimated and areas of over-design.
- Use the design programme to assess changes throughout the course of the project and to monitor progress on the project.

Other than the programming of iterative loops and integration of the design, procurement and construction programmes, this procedure is largely as would be followed in current practice. The main differences between the planning processes of current practices and ADePT occur prior to the production of the programme, when the design activities and information requirements are identified and then ordered in the DSM. The former is done in ADePT through the production of a project-specific design process model and the allocation of information classifications. Austin *et al.*[11] describe these procedures and the time that is necessary to undertake them effectively. It is necessary to spend more time than is typical in current practice in order to produce a meaningful programme with ADePT. Testing of the tools has shown that the time taken to produce a project-specific model, DSM and detailed programme (including management tasks and integration with procurement and construction programmes) was 5 to 10 working days for the case study projects which ranged in value from £16M to £35M. **Further research is currently ongoing to assess the effectiveness of ADePT on small-scale projects.** In some cases, the time taken represents considerable additional effort compared to that which is expended in current practice. However, the ADePT programme should improve both the design process, by making it more efficient, and the construction process, due to it being planned and procured with a better co-ordinated and more reliable design solution. **It should also allow the effects of change during the design to be rapidly assessed through analysis of the DSM and programme.**

5.2 Comparison of ADePT programmes with those produced in current practice

A comparison has been made between programmes produced during the testing of the ADePT tools, and those produced in practice by experienced planners. A number of observations can be made:

- The logic that forms the basis of the ADePT programme is more rigorous than in programmes produced in current practice. In the latter case it is typical for each disciplines' design programme to have approximately 50 to 200 dependencies on other disciplines. The number of dependencies within each discipline varies by a similar amount, although it is common to show more links within a single discipline's programme because there tends to be a better understanding of them. Conversely, an ADePT programme based on the building design process model contains around 1200 to 1800 cross-disciplinary links.
- The overall appearance and 'feel' of the programmes produced by the two methods is not substantially different. The ADePT programme can be viewed on the basis of discipline, work package or resource, reflecting the same information as those produced by a planner. This is an important feature of the ADePT programme, since the appearance of a programme and level of detail typically shown in practice has been established over many years and is deemed to be appropriate.
- The order of activities on the programmes is different, in particular, the timing of tasks within iterative loops, reflecting the fact that they were not identified during the production of the traditional project programmes.
- Many work package key milestone dates on the ADePT programme are earlier than the dates on the real project programmes. These tend to be smaller packages, particularly of architectural work such as finishes or fittings packages, where long periods of float are often built into the real programmes during the tender period.
- The ADePT programme issue dates are often later than the real project programme dates for work that takes a long time to complete on site or is fundamental to the construction process, such as civil engineering work or structural frame package, or where long lead-in times to construction are necessary, such as lifts or chiller packages.

These observations have been made following the testing of ADePT on a number of recently completed design projects. In order to further analyse the implications of adopting the technique, and its effectiveness, additional validation of the tools is currently being undertaken.

6. Further work

Currently, ADePT is being used to study the detailed design process on a £130M hospital project. This work is being undertaken in collaboration with the design and project management team. Work to date involves the development of a project-specific design process model. The information in this model is currently being analysed to produce a design programme which will be integrated with a procurement and construction programme. The ease with which the project-specific model was formulated (approximately one working week) and the range of building systems that it incorporates, indicates the level of detail in the generic model.

One of the projects on which testing has been carried out, a £30M pharmaceutical research laboratory, is being reviewed with respect to changes that occurred during the design. These are being simulated in the DSM and the resulting changes to the design programme are being assessed. This work will give an insight into the effectiveness of ADePT to represent changes throughout the course of a project. The same test project is being examined with consideration to problems that occurred during the design (following its initial planning) and construction. These problems are being reviewed to determine whether they could have been avoided by more effective design planning. The ADePT programme will then be reviewed to determine whether it highlights the corresponding design activities as being in need of special attention with regard to information estimates or whether they are within an iterative loop that was not identified in practice.

To date, ADePT has been used to examine the detailed design stage of projects. Further work is underway to model the concept and scheme design stages of building design. ADePT will be used to optimise the way the design in these stages is undertaken, and integrate the planning of these stages with that of detailed design to facilitate more effective overall design planning.

7. Conclusions

This paper has described how, in the final stage of the Analytical Design Planning Technique (ADePT), the output from a Dependency Structure Matrix (DSM) tool is used to produce a design programme. Programmes have been developed on the basis of the flow of information in the design process, and in a way that represents iterative loops of design work that typically require close co-ordination. Analysis of the optimal design programme results in the process being programmed more effectively. It also allows the design process to be integrated with procurement and construction in a way that means redesign can be minimised, while a satisfactory overall project programme can be maintained.

The planning methodology has been verified and tested by successfully representing the design of a number of building projects. It has proved possible to generate design programmes in an acceptable time scale. Following the DSM analysis, the procedures for generating programmes and the level of detail that they represent have proved similar to current practice, although the underlying detail is far beyond what is typically considered at present. The benefits from this detail are that the programmes accurately represent the design process more accurately in terms of the activities involved, and more so the dependencies between activities.

The design process model in the first stage of ADePT covers a wide range of building systems. This means that the design activities and information dependencies in complex building projects can be programmed. Practising designers and design managers shown the ADePT methodology have been enthusiastic about the effectiveness of the approach and the detailed level of information that is programmed. Future work will continue to examine the effectiveness of the ADePT methodology on further building projects.

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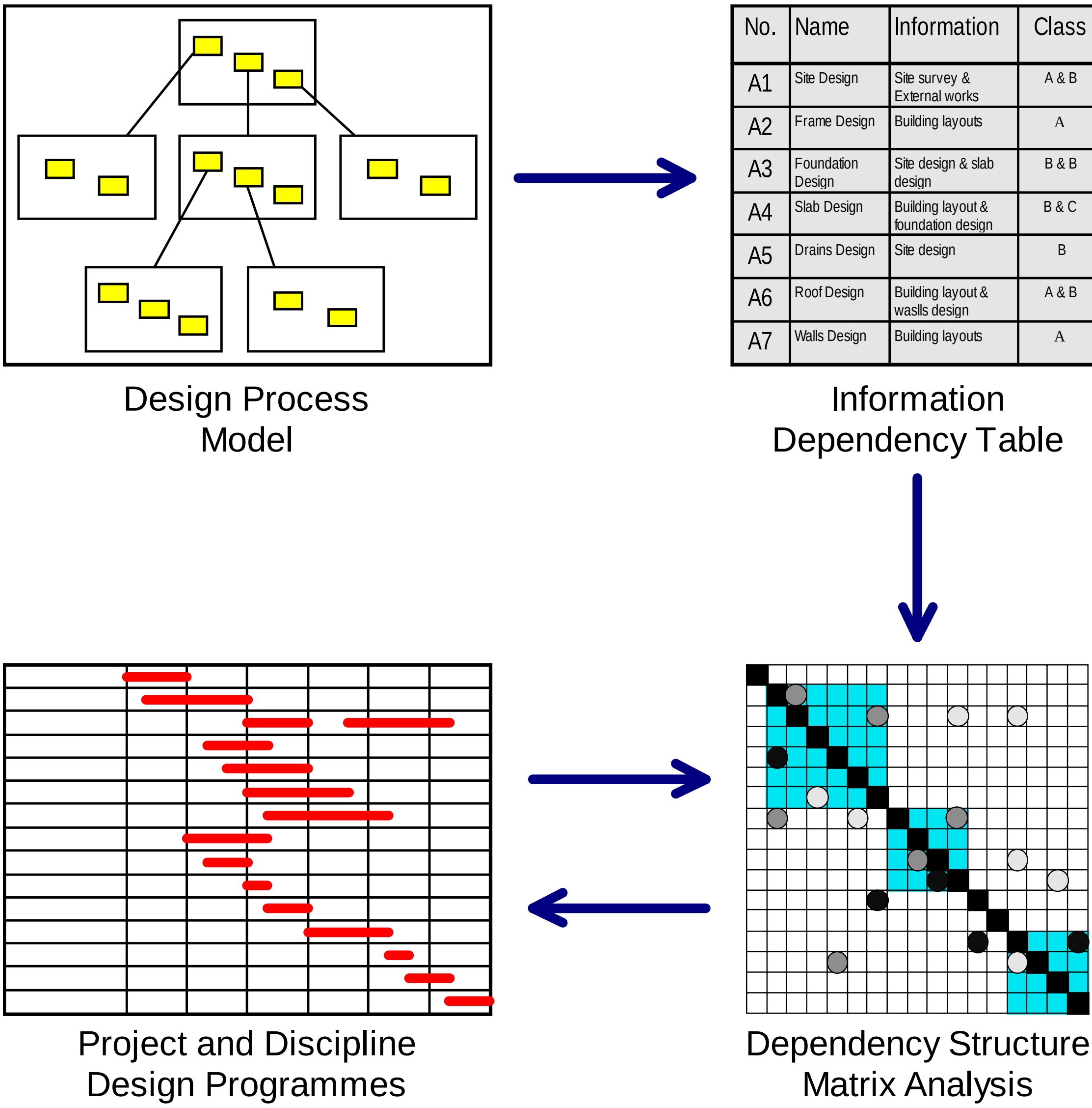

Figure 1 Analytical Design Planning Technique (ADePT)

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	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Task A		X																		
Task B	X																			
Task C	X	X																		
Task D	X		X																	
Task E		X										X								
Task F		X	X													X		X		
Task G		X		X																
Task H	X					X														
Task I					X		X													
Task J		X	X						X											
Task K								X						X						
Task L										X									X	
Task M									X						X				X	
Task N				X							X					X				
Task O			X									X								
Task P													X	X						
Task Q															X			X		
Task R																	X			X
Task S									X											
Task T													X							

(a)

	A	B	C	D	G	E	I	J	L	S	O	M	T	Q	R	F	H	K	N	P
Task A		X																		
Task B	X																			
Task C	X	X																		
Task D	X		X																	
Task G		X		X																
Task E		X							X											
Task I					X	X														
Task J		X	X				X													
Task L								X		X										
Task S							X													
Task O			X						X											
Task M							X			X	X									
Task T												X								
Task Q											X				X					
Task R													X	X						
Task F		X	X												X					X
Task H	X															X				
Task K																	X		X	
Task N				X														X		X
Task P												X							X	

(b)

Figure 2 A simple example of a Dependency Structure Matrix

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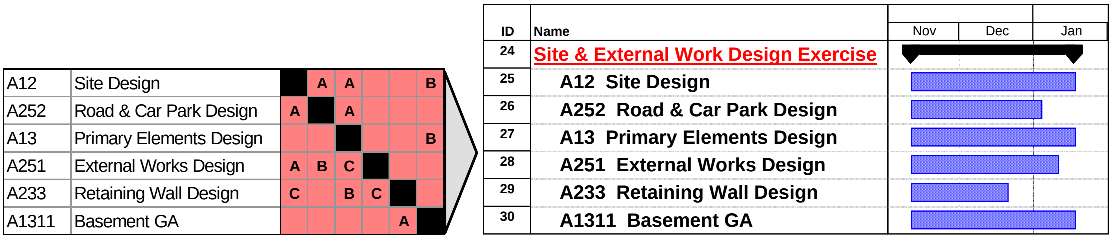

Figure 3 Use of DSM output to programme loop

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	A	B	C	D	T	G	E	I	J	L	S	O	M	Q	R	F	H	K	N	P
Task A		X																		
Task B	X																			
Task C	X	X																		
Task D	X		X																	
Task T													X							
Task G		X		X																
Task E		X								X										
Task I						X	X													
Task J		X	X					X												
Task L									X		X									
Task S								X												
Task O			X							X										
Task M								X			X	X								
Task Q												X			X					
Task R					X									X						
Task F		X	X												X					X
Task H	X															X				
Task K																	X		X	
Task N				X														X		X
Task P													X						X	

Special consideration must be given to this information estimate

Figure 4 The effect of promoting a task within the optimal sequence

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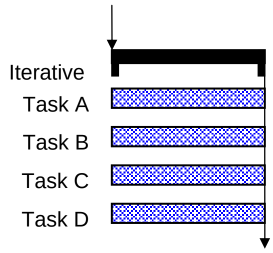
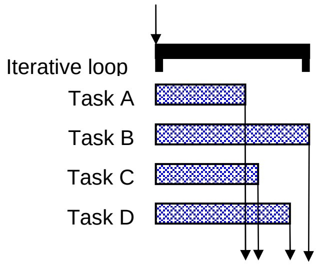
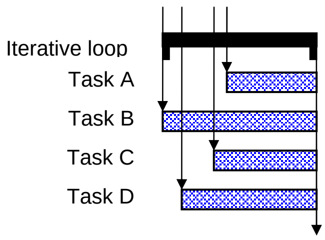
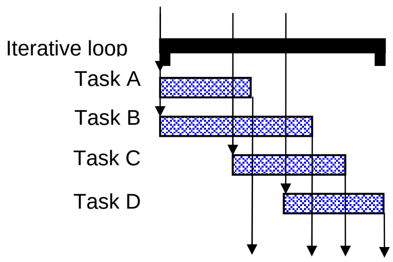
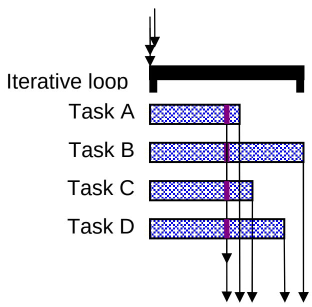
A	All tasks within the loop are allocated the same duration. Resource allocation to the tasks is not levelled. This means no task begins until all can begin, and no information is released from the loop tasks until they are all 100% complete (the undertaking of the loop is delayed) and fully co-ordinated. The project duration may be extended and resources may require heavy allocation, but co-ordination is ensured.	
B	Activity durations are allocated independently and tasks are programmed within the loop to begin simultaneously. Again, resource allocation may need to be heavy. Initial co-ordination should be achieved but final co-ordination is only achieved after the rest of the design is underway meaning some over-design may be necessary to avoid the need to readdress tasks in the loop.	
C	Activity durations are allocated independently and tasks are programmed within the loop to finish simultaneously. Again, resource allocation may need to be generous. Final co-ordination should be achieved but initially, activities are undertaken and not co-ordinated.	
D	Activity durations are allocated independently and tasks are programmed within the loop to begin and finish at times dictated by the resource levelling. This is the approach automatically assumed by the resource levelling in a project planning tool. Resource levels can easily be achieved but the project duration is extended. Some assumptions must be made because some design tasks are completed before others begin.	
E	Activity durations are allocated independently and tasks are programmed within the loop to begin simultaneously. Full co-ordination is to be achieved at a specified point in the loop, and further work is based on that co-ordination. Resource allocation may need to be heavy up to the point where co-ordination is achieved.	

Captions for tables and figures

Table 1 Options for programming iterative loops of design

Figure 1 Analytical Design Planning Technique (ADePT)

Figure 2 A simple example of a Dependency Structure Matrix

Figure 3 Use of DSM output to programme loop

Figure 4 The effect of promoting a task within the optimal sequence