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An Approach to Operational Design Co-ordination

by

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This thesis
is dedicated in its entirety to
my mother, Irene.

Abstract

Design co-ordination is aimed at improving the performance of the design development process. It can be viewed as providing the continuous coherent organisation and control of the assignment of inter-related tasks to the most relevant resources such that they can be undertaken and completed in a suitable order in a timely and appropriate manner.

The nature of operational design co-ordination is discussed resulting in the identification of key issues, i.e. coherence, communication/interaction, task management, resource management, schedule management and real-time support. Based on these key issues, existing approaches related to operational engineering management have been critically reviewed and found to exhibit a number of fundamental limitations. In addition, aimed at addressing the key issues identified and overcoming the limitations of existing approaches, a set of requirements have been established that define an approach to operational design co-ordination.

A novel, integrated and holistic approach to operational design co-ordination has been developed enabling the performance of the design development process to be improved. This approach consists of two components: a methodology and a knowledge modelling formalism. Further, the methodology consists of two parts: real-time and prospective. *Real-time* operational design co-ordination enables the coherent, timely and appropriate structured undertaking of inter-related tasks while continuously optimising the utilisation of the resources, in accordance with dynamically derived schedules, within a changeable design development process. *Prospective* operational design co-ordination facilitates the identification of deficiencies in terms of existing resources with respect to scheduled tasks and, thus, the assessment of proposed improvements to the resources. The knowledge modelling formalism of tasks, resources and schedules supports the methodology.

Three practical case studies from engineering industry have been used to evaluate the approach. A prototype agent-oriented system, called the Design Co-ordination System, has been developed to evaluate the implementation of the real-time part of the methodology by applying it to a turbine blade design process. The prospective part of the methodology has been applied to practical case studies concerning a marine vessel conversion design programme and a rotary drum dryer design development process. Based on the evaluation of the approach, its strengths and weaknesses have been identified.

Finally, areas of possible future work have been recommended to improve the approach and develop the Design Co-ordination System. In addition, based on industrial feedback, further applications of the approach have been suggested.

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During the last four years I have been immensely fortunate in having two supervisors, namely Professor Bill Hills of the University of Newcastle upon Tyne and Dr. Alex Duffy of the University of Strathclyde. The supervision provided by Bill and Alex has been exemplary and I feel extremely lucky to have been their student. Under their guidance, I have developed and improved in a variety of ways and thoroughly enjoyed my experience within a research environment, particularly working in the area of design co-ordination. As well as in a supervisory capacity, Bill and Alex have been very supportive and understanding on a personal level, far beyond what I could have optimistically hoped. For all their help, advice, encouragement, patience, debate and friendship, I am eternally grateful to Bill and Alex.

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Nomenclature

Mathematical Symbols

i, j	integer counters
Σ	arithmetic summation
$+$	arithmetic addition
x	arithmetic multiplication
$=$	arithmetic equals
$\approx$	approximately equals
$>$	greater than

Tasks

T_I	goal identification index
T_L	local task identification index
T_G	global task identification index
T_{DD}	datum duration of a task
T_S	allocated task start time
T_F	allocated task finish time
T_{ED}	estimated task duration
T_{AC}	actual completion measure of a task
T_{AC_t}	actual completion measure of a task at time t
T_{EC}	estimated completion measure for a pre-emptive task (%)
T_{EC_t}	estimated completion measure of a task at time t
$T_{[T_{In}]}$	input requirement matrix comprising the task input requirements
$T_{In,i}$	ith input requirement of a task
T_{NIn}	number of input requirements of a task
$T_{[T_{Out}]}$	output requirement matrix comprising the task output requirements
$T_{Out,i}$	ith output requirement of a task
T_{NOut}	number of output requirements of a task
T_N	number of tasks a task is dependent on
$T_{N,i}$	number of tasks that the ith task is dependent on
$T_{[T_I]}$	goal identification index matrix comprising the goal identification index of each task that a task is dependent on
$T_{[T_L]}$	local task identification index matrix comprising the local task

	identification index of each task that a task is dependent on
$T_{[T_G]}$	global task identification index matrix comprising the global task identification index of each task that a task is dependent on
$T_{I,i}$	goal identification index of the ith task in the pending scheduled task repository
$T_{L,i}$	local task identification index of the ith task in the pending scheduled task repository
T_{ON}	number of outstanding tasks that a pending scheduled task is dependent on
$T_{ON,i}$	number of outstanding tasks that the ith pending scheduled tasks is dependent on
$T_{I,i,j}$	the goal identification index of the jth task that the ith pending task is dependent on
$[T_{I,i,j}]$	the goal identification index matrix of the ith pending task comprising the goal identification index of the j tasks it is dependent on
$T_{L,i,j}$	the local task identification index of the jth task that the ith pending task is dependent on
$[T_{L,i,j}]$	the local task identification index matrix of the ith pending task comprising the goal identification index of the j tasks it is dependent on
n_{TS}	number of tasks to be scheduled
n_{TD}	cumulative number of tasks that each task to be scheduled is dependent on
n_{OTCSM}	number of outstanding tasks in the current schedule model
n_{OTRS}	optimum number of outstanding tasks to re-schedule
n_{PST}	number of pending scheduled tasks
n_{TRS}	number of outstanding tasks to re-schedule
n_{TCRS}	number of tasks that could be completed using a particular resource during re-scheduling given the estimated time to derive a revised schedule
n_G	number of goals

Resources

R_I	resource index
R_A	resource availability status
$R_{[R_{FE}]}$	resource forecasted efficiency matrix
R_{FE}	resource forecasted efficiency
R_{ME}	resource monitored efficiency
R_{ME_t}	resource monitored efficiency at time t
$R_{\{R_{ME_t}\}}$	resource monitored efficiency time series
R_{UT}	resource upper monitored efficiency threshold for a specific task
$R_{[R_{UT}]}$	resource upper monitored efficiency threshold matrix
R_{LT}	resource lower monitored efficiency threshold for a specific task
$R_{[R_{LT}]}$	resource lower monitored efficiency threshold matrix
R_C	financial cost of utilising a resource per unit time
C_{R_I}	cost of utilising a resource to complete its assigned tasks
C	cost of utilising resources to complete all of the scheduled tasks
$R^{(n)}$	nth simulated resource model
n_R	number of resources to be utilised in a schedule
n_{RAS}	number of resource available for consideration to be scheduled
n_{RUS}	number of resource to be utilised according to a schedule

Time

$\hat{T}_{CCS}$	estimated time to complete the current schedule
$\hat{T}_{DRS}$	estimated time to derive a revised schedule
$\hat{T}_{CRS}$	estimated time to complete a revised schedule
$\hat{T}_{MOGA}$	estimated execution time of the multi-objective genetic algorithm
t	time step
n	number of time steps
T	estimated time to complete an optimised schedule
T_{TCRS}	time taken to complete a number of tasks using a particular resource during re-scheduling

Design Co-ordination System

R_{DCS}	percentage resource utilisation attributed to the DCS
R_{user}	percentage resource utilisation of user processes
R_{other}	percentage resource utilisation of other processes
R_{system}	percentage resource utilisation of system processes
R_{idle}	percentage resource utilisation idle
R_{CF}	resource coefficient
R_{DCS_t}	percentage resource utilisation attributed to the DCS at time t
R_{other_t}	percentage resource utilisation of other processes at time t
R_{system_t}	percentage resource utilisation of system processes at time t
R_{idle_t}	percentage resource utilisation idle at time t
n_{ps}	number of processes being executed on a resource

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1 Introduction

The aim of this chapter is to introduce the research.

In Section 1.1, the motivation for the research is discussed. The methodology adopted to undertake the research is presented in Section 1.2. The aim and objectives of the research are highlighted in Section 1.3. Finally, the organisation of the thesis is presented in Section 1.4.

1.1 Motivation for the Research

Engineering design is challenging from both a technical and management perspective [Eppinger et al., 1990; Yassine, et al., 1999]. With regard to engineering management, the design development process [O'Donnell, 2001] of large made-to-order products can be complex, expensive and time-consuming due to the involvement of many resources and tasks, and large quantities of data, information and knowledge. The complexity is compounded by the fact that resources are often skilled in a variety of disciplines and exhibit varying proficiency regarding the completion of multiple inter-related tasks. Furthermore, due to unforeseen circumstances, resources may not perform as intended and/or scheduled tasks may not progress as expected, the outcome of which will influence the performance of the design development process.

Engineering management of the design development process has become more challenging due to (i) increased competition, (ii) increased product complexity, and (iii) increased customer requirements in terms of quality, cost, time and performance. Indeed, Wallace recognised that "in order to maintain continuing competitive advantage, and thus a strong financial position, senior management in manufacturing industries should co-ordinate and control personnel and finance to fulfil the main business activities, which include marketing, research, design, development, production, sales and service" [Wallace, 1987].

A methodical and well-organised design development process lies at the heart of an effective engineering company since it can enable the reduction of development costs and cycles while meeting customer quality requirements. Thus, to remain competitive, new approaches to managing the design development process are needed to ensure effective and efficient processes, i.e. to do the right things and to do things right.

Inspiration for this research stems from the present lack of comprehensive approaches to operational engineering management, particularly in the area of design co-ordination. Within the engineering design community, relatively little research has been conducted on design co-ordination, which is reflected in the lack of existing approaches and disseminated work. However, there is a growing interest within academia calling for further research in this area

[Duffy, 1998; Duffy et al., 1999]. Such research will lead to increased understanding and knowledge of design co-ordination.

Management has been viewed as consisting of a strategic and operational level [Greenley, 1989; Cole, 1994]. These levels can be considered as strategically setting out aims and goals and operationally employing techniques and means to facilitate their achievement. The boundary of the research presented in this thesis is defined as design co-ordination from an operational perspective. Specifically, enabling inter-related tasks to be undertaken and completed in a structured manner while optimising the allocation and utilisation of the available resources in real-time within the dynamic and unpredictable design development process. Thus, the aim of this research is to comprehensively identify the constituents of operational design co-ordination, and, more significantly, link them together in an integrated fashion within a supporting approach.

1.2 Research Methodology

The research presented in this thesis has been conducted in accordance with the methodology illustrated in Figure 1.1 [Duffy & O'Donnell, 1998].

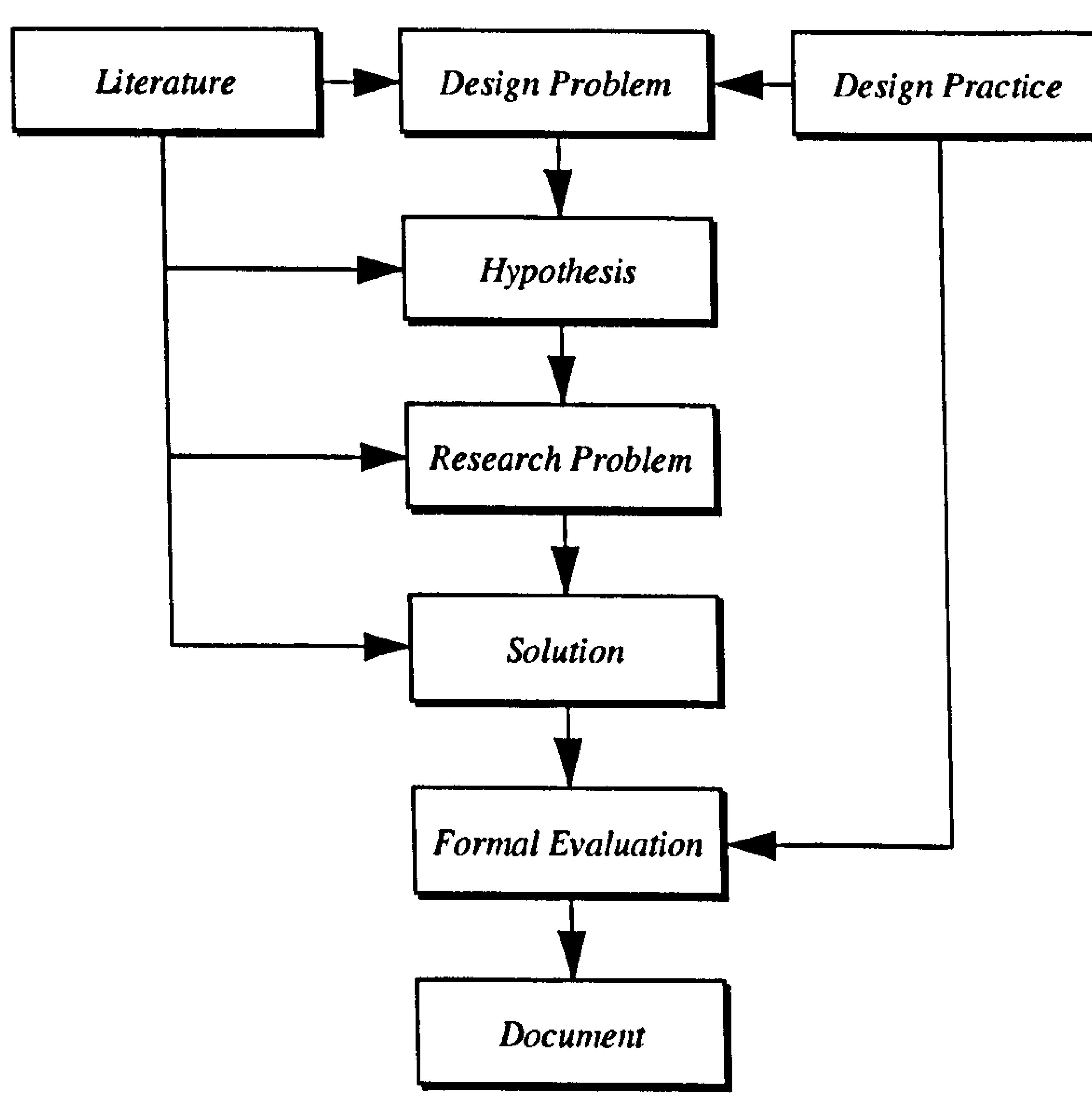

Figure 1.1 Overall Research Methodology [Duffy & O'Donnell, 1998]

With regard to Figure 1.1, from design practice and pertinent literature, a design problem is identified. Based on the design problem, a hypothesis is proposed and then formulated into a research problem. A solution to the research problem is then developed. Literature is considered from the identification of the design problem to the solution of the research problem. The solution is evaluated based on design practice. Finally, the research is reported.

1.3 Aim and Objectives

The aim of the work presented in this thesis is to develop an approach to operational design co-ordination that will enable the improved performance of the design development process. In order to achieve this aim, a number of objectives have been identified as needing to be met:

- establish the need for a more comprehensive approach to engineering management than currently exists,
- identify design co-ordination as the basis for a more comprehensive and improved approach to engineering management,
- review the nature of operational design co-ordination in order to establish its key issues,
- recognise the limitations of existing approaches related to operational engineering management / operational design co-ordination,
- identify the requirements of operational design co-ordination,
- develop a novel, integrated and holistic approach to operational design co-ordination that satisfies the requirements identified and overcomes the limitations recognised in existing approaches,
- develop a prototype computer-based system in order to enable part of the approach to operational design co-ordination to be evaluated,
- evaluate the approach with respect to the requirements of operational design co-ordination using a number of practical case studies from engineering industry,
- identify strengths and weaknesses of the approach based on its evaluation and considering the requirements for operational design co-ordination, and,
- identify areas for future work.

1.4 Organisation of the Thesis

With the exception of Chapter 13, the purpose of the remainder of this thesis is to accomplish the aim of *developing a novel, integrated and holistic approach to operational design co-ordination that will enable the improved performance of the design development process* through meeting the objectives described in Section 1.3. As such, the thesis has been organised into three parts.

Part I - Research Problem Formalisation (Chapters 2, 3, 4 and 5)

- Chapter 2 sets the scene by declaring that engineering management is the basis for an organisation to be competitive. Design co-ordination is identified as an important and pervasive characteristic within existing approaches to engineering management, however, the lack of an understanding of its nature is highlighted. Design co-ordination is then hypothesised as the basis for a more comprehensive approach to engineering management than currently exists, which is aimed at improving the performance of the design development process.

- Chapter 3 presents a literature review of design co-ordination from an operational perspective. The nature of operational design co-ordination is discussed with regard to engineering. However, in order to gain a broader understanding, literature is included from the areas of organisational theory and distributed artificial intelligence in which co-ordination has also been identified as being important. As a result of the literature review, the key issues of operational design co-ordination are identified.

- Chapter 4 presents a critical review of existing approaches related to operational engineering management / operational design co-ordination in order to identify their limitations. The key issues identified in Chapter 3 are used as the basis for the critical review.

- Chapter 5 identifies and discusses the requirements of operational design co-ordination. The identification of these requirements is based on the key issues identified in Chapter 3. Satisfying these requirements will address the key issues of operational design co-ordination and overcome the limitations of existing approaches identified in Chapter 4.

Part II - An Approach to Operational Design Co-ordination (Chapters 6, 7 and 8)

- Chapter 6 presents an overview of a novel, integrated and holistic approach to operational design co-ordination. The approach comprises of two components, i.e. a methodology and knowledge modelling formalism.

- Chapter 7 presents the knowledge modelling formalism component of the approach that supports the methodology.

- Chapter 8 presents the operational design co-ordination methodology component of the approach. The methodology consists of two parts, i.e. real-time and prospective.

Part III - Evaluation and Discussion (Chapters 9, 10, 11, and 12)

- Chapter 9 presents a prototype agent-oriented computer-based system, called the Design

Co-ordination System (DCS), that implements and enables the evaluation of the real-time part of the operational design co-ordination methodology. The system architecture, component modules and functionality of the DCS are described.

- Chapter 10 presents the application of the approach to three practical case studies from engineering industry. The real-time part of the methodology, using the DCS, is applied to a turbine blade design process. The prospective part of the methodology is applied to a marine vessel conversion design programme and the design development phase of a rotary drum dryer.
- Chapter 11 presents an evaluation of the approach as a result of its application to the practical case studies presented in Chapter 10. The evaluation is presented in terms of the requirements of operational design co-ordination identified in Chapter 5. Further, based on the evaluation, strengths and weaknesses of the approach are recognised.
- Chapter 12 presents a discussion of a number of aspects of the work presented in the thesis. The research methodology adopted is summarised. Techniques used within the approach and system are also discussed. Based on the evaluation of the approach in Chapter 11 and company feedback, recommendations are made for future work. In addition, the future direction of design co-ordination research is also considered.

Finally, Chapter 13 concludes by summarising the work presented in the thesis and the contributions of the research.

2 Engineering Management

The development of an effective approach to engineering management is key to the success of an engineering organisation. The aim of this chapter is to identify design co-ordination as being a fundamental element of engineering management. Furthermore, it is proposed that design co-ordination provides the foundation for a more comprehensive approach to engineering management than currently exists.

In Section 2.1, an introduction to engineering management is presented and reasons are given for the need for further research in this field. A number of prominent existing management approaches are briefly discussed in Section 2.2. In Section 2.3, co-ordination is recognised as a characteristic within a number of existing approaches. In Section 2.4, design co-ordination is hypothesised as being fundamental to a more comprehensive approach to engineering management. Finally, Section 2.5 summarises the chapter.

2.1 Introduction

In 1916, Fayol wrote *General and Industrial Management*, first published in 1949, in which management was described as a process consisting of planning, organisation, co-ordinating, directing and controlling [Fayol, 1949]. More specifically, it was defined that: "To manage is to forecast and plan, to organise, to command, to coordinate and to control. To foresee and provide means examining the future and drawing up a plan of action. To organise means building up the dual structure, material and human, of the undertaking. To command means maintaining activity among the personnel. To coordinate means binding together, unifying and harmonising all activity and effort. To control means seeing that everything occurs in conformity with established rule and expressed command."

Referring to Fayol, Lock named him as the founding father of engineering management and modern management theory [Lock, 1993]. In addition, Bennett cited the work of Fayol as the origin in the field of the management process forming the basis for much other work in this area [Bennett, 1996]. Bennett also cited Williamson's definition, which is similar to that offered by Fayol, where engineering management was stated as "the art and science of planning, organising, allocating resources, directing and controlling activities which have a technological component" [Williamson, 1982]. Although Fayol's definition was specific to management and Williamson's definition aimed at engineering management, it is observed that despite this difference, coupled with the passage of time, the components of each definition are similar. Indeed, Lock stated that "successful engineering management bridges the two cultures and links engineering and management disciplines to address the planning, development and implementation of engineering capabilities and shape and attain the strategic and operational objective of an organisation" [Lock, 1993].

Despite Fayol's pioneering work on management in the early 1900s, engineering management has only emerged as a discipline in its own right in the latter part of the 20th century. As such, various interpretations of the term engineering management have emerged and, consequently, numerous definitions exist [Leech, 1972; Thamhain, 1992; Lock, 1993; O'Conner, 1994; Bennett, 1996].

Only in recent years has engineering management started to attain the status of a recognised discipline [Lock, 1993]. Despite this recognition, research efforts in engineering management have been described as fragmented and unco-ordinated. Furthermore, it is noted that in the current climate of rapid technological change and an intensively competitive global environment there is a demand for a renewed emphasis on effective engineering management and a re-evaluation of traditional attitudes and approaches. This point is echoed by Thamhain who also recognised that today's engineering environment is more challenging than ever before due to increased technical complexity, and interdependency of technical tasks [Thamhain, 1992].

In addition to the need for co-ordinated research effort in the field of engineering management, there is also a requirement to continue improving existing approaches and introduce new approaches. Duffy et al. indicated that improving the engineering design process will remain the focus of research until adequate solutions, which can be implemented in industry, can be found [Duffy et al., 1993]. On a similar theme, Andreasen et al. recognised that it is increasingly evident that significant improvements and efficiency gains can be made within engineering design since much time and effort is lost due to the lack of focus on both the application and management of design work [Andreasen et al., 1996].

The theme of the forthcoming International Conference on Engineering Design in 2001, i.e. unifying engineering design - building a partnership between research and industry, is based on the recognition that in order to maintain the recent considerable improvements in the performance and quality of engineering products, the product development process must be enhanced [ICED '01, 2000]. Thus, an emphasis of the conference has been placed on engineering design management. As such, this conference will provide a platform to facilitate the convergence of disseminated research efforts toward engineering management. Specifically, the conference will provide the opportunity to steer future research effort aimed at the improvement and introduction of approaches to engineering management.

Competitive pressure is a perennial problem of engineering organisations compelling them to out perform their contemporaries in order to be more attractive to existing and potential customers. It is widely acknowledged that gaining competitive advantage can be achieved by improving product quality while lowering cost and reducing time to market. Hubka indicated that engineering design aims to attain an optimum product in the shortest time at a minimum cost [Hubka, 1982]. The fundamental objectives of engineering organisations regarding quality, time and cost are illustrated in *the eternal triangle* in Figure 2.1.

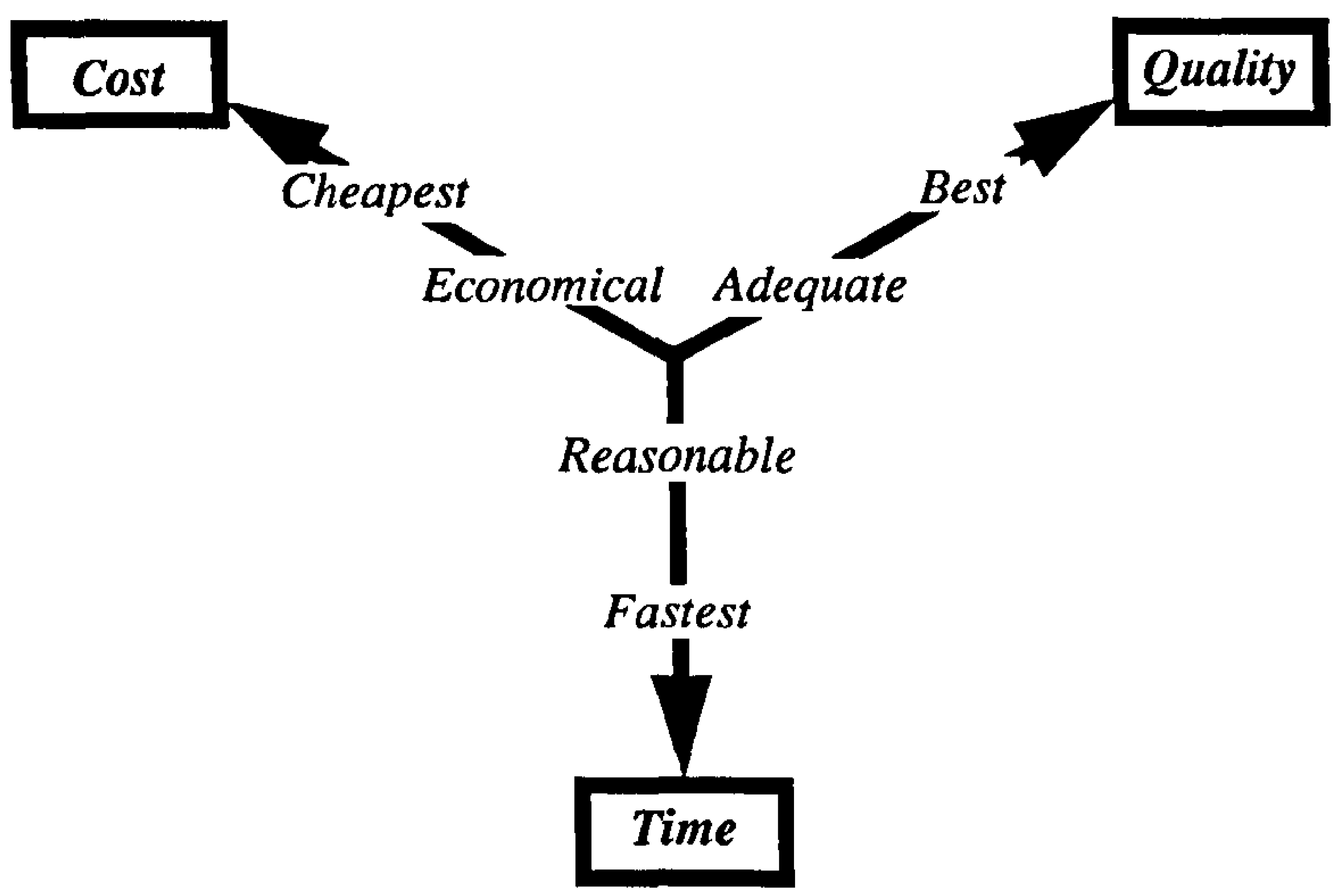

Figure 2.1 The Eternal Triangle [Kharbanda et al., 1980]

The ideal scenario would be to achieve the best quality in the fastest time at the cheapest cost, however, it is acknowledged that a compromise between these objectives is often needed. Several authors have referred to the eternal triangle [Snowdon, 1977; Reiss, 1992; Lock, 1996] with Snowdon describing it as a delicate equilibrium. Effective engineering management is recognised as a means of achieving an efficient process contributing toward the deliverance of a quality product in less time at reduced cost.

The need for greater research effort in the area of engineering management can also be attributed to the fact that products have become considerably more complex than has been known previously. In tandem, the complexity of the design development process has also increased necessitating the introduction of a more comprehensive approach to engineering management that currently exists.

With the seemingly unfaltering rapid technological advances, there is a requirement for an appropriate means of managing this technology such that it can be utilised to its true potential in order to gain a competitive advantage. Technological advancements may put an engineering organisation at a possible advantage, however, it is the ability to harness those advancements effectively in order to realise and, thus, provide improved or new products within timescales at an acceptable cost that is of key importance.

In summary, it is suggested that there is a requirement for an improved approach to engineering management in order to cope with growing competitive pressure, increased complexity of the design development process and products, and continuous technological advances. Furthermore, it is considered that for the foreseeable future, these three issues will remain the impetus for greater research effort and continuous progress to be made in the field of engineering management.

Prior to hypothesising the underlying concept of an improved approach to engineering management it is appropriate to briefly discuss a number of prominent existing approaches. That is, Section 2.2 is aimed at identifying the main focus of these approaches and their respective objectives.

2.2 Existing Approaches to Engineering Management

The latter part of the 20th century has seen the introduction of an increasing number of new management initiatives or philosophies aimed at improving the competitiveness of organisations. Engineering design has seen the advent of a range of management approaches, which have been implemented within industry.

For the purposes of this section, each approach to be discussed has been categorised as an approach to engineering management. The aim of this section is to briefly discuss a number of prominent approaches to engineering management, offering a representative definition where appropriate and highlighting the main objective.

2.2.1 Models of the Engineering Design Process

The design process is viewed as a map for successful engineering work [Voland, 1999]. As such, models of the design process can be thought of as charting the course of action to be followed in order to carry out engineering design. Pahl and Beitz indicated that systematic procedures attempt to steer design effort from unconscious to conscious and more purposeful paths [Pahl & Beitz, 1996]. It is perceived that a benefit of a systematic approach is that none of the stages of the design process will be inadvertently omitted. However, it is also viewed that such an approach may reduce the opportunity for creative design. Thus, design is a process requiring a systematic approach while simultaneously permitting the freedom for creativity [Hawkes & Abinett, 1984; Shahidipour et al., 1999].

In order to improve the practice of engineering design, a variety of models of the design process have emerged over the last two decades [Hubka, 1982; Pugh, 1991; Ullman, 1992; Cross, 1994; Pahl & Beitz, 1996; French, 1999]. Many models exhibit common characteristics, although variations do exist due to the designer's personal perspective and experience, and the particular engineering application. One of the most well known models of the engineering design process is that proposed by Pahl and Beitz [Pahl & Beitz, 1996]. This model is divided into four main phases, namely (i) product planning and clarifying the task, (ii) conceptual design, (iii) embodiment design, and (iv) detail design.

Engineering design process models have been categorised as descriptive, prescriptive, and computer-based [Finger & Dixon, 1989; Evbuomwan et al., 1996]. Descriptive models can be considered as describing how design teams design and work during the design process. Prescriptive models can be thought of as procedural steps, which prescribe how the design process should be carried out. In addition to these more traditional and established models, recent design research has focused on the use of computer-based models within the engineering design process. Computer-based models can be viewed as involving software tools employing engineering methods in order to assist the designer in his/her work.

Models of the engineering design process appear to have concentrated on the technical aspects of design rather than the managerial aspects. Technical aspects are a key requirement of engineering design, however, managerial aspects also provide an opportunity for potential improvement. Indeed, Fayol recognised that management knowledge is the indispensable complement of technical knowledge [Fayol, 1949]. Thus, it can be argued that models of the design process do not offer sufficient engineering management support to enable efficient process performance.

2.2.2 Concurrent Engineering

Concurrent engineering is one of the most prominent contemporary engineering management approaches, which is reflected by the extensive research coverage it has received [Karandikar et al., 1991; Kusiak & Belhe, 1992; Prasad, 1996; Anumba et al., 1999]. Several surveys on concurrent engineering have been produced [Evbuomwan et al., 1994; Lawson & Karandikar, 1994], and a number of approaches discussed [Coates et al., 2000a].

One of the most often cited and well-known definitions of concurrent engineering is that offered by Winner et al. who defined it as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developer from the outset, to consider all elements of the product life cycle from conception through disposal including quality, cost, schedule and user requirements" [Winner et al., 1988].

The primary aim of concurrent engineering is time reduction through performing activities in parallel. Handfield indicated that the central point of concurrent engineering is the reduction of product development leadtime, which is achieved by collapsing activities so they are completed concurrently rather than sequentially [Handfield, 1994]. Ainscough and Yazdine viewed concurrent engineering as an initiative which can enable a company to reduce the time in which it designs, develops and introduces a product to the market by executing each phase of the product development process in parallel [Ainscough & Yazdine, 1999]. With respect to faster design cycles, Voland indicated that concurrent engineering can satisfy the need to produce engineering solutions quickly and effectively [Voland, 1999].

Collaborative teams are viewed as essential for managing concurrent engineering organisations, and, thus, one of the basic principles of concurrent engineering is teamwork [Prasad, 1996]. The key enabler for achieving teamwork is said to be co-operation which comprises seven elements, namely collaboration, commitment, communications, compromise, consensus, continuous improvement, and co-ordination. Indeed, many issues have been identified as essential requirements with regard to ensuring that concurrent engineering is effective when implemented and operated within an engineering organisation or a complex design process. The most prominent issues involved in concurrent engineering have been cited as co-ordination, communication, co-operation, teamwork, integration, information sharing, multi-functional teams, planning, scheduling, self-discipline and productivity [McCord & Eppinger, 1993; Gatenby et al., 1994; Tan et al., 1996; Matta & Cointe, 1997; Tomiyama, 1997].

Concurrent engineering induces parallelism, which may contravene the relationships that exists between activities, with potential penalties attached such as exacerbating major re-work resulting in additional financial costs and leadtime delays. Handfield statistically determined that while concurrent engineering can lead to shorter development times than sequential processes, the former will result in more defects than the latter [Handfield, 1994]. Thus, concurrent engineering can be considered to suffer from major drawbacks that could only be overcome by performing design work when and where appropriate. The concept of performing design work appropriately may include opportunities for concurrency.

2.2.3 Design Decomposition

Design decomposition has been defined as "the systematic approach for the decomposition of an overall design task into subtasks with the minimal interdependence between subtasks to enhance concurrency of the design process" [Kusiak & Wang, 1993a], and "structuring complex design projects in order to develop better products more quickly" [Eppinger et al., 1994]. From these two definitions, a relationship between concurrent engineering and decomposition is apparent. That is, decomposition is regarded as complementary to concurrent engineering [Kusiak & Park, 1990; Kusiak & Wang, 1991] and an essential element of concurrent engineering [Prasad, 1996].

Decomposition is viewed as one way of reducing the complexity introduced into the design process by concurrent engineering [Kusiak & Wang, 1991] and a fundamental approach to handling complexity in engineering design [Pimmler & Eppinger, 1994]. Strategies such as partitioning, re-sequencing, and clustering can be used to aid decomposition in order to reduce complexities as far as possible by ensuring that strong interactions occur within subtasks while weak interactions occur between subtasks [Kusiak & Park, 1990; Eppinger, 1991; Kusiak & Wang; 1991; Eppinger et al., 1994; Pimmler & Eppinger, 1994]. Grouping tasks in this manner allows the determination of potential groups of tasks that may be managed and performed simultaneously.

A number of process modelling tools can be used to represent relationships between entities such as directed graphs, activity network diagrams, and Petri nets [Kusiak, 1999; Park & Cutkosky, 1999]. A common modelling tool used in design decomposition is the design structure matrix. The introduction of the design structure matrix is often attributed to Steward [Steward, 1981], however, Kusiak and Wang [Kusiak & Wang, 1991] cited Warfield [Warfield, 1971] as making the earliest use of an incidence matrix to model system relationships. An incidence matrix can be used as a modelling tool in two ways [Kusiak & Wang, 1993b]. A one mode matrix refers to the same set of entities being represented such as variables [Steward 1981], activities [Kusiak & Wang, 1991], tasks [Kusiak & Wang, 1993a; Kusiak & Wang, 1993b; Eppinger et al., 1994], information flow [McCord & Eppinger, 1993], product elements [Pimmler & Eppinger, 1994], and modules [Rogers & Bloebaum, 1994]. A two mode matrix allows two distinct entities to be represented such as procedures and parameters [Kusiak & Wang, 1991], parameters and variables [Kusiak & Wang, 1993b], modules and activities [Kusiak & Park, 1990].

A misleading and deficient description of decomposition is that it can reduce process complexity. It is suggested that this description is inadequate since it fails to elaborate on the particular context of process complexity. It is viewed that decomposition may simplify technical engineering in that it is easier to mentally comprehend the intricacies of smaller individual sub-processes as opposed to a single large process. However, from an engineering management perspective, decomposition increases complexity since there are more sub-processes and relationships to manage. A number of techniques used to simplify process complexity are based on defining relationships as either weak or strong, or on a gradual scale of importance, with the aim of relaxing or neglecting those considered to be weak or less important [Kusiak & Park, 1990; Pimmler & Eppinger, 1994; Rogers et al., 1996]. However, Rogers et al. stressed that removing relationships must not compromise the accuracy of the overall solution. In addition, it has been recognised that failure to understand relationships between sub-processes can lead to sub-optimisation, i.e. improved operation of sub-processes but reduced efficiency of the overall process [Johnson & Lofgren, 1994]. Thus, a main challenge of decomposition is maintaining the overall integrity of the process.

In conclusion, decomposition offers an approach of dividing large complex processes into smaller sub-processes, however it does not offer a means of managing them.

2.2.4 Design Integration

Design integration is a concept that is ill-defined. Thus, there is a need to consider how integration is perceived in order to establish an understanding of the concept.

Prasad identified integration as a potential contributor to improving productivity and efficiency [Prasad, 1996]. As such, effective integration was defined as "requiring people throughout an entire organisation working together within a well-thought process or system of management". On a similar theme, Todesco viewed design integration as considering design aspects together [Todesco, 1998]. With specific application to building construction, the efficient integration, or simultaneous consideration, of architectural and mechanical design was said to result in an optimised building.

McCord and Eppinger described the integration problem in concurrent engineering as integrating the activities of a multi-functional team [McCord & Eppinger, 1993]. Thus. a design structure matrix, as discussed in Section 2.2.3, was used to gain an accurate understanding of the necessary information flow in complex engineering projects. Consequently, the use of the design structure matrix determined where communication must occur. De Martino et al. indicated that to integrate diverse engineering activities, an information technology infrastructure is required to describe, represent and exchange product and process data across a network [De Martino et al., 1998].

Tichkiewitch and Veron viewed integration as the linkage of computer tools [Tichkiewitch & Veron, 1998]. Adler and Helleloid also discussed integration, or linkage, of computer support, specifically CAD and CAM [Adler & Helleloid, 1987]. However, integrated CAD/CAM was seen as only a small step toward functional integration, and realising improved quality, reduced cost, increased product performance, and shortened development cycles. Carter viewed a proviso for achieving integrated engineering design as adequate, existing systems not having to be replaced or modified significantly [Carter, 1991]. The requirement for integration was said to exist since it would be unrealistic to significantly modify existing systems or procedures due to the time, cost and effort required to radically adapt them.

It is concluded that design integration can be thought of as enabling different entities to be metaphorically brought together to work through the removal of barriers thus allowing interactions, involving the flow of information and knowledge, to occur freely. The two main issues regarding design integration are viewed as (i) bringing entities together, and (ii) information and knowledge flow. Based on this interpretation, it is considered that design integration does not constitute an approach to engineering management in itself. That is, design integration enables entities to be brought together such that they can work and interact together, allowing the flow of information and knowledge, and, therefore, facilitate improved management practice. However, design integration does not provide a means of managing how entities work together and when information/knowledge flow should occur.

2.2.5 Workflow Management

Numerous definitions of workflow management exist [Brockman & Director, 1995; Goell, 1995; Alonso et al., 1996; Shih & Tseng, 1996; Yu, 1996]. A widely acknowledged definition is "workflow management consists of the automation procedures or workflows where documents, information or tasks are passed from one participant to another in a way that is governed by rules or procedures". This definition is provided by the Workflow Management Coalition, which was established in 1993 as an international body for the development and promotion of workflow standards [Lawrence, 1997].

A goal of workflow technology, in combination with business process re-engineering, is to enable more work to be processed in less time by automating entire procedures [Goell, 1995]. Goell stressed that it is only appropriate to automate inefficient processes with a major impact on the business such as those that are mission critical, time-consuming and/or frequently occurring. Alonso et al. elaborated on the means of achieving the goal of workflow technology by declaring that not only does it automate the execution of business processes, but it also allows concurrent execution of multiple process instances [Alonso et al., 1996].

Workflow management systems are seen as requiring a complete model to be available before execution starts, and that they are only used for repetitive processes [Maurer, 1996; Petrie, 1997]. While these are common assumptions of workflow management systems, there are cases of dynamic workflow management systems [Kwan & Balasubramanian, 1997], however they are considered rare and costly [Du & Elmagarmid, 1997]. Whitfield et al. reviewed several workflow management systems and acknowledged that one shortcoming was their inability to manage change [Whitfield et al., 2000b].

Since workflow management has been reported as only being applicable to well-defined repetitive processes, it can be considered to be limited. In addition, one of two main issues of workflow management has been identified as execution co-ordination [Du & Elmagarmid, 1997]. Specifically, it was indicated that the key of execution co-ordination is transferring process information to a site when it is needed in the right order. Thus, it is concluded that workflow management offers the technology to automate processes rather than an approach to engineering management.

2.2.6 Project Management

Project management is a well-documented subject [Reiss, 1992; Spinner, 1992; Burke, 1993; Turner, 1993; Lock, 1996; Field & Keller, 1998; Keeling, 2000] with a number of authors specifically addressing engineering project management [Snowdon, 1977; Wearne, 1989; Oberlender, 1993; Smith, 1995].

A typical definition of project management is given as "the planning, organisation, monitoring and control of all aspects of a project and the motivation of all involved to achieve project objectives safely within a defined time, cost and performance" [Smith, 1995]. From this definition and the numerous others offered, project management can be observed as comprising a number of main elements. These elements are regarded as planning, scheduling, control and monitoring. However it is recognised that different authors place varying degrees of emphasis on each. Table 2.1 presents a summary of how some authors perceive the main elements of project management.

Author(s)	Planning	Scheduling	Control	Monitoring
[Snowdon, 1977]	✓	×	✓	✓
[Wearne, 1989]	✓	×	✓	×
[Reiss, 1992]	✓	✓	✓	✓
[Spinner, 1992]	✓	✓	✓	×
[Burke, 1993]	✓	✓	✓	✓
[Oberlender, 1993]	×	✓	×	✓
[Turner, 1993]	✓	✓	✓	✓
[Smith, 1995]	✓	×	✓	✓
[Lock, 1996]	✓	✓	×	✓
[Field & Keller, 1998]	✓	✓	✓	✓
[Keeling, 2000]	✓	×	✓	×

Table 2.1 Elements of Project Management

In Table 2.1, a tick indicates that the element is emphasised in the respective author's interpretation of project management, whereas a cross signifies that it is not. In addition, shaded rows represent authors who refer to engineering project management whereas rows not shaded refer to project management in general.

Project management can be thought of as a top-down approach [Cleetus et al., 1996] with the primary responsibility lying with a single person known as the project manager [Smith, 1995; Lock, 1996; Field & Keller, 1998]. The demands placed on this single point of management may not permit the effective performance of engineering design work. Thus, a bottom-up approach is required in order to allow management to permeate throughout a project team. In addition, the interactions between the various elements of project management are described at a level, which can be considered inappropriate in terms of enabling its direct implementation and, thus, operation.

2.2.7 Business Process Re-engineering

A widely accepted definition of Business Process Reengineering (BPR), according to Born [Born, 1995], is that offered by Hammer and Champy who stated that "BPR is the fundamental rethinking and radical redesign of business processes to achieve dramatic improvement in critical, contemporary measures of performance, such as cost, quality, service, and speed" [Hammer & Champy, 1993].

BPR can potentially improve the competitiveness and performance of organisations by radically changing and replacing a business's key processes [Bovey, 1994; Love & Gunasekaran, 1997]. As such, a number of enablers have been identified as information technology, organisational, human resources, and total quality management (TQM). BPR is cited as co-existing with TQM, however, BPR is described as the radical re-think or re-design of a business process to bring about drastic performance improvements whereas TQM is aimed at gradual, continuous and incremental change of existing processes [Dey, 1999; O'Neill & Sohal, 1999].

In the literature review conducted by O'Neill and Sohal, BPR was said to be driven by customers, competition and change aimed at radical improvements in process performance leading to sustainable competitive advantage. Tools and techniques are required for process improvement including process visualisation, organisational change, information change management, operational research/method study, benchmarking, and process and customer focus [Dey, 1999; O'Neill & Sohal, 1999].

In conclusion, BPR can be viewed as enabling the fundamental re-design of existing processes. As such, it is considered that BPR offers a means of eliminating activities from a process that do not add value. That is, BPR does not enable the management of a process but a form of streamlining aimed at improving process performance.

2.2.8 Computer Supported Co-operative Work

Computer Supported Co-operative Work (CSCW) refers broadly to various topics relating to groups interacting with one another via computer technology. A representative definition of CSCW is given as "an endeavour to understand the nature and requirement of co-operative work with the objective of designing computer-based technologies for co-operative work settings" [Bannon, 1992]. Schal indicated that the focus of this definition is on understanding the nature of co-operative work with the objective of designing computer support [Schal, 1996]. Furthermore, Schal suggested that there are three types of co-operation, namely co-ordination, collaboration, and co-decision. In addition, it was stated that when considering tools for supporting co-operative work, it is important to understand that the three principal types of co-operation need different types of support. In agreement with Schal, Wilson noted that the main components of CSCW fall into two categories, i.e. the support of human groups and the technology used for that purpose [Wilson, 1991]. The technology aspect of CSCW is often termed groupware since the main focus is placed on groups working together. One of the clearest examples of groupware is electronic mail [Bannon & Hughes, 1993].

The aim of CSCW is to provide integrated support to groups of people across three key variable conditions of work: face-to-face group activity, activity at different times, and activity at different geographical locations [Wilson, 1991]. Malone and Crowston indicated that there is an interest in designing computer tools to help people work together more effectively [Malone & Crowston, 1994]. These tools are said to offer a broad range of assistance such as enabling people to collaborate on writing the same document, managing projects, and task tracking.

The emphasis of CSCW is on co-operative work involving groups of people using computer-based technology. That is, the focus appears to be directed toward understanding how people work co-operatively and, thus, providing an information technology infrastructure conducive to enabling people to do so. A fundamental issue with regard to co-operative work within a group is the need for people to be aware of the activities of other members, i.e. knowledge is required such as what work they have done, what work they are doing, what work they intend to do, and when. It is concluded that CSCW provides a computational platform to facilitate co-operative work, however, the management of human groups to enable work to be conducted in a co-operative manner has yet to be comprehensively achieved. As such, the groupware of CSCW requires to be coupled with a management approach to permit the aspect of co-operative group working.

2.2.9 Knowledge Management

Knowledge management represents an approach to the problems of competitiveness and innovation confronting organisations [Scarbrough et al., 1999]. A definition of knowledge management, typical within the literature review conducted by Scarbrough et al., is offered as "any process or practice of creating, acquiring, capturing, sharing and using knowledge, wherever it resides, to enhance learning and performance in organisations".

The objectives of knowledge management are to make an enterprise act as intelligently as possible to secure its viability and overall success, and realise the best value of its knowledge assets [Wiig, 1997]. In addition, it was said that actively pursuing comprehensive knowledge management will ensure the viability and profitability of an enterprise.

Knowledge management can be viewed as being founded on the belief that within an organisation, intellectual capital has greater importance than financial capital. This view is supported by the recognition that the only sure source of lasting competitive advantage is knowledge [Harvard Business School, 1998]. Consequently, an emphasis is placed on identifying and codifying knowledge assets of an organisation such that they can be exploited and protected as a source of competitive advantage. Indeed, Winch identified three drivers for competitive advantage in engineering and manufacturing as knowledge, innovation and technological advancement [Winch, 1999]. Winch also noted that the basis for competitive advantage is moving from the historical foundation of physical assets to intellectual assets leading to the observation that knowledge management is probably much more important than resource management.

It is deduced that knowledge management suffers two main problems with regard to the necessity that knowledge is codified. Firstly, it may not always be possible for knowledge to be appropriately expressed in a codified form, i.e. convert tacit knowledge into explicit knowledge. Secondly, on a social level, humans by nature are reluctant to codify the knowledge they hold as it may jeopardise their position within an organisation making them dispensable. Indeed, McGuigan stated that "knowledge is too often seen as power by the individual that holds it" [McGuigan, 2001]. Thus, due to the two main problems recognised, the successful implementation of a knowledge management approach is viewed as being non-trivial.

In conclusion, knowledge management is concerned with codifying, identifying and storing knowledge, such that it becomes a permanent intellectual asset within an organisation. Thus, in the event of people leaving an organisation, their knowledge will remain and be accessible to all others. That is, people will be able to obtain what knowledge they require. However, when and where this knowledge is needed is not an aspect of knowledge management. As such, it can be considered that knowledge management is an important approach but it is argued that it must be coupled with a complimentary approach able to manage the use of knowledge.

2.3 Co-ordination: An Important and Pervasive Characteristic

Each of the approaches briefly discussed in Section 2.2 are considered to be significant within the field of engineering management. Co-ordination has been observed as an important and pervasive characteristic within a number of interpretations of these management approaches, i.e. models of the engineering design process [Ray, 1985; Cross, 1994], concurrent engineering [Duffy et al., 1993; McCord & Eppinger, 1993; Prasad, 1996; Tan et al., 1996; Perrin, 1997; Coates et al., 1999c], workflow management [Alonso et al., 1996; Yu, 1996; Piccinelli, 1998; Du & Shan, 1999], project management [Oberlender, 1993; Bailetti et al., 1994; Cleetus et al., 1996; Lock, 1996; Bendeck et al., 1998], design integration [Hansen, 1995], computer supported co-operative work [Malone & Crowston, 1994; Schal, 1996]. Despite being widely cited as an important characteristic of these approaches it can be seen that the understanding conveyed varies considerably. Thus, the aim of this section is to focus upon the importance and pervasiveness of co-ordination while highlighting that it has been interpreted by many as having many meanings.

With regard to models of the engineering design process, Cross recognised that despite having contrasting preferences in models, proponents of systematic procedures all agree that there are compelling reasons for improving traditional design procedures [Cross, 1994]. One reason offered is that there is a need to co-ordinate a team of specialists such that their effort is made at the appropriate point in the process. Similarly, Ray described the technical management of engineering design as involving co-ordinating the work of a design team and assigning particular tasks to individuals or groups [Ray, 1985].

With reference to concurrent engineering, co-ordination has been described as the vehicle for its realisation [Duffy et al., 1993], a main challenge [McCord & Eppinger, 1993], the key design component for group problem solving [Tan et al., 1996], and the principal requirement for its successful implementation [Coates et al., 1999c]. In addition, Perrin stated that "concurrent engineering is an organisational innovation which relies on new ways to divide and co-ordinate all the different activities implied by the design and development of a new product" [Perrin, 1997]. Prasad identified co-ordination as an element of co-operative teams within concurrent engineering organisations [Prasad, 1996]. Co-ordination was described as involving actors performing independent activities that achieve goals, and its analysis includes goal decomposition, resource allocation, synchronisation, group decision making, communication, and the preparation of common objectives.

Co-ordination has been recognised as being required for workflow management computer-based technology to automate processes in order to speed-up execution [Alonso et al., 1996; Yu, 1996; Piccinelli, 1998; Du & Shan, 1999]. Yu indicated that attempts to build workflow tools have been hampered due to designers having no theory on which to build them, however, approaches for modelling workflow using co-ordination theory are being studied [Yu, 1996]. Furthermore, Yu defined workflow as a co-ordinated set of interdependent activities, which are performed by actors in order to achieve a set of common goals. Alonso et al. identified synchronisation and co-ordination as necessary in workflow management, where co-ordination was said to avoid inconsistencies due to concurrent access to the same application with respect to different process instances [Alonso et al., 1996]. Piccinelli indicated that co-operation and co-ordination are crucial since distributed workflow management resources needed to enact a single process may come from different parts of an organisation and/or from different organisations [Piccinelli, 1998]. Du and Shan stated that a workflow process is said to involve the co-ordinated execution of tasks by workflow resources [Du & Shan, 1999].

Project management is a discipline in which co-ordination has been cited as a key factor [Oberlender, 1993; Bailetti et al., 1994; Bendeck et al., 1998; Cleetus et al., 1996; Lock, 1996]. Bailetti et al. viewed co-ordination as an important factor differentiating successful and unsuccessful projects with performance in product development described as being linked to a higher degree of co-ordination [Bailetti et al., 1994]. Co-ordination mechanisms useful for the management of projects were named as including (i) task partitioning to decrease task interdependencies, (ii) broad skilled engineers, (iii) overlapping engineering stages with early downstream involvement and intensive cross-stage communication, (iv) customer driven development, (v) simulations and computer based tools, (vi) cross-functional teams. Oberlender defined project management as "the art and science of coordinating people, equipment, materials, money, and schedules to complete a specified project on time and within approved cost", and, as such, the duty of the project manager was described as organising a project team of people and co-ordinating their efforts in a common direction to bring a project to successful completion [Oberlender, 1993]. Similarly, Lock indicated that project management involves planning, co-ordinating and controlling the complex and diverse activities of modern industrial projects causing much of a project manager's time being spent co-ordinating, which was described as steering and integrating the activities of some departments and relying on others for information and supporting services [Lock, 1996].

Cleetus et al. stated that previously, much emphasis in project management had been placed solely on management [Cleetus et al., 1996]. It was implied that rather than control or management by one person, the objective should be co-ordination among people engaged in tasks. Co-ordination was said to be brought about by communication and responsible workers knowing about the completion of tasks on which they are dependent. Oberlender also stated that co-ordination could be achieved through effective communication, specifically at regularly scheduled team meetings. Remaining on the theme of communication, Bendeck et al. implied that co-ordination could be achieved by providing a notification mechanism that keeps all team members up to date on the current project state [Bendeck et al., 1998].

Hansen stated that computer integration provides significant opportunities for improved co-ordination between people, departments, and firms [Hansen, 1995]. That is, computer integration is a co-requirement for efficient organisational co-ordination. With regard to Computer Supported Co-operative Work (CSCW), Malone and Crowston described how co-ordination theory from a number of disciplines has aided in (i) the suggestion of new systems, (ii) classifying systems, and (iii) analysing how the systems are used [Malone & Crowston, 1994]. A taxonomy of co-operative work tools was presented based on the co-ordination processes that they support such as managing shared resources, managing producer/consumer relationships, managing simultaneity constraints, group decision-making, and communication. Schal identified that co-ordination is a principal type of co-operation within CSCW [Schal, 1996]. Co-ordination was defined as "a co-operative process where individuals need to coordinate their actions with those of others". Actions of individuals gives meaning to the action of others and the other's actions contribute to an individual action.

In summary, it has been illustrated that co-ordination is indeed important and pervasive within existing management approaches, and in some cases is acknowledged as the basis for their successful implementation. However, it is viewed that co-ordination lacks a unified understanding. The existence of varying perceptions of co-ordination leads to the recognition that there is a requirement for further research in this field with the aim of gaining a better understanding of its nature and potential as an approach to engineering management in its own right.

2.4 Design Co-ordination: An Improved Approach

The aim of this section is to introduce the notion that design co-ordination is the key to an improved approach to engineering management, which will enable the achievement of performance improvements in the design development process. More specifically, in order to contribute to the success of an engineering organisation, it is considered that the fundamental objective of a design co-ordination based approach to engineering management is the improvement of the performance of the design development process. Indeed, with respect to engineering management, Duffy et al. stated that "a more relevant, comprehensive, and appropriate approach is required for optimum performance", and, thus, suggested design co-ordination as such an approach [Duffy et al., 1999]. In addition, Andreasen et al. identified that the effective co-ordination of the design process is the key to achieving optimal design performance [Andreasen et al., 1996].

In Section 2.3, co-ordination was established as an important and pervasive characteristic within a number of approaches to engineering management, however the term co-ordination was seen to have various meanings. In this research, it is considered that design co-ordination does not just play a peripheral role in engineering management but lies at the heart of an effective approach, which is more comprehensive than any that currently exist. In addition, design co-ordination not only embraces some aspects of existing approaches, it also offers a more comprehensive means of coping with the complexities of the management of the design development process. Thus, it is hypothesised that in order to achieve the objective of improving the performance of the design development process, design co-ordination should form the nucleus of an improved approach to engineering management.

Management has been considered as comprising two levels, i.e. strategic and operational [Greenley, 1989; Cole, 1994]. In addition, it has been identified that an organisation comprises a number of parts including a strategic apex to oversee the whole of the business, and an operational core described as the people who perform the basic, day-to-day processes [Finlay, 2000]. Greenley described strategic management as being at a conceptually higher level than operational management, though both were said to be equally important [Greenley, 1989]. Strategic management was said to provide a framework for operational management, which was described as being concerned with the efficient use of the existing production capacity. Similar to Greenley, Cole described the relationship between the two levels by stating that "strategic management produces the primary goals and framework within which they can be realised for operational management" [Cole, 1994]. Furthermore, it was indicated that the concerns of strategy were effectiveness, i.e. ensuring that the organisation is doing the right thing, whereas the concerns of operations were efficiency, i.e. doing things right.

In conclusion, strategic management can be viewed as setting out the aims and goals, i.e. *what is the right work to do,* whereas operational management can be thought of as the mechanisms and means to ensure their achievement, i.e. *how to do the work right.* It is suggested that the performance of the design development process can be improved through the application of design co-ordination at the strategic and operational levels of management. The work presented in this thesis is aimed at design co-ordination at the operational level of management only. However, research on design co-ordination at the strategic level of management has been conducted in collaboration with this work [Whitfield et al., 2000a].

2.5 Summary

This chapter has aimed to identify design co-ordination as being fundamental to engineering management. In Section 2.1, effective engineering management was introduced as a means for contemporary engineering organisations to achieve and maintain a competitive advantage in an increasingly aggressive global market. The requirement for an improved approach to engineering management was proposed in order to (i) increase the competitiveness of an organisation by contributing toward delivering quality products in shorter timescales at an acceptable cost, (ii) cope with the increasing complexity of contemporary engineering processes and products, and (iii) complement and facilitate the best use of rapidly advancing technology. The need to increase the competitiveness of organisations has resulted in the proliferation of a variety of approaches to engineering management, a number of which were briefly discussed in Section 2.2. In Section 2.3, co-ordination was identified as important and pervasive within a number of approaches, however, it was shown that currently there exists a broad and varied understanding. Thus, in Section 2.4, design co-ordination was proposed as the basis for a more comprehensive approach to engineering management.

The main conclusion that can be drawn from this chapter is that design co-ordination potentially offers an original and significant approach to engineering management. Previously regarded as a ubiquitous characteristic of other approaches, it is proposed that design co-ordination exists as an approach to engineering management in its own right. Furthermore, it has been hypothesised that design co-ordination offers a more comprehensive approach than presently exists with the objective of improving the performance of the design development process.

3 Operational Design Co-ordination

In Chapter 2, design co-ordination was revealed as an important and pervasive characteristic of engineering management, and, in addition, proposed as offering a more comprehensive approach than currently exists. Furthermore, the focus of the research presented in this thesis was stated and justified as being aimed at the operational level of management only. The aim of this chapter is to present a review of literature related to design co-ordination from an operational perspective. Based on the literature, the objective of the review is to establish the nature of operational design co-ordination leading to the identification of the key issues involved. Further, the key issues will provide the basis for (i) a critique of existing approaches presented in Chapter 4, and (ii) the requirements of operational design co-ordination, which will be discussed in Chapter 5.

In Section 3.1, the scope of the literature review is outlined. The foundation of the research presented in this thesis is introduced in Section 3.2. In Section 3.3, the nature of operational design co-ordination is discussed in terms of the key issues identified. Finally, the chapter is summarised in Section 3.4.

3.1 Scope of the Literature Review

The literature reviewed in this chapter is concerned with operational co-ordination in the context of engineering design. However, in order to gain an understanding of the key issues of operational co-ordination, the review not only includes literature pertaining to engineering design, but also from organisational theory and distributed artificial intelligence[1]. The justification for including literature from these disciplines is that co-ordination has been identified as relevant and important in these areas, and a key research problem [Jennings, 1993; Malone & Crowston, 1994; Findler & Elder, 1995; Crowston, 1996; Nwana et al., 1996; Greenwood et al., 1997; Heck, 1999]. Indeed, Durfee indicated that while co-ordination has been studied from a number of discipline viewpoints, and alternative approaches have been proposed, the final objective is the same in each case [Durfee, 1993]. That is, the meshing of behaviour to promote co-operation and avoid conflict. Durfee's indication has been supported by the work of Wilson and Shi who developed co-ordination mechanisms from artificial intelligence for application in engineering design [Wilson & Shi, 1996]. However, it has also been indicated that there is no single best co-ordination mechanism for all environments [Decker & Lesser, 1995a].

1.Since many of the computer-based systems generated in the area of distributed artificial intelligence are *agent-oriented*, an introduction to the term agent and multi-agent system is presented in Appendix A.

Prior to discussing the nature of operational design co-ordination, it is appropriate to present the foundation and starting point of the research presented in this thesis.

3.2 The Foundation of Design Co-ordination Research

The impetus for design co-ordination research stems from the requirement to improve engineering management and, thus, the performance of the design development process. More specifically, as hypothesised in Chapter 2, design co-ordination should form the nucleus of an improved approach to engineering management aimed at facilitating the improvement of the performance of the design development process.

Furthermore, the foundation and starting point of the research presented in this thesis has been the main outcome of European funded collaborative research effort into design co-ordination, i.e. the Design Co-ordination Framework. In 1992 a unified research effort into design co-ordination was launched by a working group known as DEVices in Computer Integrated Manufacture (CIMDEV) [Duffy et al., 1994]. The work of the design co-ordination group of CIMDEV ceased in 1995, however, the research effort continued until 2000 through a sub-group of the thematic network known as Integration In Manufacturing and Beyond (IIMB) [Duffy et al., 1999]. Members of these working groups included academics from a number of European universities such as the Technical University of Denmark, the University of County Cork in Ireland, Delft University of Technology in the Netherlands, and the University of Strathclyde in the United Kingdom. The common mission of both working groups has been to "achieve a quantum leap in the performance of the product development process" [Duffy et al., 1999], with the principal goal of "developing a computer based environment which supports the effective utilisation and integration of resources in order to optimise the design process" [Andreasen et al., 1996]. Andreasen et al. also indicated that CIMDEV and IIMB have played a significant role in developing the concept of design co-ordination.

As stated above, the main outcome of the research effort within the CIMDEV and IIMB working groups was the Design Co-ordination Framework (DCF) [Andreasen et al., 1994], which is a prominent framework within the area of design co-ordination. Since its inception, the DCF has been discussed in a number of publications [Duffy, 1995; Duffy et al., 1995; Andreasen et al., 1996; Duffy, 1998; Duffy et al., 1999] and has provided the basis for further research [MacCallum & Liu, 1995; Girod, 1997; O'Donnell, 1997; Cantamessa et al., 1999; Girard et al., 1999; Whitfield et al., 2000a] including the work presented in this thesis. The DCF has been described as a concept for an "ideal" design co-ordination system with the abilities to support the co-ordination of various aspects of product development [Andreasen et al., 1994]. In addition, the DCF has been considered as identifying new and critical issues for future research [Duffy, 1998].

This framework consists of eleven frames, as illustrated in Figure 3.1.

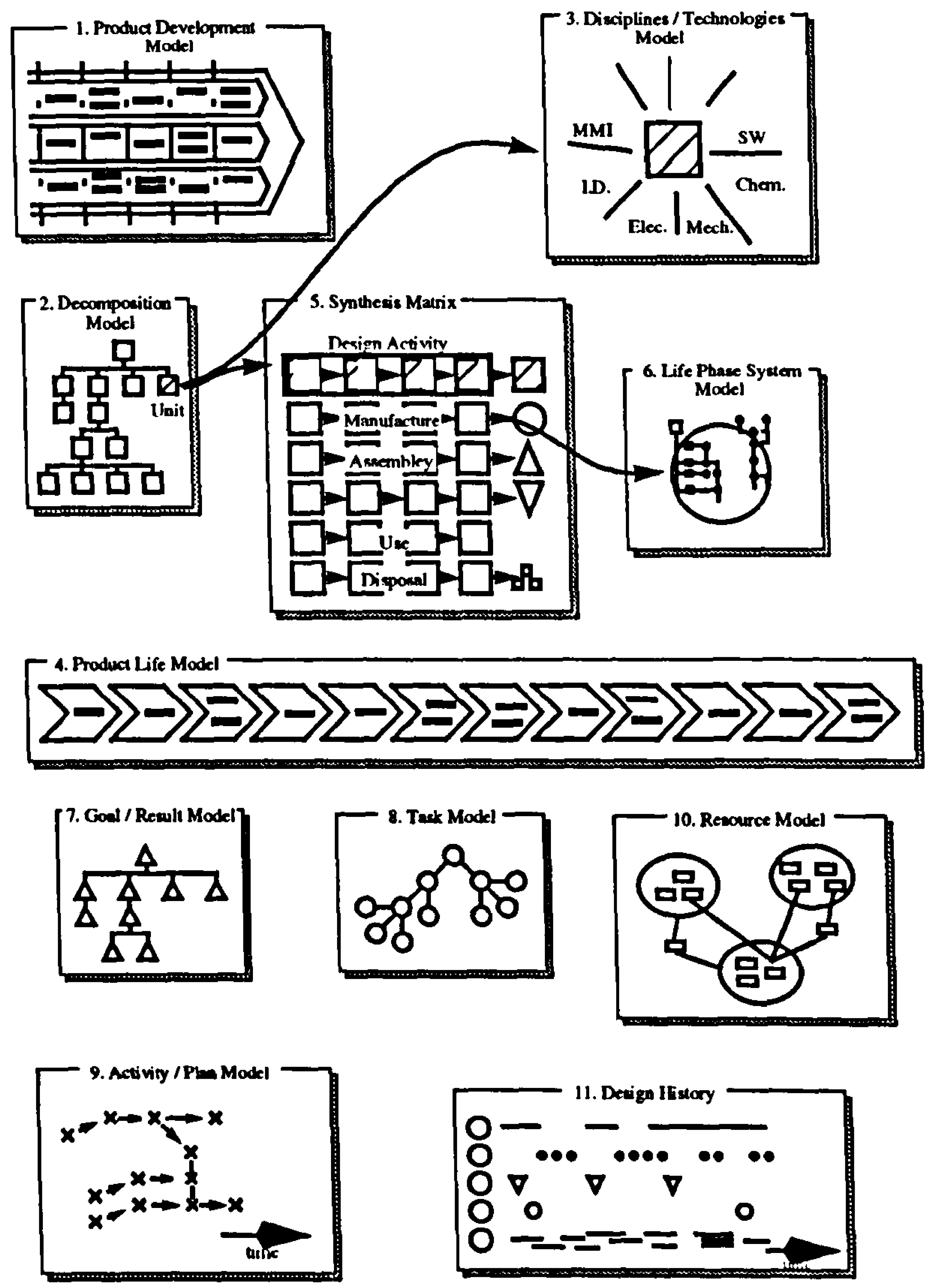

Figure 3.1 The Design Co-ordination Framework [Andreasen et al., 1994]

Frame 1 - Product Development Model charts the development of a product from the identification of a need through to its introduction to the market.

Frame 2 - Decomposition Model represents the breakdown structure of a product with respect to entities and relations.

Frame 3 - Disciplines/Technologies Model consists of the make-up of engineering disciplines and technologies for a product.

Frame 4 - Product Life Model represents the product during various life phases.

Frame 5 - Synthesis Matrix models a product and its components through the stages of each product life phase.

Frame 6 - Life Phase System Model represents the systems that are involved during the various life phases of a product.

Frame 7 - Goal/Result Model shows the goals and sub-goals, which are specifications of the product to be developed.

Frame 8 - Task Model represents the breakdown of the tasks to be completed.

Frame 9 - Activity/Plan Model introduces the time dimension to the task model and explains when tasks are to be done.

Frame 10 - Resource Model represents the structure of the available resources.

Frame 11 - Design History Model represents a record of the development of a product.

Andreasen et al. stated that "co-ordination relates to the effective control and management of the inter-relations between these frames, through appropriate design co-ordination mechanisms" [Andreasen et al., 1996]. In agreement, Duffy indicated that the frames of the DCF do not represent design co-ordination but rather the elements involved [Duffy, 1998]. Furthermore, design co-ordination was described as the effective integration, networking, control, and management of the elements of the DCF as a whole. That is, design co-ordination is focused on the interaction between the models of the DCF [Duffy et al., 1999]. As such, the lack of understanding regarding the contents of each model and how the models relate to each other was recognised as a main goal of future research. That is, the links need to be identified, managed and controlled to realise a co-ordinated environment.

The DCF has been validated to a degree from an academic perspective using design complexities [Duffy et al., 1995]. Each frame of the DCF was discussed in relation to six design complexity factors, namely: (i) the artefact being designed, (ii) the design activity itself, (iii) the actors involved, (iv) the design decision-making process, (v) the aspects impinging upon design, and (vi) the knowledge and sources used and generated. As a result of these discussions, particular issues involved with the factors were recognised, and the complexities each frame of the DCF can support were identified. In addition, the use of design co-ordination to manage complexities was said to enhance harmony.

From an industrial perspective, Cantamessa et al. showed that the DCF is a valid model through a case study involving optics for missile guidance systems [Cantamessa et al., 1999]. The operational requirements and issues involved in the work within the case study were mapped to various frames of the DCF. It was stated that "the main co-ordination problem was related to changing the process (product development model) and setting deliverables (goal/

result model) that could be compatible with the existing resources and their skills (resources model and discipline/technology model), with their availability in time (activity/plan model), and the project's time constraints (activity/plan model)".

A further notable outcome of the CIMDEV and IIMB working group research effort was the definition: "design co-ordination is a high-level concept of the planning, scheduling, representation, decision making and control of product development with respect to time, tasks, resources and design aspects" [Duffy et al., 1993]. This definition has been recognised by a number of authors [MacCallum & Liu, 1995; Cantamessa et al., 1999; Coates et al., 1999b; Girard et al., 1999]. For example, Coates et al. stated that their design co-ordination methodology embraced the definition since it involved aiming to optimise the scheduling and planning of a design analysis with respect to the allocation and utilisation of the available resources [Coates et al., 1999b].

In summary, the DCF has provided the starting point for the research presented in this thesis. Specifically, with the emphasis toward operational design co-ordination as discussed in Section 2.4 of Chapter 2, three frames of the DCF have been used as the basis for this research, namely the task model (Frame 8), activity/plan model (Frame 9), and resource model (Frame 10).

3.3 The Nature of Operational Design Co-ordination

In Chapter 2, a range of views of co-ordination were reported as originating from various existing approaches to engineering management, i.e. "the appropriate application of effort" [Cross, 1994], "organising resource efforts and managing people and schedules" [Oberlender, 1993], "resources knowing about the tasks they are dependent on" [Cleetus et al., 1996], "managing shared resources and simultaneity constraints" [Malone & Crowston, 1994], "assigning particular tasks to individuals or groups" [Ray, 1985], "the division and management of activities" [Perrin, 1997], "steering and integrating activities" [Lock, 1996], "avoiding inconsistencies" [Alonso et al., 1996], and "coping with distributed parts" [Piccinelli, 1998]. The aim of this section is to build upon these perceptions in order to identify the key issues of co-ordination according to dedicated research in the field.

3.3.1 Coherence

"Everyone has an intuitive idea of what coordination means, however it is difficult to explain what it is and why it is needed" [Cruz et al., 1996]. Despite this reported difficulty, a number of authors have offered their respective view of co-ordination [Fayol, 1949; Van de Ven et al., 1976; Kleinman, 1990; Findler & Elder, 1995]. Fayol stated that "to coordinate was to layout the timing and sequencing of activities, bind together, unify, and harmonise all activities and effort". Van de Ven et al. defined co-ordination as "integrating or linking together different parts of an organisation to accomplish a collective set of tasks". In addition, co-ordination has been regarded as involving "the timely exchange of information and resources, the division and allocation of tasks, and the synchronisation of actions" [Kleinman, 1990], and "intelligent decision making agents sharing information and resources in order to solve a common set of tasks" [Findler & Elder, 1995].

In the context of engineering design, co-ordination has been described as involving "the effective utilisation of resources in order to carry out tasks for the right reasons, at the right time, to meet the right requirements and give the right results" [Duffy, 1995; Duffy et al. 1999]. Based on this description, Coates et al. reported co-ordination as the concept of the appropriate activities being performed, in a certain order, by a set of capable agents, in a fitting location, at a suitable time, in order to complete a set of tasks [Coates et al., 1999a; Coates et al., 2000c]. Also related to engineering design, Crabtree et al. identified a co-ordination challenge as "how can each engineer's design tasks be managed so that it interacts and integrates well with the efforts and results of other engineers?", and intimated that a lack of co-ordination would lead to schedule delays, re-work, and cost increase [Crabtree et al., 1997].

"Engineering design problems are often solved by a group of individual participants with different expertise, loosely organised as a design team" [Wilson & Shi, 1996]. As such, Wilson and Shi recognised that design participant's activities must be co-ordinated in order to maintain coherence. Similarly, Durfee and Montgomery viewed a co-ordination technique as "how a group of people organise themselves to work as a coherent team in order to accomplish some task" [Durfee & Montgomery, 1990].

With regard to a distributed artificial intelligence setting, Chauhan indicated that co-ordination and coherence are related in that "greater co-ordination results in a more coherent solution to the overall problem" [Chauhan, 1997]. Bond and Gasser suggested that coherence involves how well the entire system behaves as a whole while solving a problem [Bond & Gasser, 1988]. On the theme of coherence, Nwana et al. viewed the prevention of chaos as a main reason for needing co-ordination and, thus, described co-ordination as "a process in which agents engage in order to ensure their community acts in a coherent manner, i.e. agent actions gel well and do not cause conflict with one another" [Nwana et al., 1996]. Chaos avoidance in multi-agent environments has been widely recognised as the requirement for co-ordination [Jennings, 1996; de Jong, 1997; Jamali et al., 1999]. Jennings recognised that without co-ordination, the advantages of decentralised problem solving disappear and a society of agents can rapidly become a collection of chaotic individuals. Jamali et al. described several scenarios in which the lack of co-ordination in large agent ensembles resulted in chaotic behaviour.

In distributed artificial intelligence, the co-ordination technique to be applied is dependent on the nature of the agents and the environment in which they work. For example, in a society of self-interested agents, negotiation may be appropriate [Smith, 1980; Findler & Elder, 1995]. Negotiation can be thought of as the act of agents communicating with one another in order to reach an agreement that is a compromise between conflicting preferences. Conversely, a group of benevolent or co-operative agents may use multi-agent planning as a suitable co-ordination technique [Durfee, 1993; Cruz et al., 1996]. Since the research presented in this thesis is oriented toward engineering design, it is viewed that designers work toward common goals and, as such, they are co-operative rather than self-interested. Thus, this thesis focuses on the co-ordination of design in the engineering domain, where everyone aims to work together in accomplishing common goals. That is, in a coherent and co-operative manner.

3.3.2 Communication / Interaction

In Section 3.3.1, views of co-ordination were reported as involving "sharing information" [Findler & Elder, 1995] and "the timely exchange of information" [Kleinman, 1990]. Implicit within these perceptions is the aspect of communication, or interactions, between entities.

Durfee indicated that agents need to interact with each other to co-operatively achieve their objectives [Durfee, 1993]. Chauhan stated that "communication enables the agents in a multi-agent system to exchange information on the basis of which they co-ordinate their actions and co-operate with each other" [Chauhan, 1997]. Hayden et al. recognised that in multi-agent systems, interactions between the agents are decisive in determining the effectiveness of the system [Hayden et al., 1999]. Cruz et al. proffered that co-ordination problems arise in the organisation of interactions of a group of entities that collaborate and co-operate to accomplish some task and to satisfy some goals [Cruz et al., 1996]. Jennings identified the dependencies between multiple agent actions as a main reason for the need to co-ordinate those actions [Jennings, 1996]. Bond and Gasser indicated that co-ordination is the interaction among a set of agents performing some collective action [Bond & Gasser, 1988]. As such, co-ordination has been viewed as the management of interactions between agents [Tichelaar, 1997; Arbab, 1998].

"In a general sense, coordination is brought about by communication" [Cleetus et al., 1996]. Thus, it was indicated that a communication infrastructure should be the basis for successful co-ordination. Similarly, Carstensen stated that "communication is the basic means of coordination" [Carstensen, 1996]. This statement was elaborated on by emphasising that it is the structure of interaction that is of importance. Similarly, de Jong also recognised that most co-ordination mechanisms for multi-agent systems rely on the exchange of structured information between agents [de Jong, 1997].

Langston also viewed communication as a requirement for inter-disciplinary design co-ordination [Langston, 1994]. Communication was seen as being enhanced by Computer Aided Design and Drafting, which uses reference files accessible by technical personnel from each discipline such that they can view real-time progress of the work being completed by others and avoid conflicts where possible. However, it was noted that in situations where conflicts could not be avoided, dialogue could commence early when engineers are more receptive to changing their design.

Related to a common means of viewing and accessing information, Carter identified a requirement of design co-ordination as being product modelling [Carter, 1991]. That is, the use of a product description language was said to ensure that confusion and/or inconsistency were avoided or minimised in the situation where many people were working on different parts of the same product. The view of co-ordination being a means of "avoiding inconsistencies" was also reported in Chapter 2 [Alonso et al., 1996]. Similar to Carter, with regard to co-ordination, Bailetti et al. discussed the use of object based representations to provide "a common vocabulary of discourse to effectively communicate" [Bailetti et al., 1994].

While communication has been viewed as an aspect of co-ordination, Huber and Durfee departed from this perception by considering observing the intention of others, rather than direct communication, as a means of co-ordinating the activities of agents [Huber & Durfee, 1995]. This approach was said to be necessary in situations where direct communication may be unreliable or impossible. Similarly, Sen et al. discussed the concept of agents co-ordinating their activities by learning, or acquiring knowledge, about the actions of others rather than communicating [Sen et al., 1994]. However, a limitation of this concept was that agents must repeatedly perform the same task in order for others to recognise patterns regarding intended actions.

On the theme of co-ordination through communication, Van de Ven at al. classified one mechanism for co-ordinating work activities within organisations as the personal mode [Van de Ven et al., 1976]. Personal co-ordination was described as individual role occupants serving as the mechanism for making mutual task adjustments through either vertical or horizontal channels of communication. Previously, March and Simon had indicated that one way of co-ordinating an organisation was by feedback [March & Simon, 1958]. Co-ordination by feedback, also known as mutual adjustment [Thompson, 1967], corresponds to Van de Ven's personal and group mode classifications. Group co-ordination mechanisms were viewed as scheduled or unscheduled meetings, which have been discussed by a number of authors [Fayol, 1949; Hegazy & Khalifa, 1996; Hansen et al., 1997; Hegazy et al., 1998].

Co-ordination between team members was said to be maintained through meetings when problems arise and consultation with the team leader [Hegazy & Khalifa, 1996; Hegazy et al., 1998]. Further, a quality design was described as being highly dependent upon effective co-ordination among the various discipline teams involved in medium to large sized projects. Fayol viewed conferencing of departmental heads as a means of informing a management of the running of a concern in order to clarify the co-operation to be expected between the various departments. The frequency of conferences was described as that which would ensure harmonising activity, i.e. co-ordination, and focusing of effort between successive conferences. Hansen et al. conducted a study into co-ordination activities in the context of engineering design by assigning a number of equivalently structured teams to undertake the same engineering project [Hansen et al., 1997]. Activity logs where used to measure the level of co-ordination, i.e. time used on meetings and planning as a percentage of the total time of the project. The findings of the study indicated that either a low or high level of co-ordination resulted in low project quality, whereas a medium level of co-ordination produced a high project quality. Furthermore, the underlying hypothesis of the results was that the nature and amount of co-ordination activities required was dependent on the character of the specific activities, the organisation of the team involved, and the specific actors involved in the project.

Similar to the work of Hansen, Crabtree et al. conducted a study aimed at identifying co-ordination problems within collaborative design and assessing the proportion of an engineer's time attributed to performing co-ordination activities [Crabtree et al., 1997]. A survey of engineering organisations showed that the time to complete a project increased by 20-30% as a result of co-ordination problems such as: (i) information/knowledge acquisition and access, (ii) decision interdependence, (iii) activity management, and (iv) agent access. Further, the survey revealed that in collaborative design, co-ordination activities, such as: (i) information gathering, (ii) documentation, (iii) planning and scheduling, (iv) negotiation, and (v) support and consulting, occupied 69% of an engineer's time. These statistics corroborate with those indicated by Andreasen et al. who reported that engineers only spend approximately one third of their time doing "real design" [Andreasen et al., 1996]. As such, it was stated that "a considerable amount of time and effort is wasted by the lack of focus on the application and management of design effort" and, further, "the potential for improvement in better productive use of engineering design resource is substantial - providing we have the mechanisms to realise it".

3.3.3 Management of Activities / Tasks

In Chapter 2, co-ordination was reported as being viewed as "steering and integrating activities" [Lock, 1996], and "the division and management of activities" [Perrin, 1997]. Furthermore, in Section 3.3.1, Fayol viewed an aspect of co-ordination as the laying out of the timing and sequencing of activities [Fayol, 1949]. In agreement with these perceptions, Kleinman viewed "the division and allocation of tasks" as an aspect of co-ordination [Kleinman, 1990], and Duffy et al. described the planning and control of activities as being central to design co-ordination [Duffy et al., 1994]. In addition, Decker and Lesser indicated that, in many application areas, individuals are responsible for deciding what order tasks should be done and when to do them [Decker & Lesser, 1995b].

Prior to further discussing the management of activities/tasks as a key issue of operational design co-ordination, it is appropriate to offer the definition that "goals are accomplished or achieved through undertaking tasks that are completed by performing or carrying out activities". The inconsistent, ambiguous, and often synonymous, use of the words *activity* and *task* has been made throughout the literature referenced in this thesis[1], and, as such, the definition proposed aims to clarify the relationship between them. Thus, from this point onwards, the definition offered will be adhered to in the thesis. However, with regard to the disseminated work of others, the respective author(s) interpretations will be reported.

Fayol viewed co-ordination as the harmonisation of all activities of a concern so as to facilitate its working, and its success [Fayol, 1949]. In a well co-ordinated enterprise, an organisation was said to require each department to work in harmony with others, i.e. all departments to carry out their activities in an orderly fashion. Similarly, Duffy et al. stated that "design co-ordination provides a means of integrating and controlling disparate activities" [Duffy et al., 1993], and "design co-ordination is aimed at structuring activities in such a fashion to achieve optimal performance" [Duffy, 1995].

A number of approaches to design management have been proposed with the emphasis placed on sequencing activities/tasks [Eppinger et al., 1990; Kusiak & Park, 1990; Eppinger, 1991; Eppinger et al., 1994; Scott, 1999]. However, these approaches are oriented toward concurrent engineering and, thus, focused on sequencing activities/tasks such that they could be performed/undertaken in parallel. The design structure matrix [Steward, 1981] was used in each of these approaches as a tool to re-arrange activities/tasks such that parallel groups could be identified. Furthermore, the strength of dependencies between activities/tasks was assessed,

1.Appendix B includes a matrix, which presents the inconsistent and ambiguous use of the words *activity* and *task* throughout the literature referenced in this thesis.

and relaxed if deemed to be weak. This feature of inducing concurrency departs from the view offered by Duffy et al. who emphasised that in order to optimise design, activities should not necessarily be carried out concurrently but rather structured in a fashion as to achieve optimal performance [Duffy et al., 1993].

Related to the issue of structuring activities appropriately, the management of dependencies between activities has been identified as a key issue of co-ordination [Malone & Crowston, 1994]. In addition, Crowston stressed that "coordination and dependencies are important issues within organisational studies" [Crowston, 1996]. An interdisciplinary study of co-ordination conducted by Malone and Crowston resulted in co-ordination being defined as "the process of managing dependencies between activities". Indeed, this definition has been widely cited and influential in the areas of distributed artificial intelligence and organisational theory [Decker & Lesser, 1995a; Greenwood, 1995; Cruz et al., 1996; Jennings, 1996; Hansen et al., 1997; Lesser, 1998]. For example, Lesser indicated that co-ordination of agent activities becomes necessary when there are interdependencies between them. Similarly, Cruz et al. described co-ordination problems as being primarily concerned with dependencies between the activities performed by the system entities. Furthermore, a requirement for co-ordination was said to exist within contemporary organisations due to the increased complexity of many people and software tools working across various disciplines [Kawalak, 1996; Greenwood et al., 1997]. Thus, the *coordination layer* was presented as a device to manage dependencies between (i) tools, (ii) people and tools, and (iii) people.

The focus of much work reported in Malone and Crowston's interdisciplinary study was said to be directed at co-ordination in parallel and distributed computer systems, human systems, and a combination of them both. Based on their definition, the requirement for identifying types of dependencies and co-ordination mechanisms was recognised. Thus, goal decomposition, resource allocation and synchronisation were identified as co-ordination mechanisms to manage different types of dependencies such as: (i) task/subtask dependencies, (ii) shared resources, and (iii) simultaneity constraints respectively. Engineering design was a noticable absence from the list of disciplines considered in arriving at Malone and Crowston's definition of co-ordination. In addition, an implication of their definition is that where there are no dependencies between tasks, there is no co-ordination. In this thesis, the view is held that the existence of dependencies between tasks does not solely determine the requirement for co-ordination. That is, independent tasks still need to be co-ordinated since there are other issues involved. Thus, it is considered that Malone and Crowston's definition of co-ordination is inadequate with respect to engineering operational design co-ordination.

Dependencies between activities or tasks can be represented using precedence network techniques such as Program Evaluation Review Technique (PERT) and Critical Path Method (CPM) [Park & Cutkosky, 1999], which have been identified as two major, and the most common, (i) approaches for project scheduling [Bailetti et al., 1994; Chan, 1997] and (ii) planning techniques [Goldmann, 1996]. Extensive literature exists on PERT and CPM often with an emphasis placed on simplifying the techniques in some capacity [Kamburowski, 1985; Di Battista et al., 1989; Ord, 1991; Zhu & Heady, 1994; Soroush, 1994; Aikat, 1996; Cho & Yum, 1997]. In the late 1950s, the US Navy first developed PERT as part of the Polaris Missile System Program, which was introduced for application in projects involving uncertainty. For each project activity, three time estimations were required to estimate the expected mean time, namely: (i) optimistic time, (ii) most likely time, and (iii) pessimistic time. In 1957, DuPont developed CPM, which is a deterministic approach where an estimation of one time quantity is used for each activity and there is no statistical feature on uncertainty. As stated, PERT and CPM use network diagrams showing precedence relationships between a number of activities required to be performed to meet some defined objective. A procedure is then used to find the primary project parameters such as the critical path, the minimum project completion time, and the various leeway times. Bailetti et al. recognised a number of difficulties in the use of PERT and CPM to co-ordinate including: (i) no facility to enable the re-allocation of task assignments, (ii) lack of visibility in terms of co-ordinating the efforts of project members, and (iii) large numbers of activities quickly led to a loss of perspective for the project manager and project members. In addition, Liu et al. recognised that PERT and CPM ignore resource capacity [Liu et al., 1998].

The structuring or sequencing of activities/tasks, through the consideration of the dependencies between them, has been recognised as a key issue of operational design co-ordination. However, when contemplating the structuring of activities/tasks, consideration must simultaneously be given to the resources available. The importance of this coupled consideration is highlighted by Eppinger's assumption that with no limitations on resources, independent tasks could be completed concurrently and, hence, more quickly [Eppinger et al., 1994]. Failure to consider resources may result in an optimised sequence of tasks with inadequate resources able to complete them in the desired manner. In reality, resources are scarce and, as such, need to be utilised appropriately with respect to the tasks they will be used to undertake and complete. Thus, the structuring of tasks is inextricably linked to the resources available, and, consequently, managing the assignment of tasks to resources is a key co-ordination issue needing to be addressed.

3.3.4 Managing the Assignment of Tasks to Resources

With regard to engineering design, in Chapter 2, Ray was reported as viewing co-ordination as "assigning particular tasks to individuals or groups" [Ray, 1985]. With regard to dedicated co-ordination research, the assignment of tasks to resources has also been recognised as an issue [Malone, 1987; Findler & Elder, 1995; Lesser, 1998]. Malone viewed the assignment of tasks to processors as one of the fundamental components of co-ordination. Similarly, Findler and Elder considered assigning tasks to a group of geographically distributed agents as a co-ordination problem. Lesser indicated that co-ordination strategies enable groups of agents to solve problems effectively through decisions about which agents should perform which tasks and when, and whom should communicate the results.

In this thesis, assigning tasks to resources is viewed as being synonymous with scheduling. In addition, planning is thought of as a pre-scheduling activity. Fayol commented that planning involved examining the future and laying out the actions to be taken [Fayol, 1949]. Durfee indicated that planning has been viewed as the co-ordination problem by many researchers in the area of artificial intelligence [Durfee, 1993]. Goldmann differentiated between planning and scheduling by stating that "planning is the division of tasks into sub-tasks" and "scheduling is the assignment of resources and start and end times to tasks" [Goldmann, 1996]. Similarly, Duffy et al. considered planning as the definition of the logical links between interrelated activities or tasks [Duffy et al., 1993]. Furthermore, in agreement with Goldmann, scheduling was viewed as specifying the resources and start-finish times of the activities, and as a means for the plan to be achieved. Duffy et al. also indicated that plans and schedules are not truly effective unless they are properly monitored and controlled. Indeed, Bendeck et al. indicated that co-ordination involves planning and scheduling, and monitoring during execution [Bendeck et al., 1998]. In the context of engineering project management, monitoring has been described as the process during work of checking and verifying to compare actions and results with predictions and intentions, in order to demonstrate what changes are needed to overcome problems and achieve objectives [Wearne, 1989].

Goldmann indicated that project plans are usually invalidated soon after the beginning of a project [Goldmann, 1996]. Thus, a project management tool, called Procura, was presented and described as interleaving planning, scheduling, and task execution. Scheduling was said to be a prediction and, consequently, had to be verified by comparing the schedule with the actual facts. As such, Procura was described as supporting planning/re-planning and scheduling/re-scheduling. Similar to Procura, CoMo-Kit was presented as a work process co-ordination tool, which allows planning and execution to be alternated [Dellen & Maurer, 1996; Maurer, 1996]. The need to modify planning decisions was described as being required since the design process can change and, further, certain planning decisions can only be made as a result of the completion of particular stages of the design process. Thrampoulidis et al. also recognised that due to unexpected events, the realisation of a planned time table is impossible [Thrampoulidis et al., 1997]. As such, it was asserted that there is a requirement to change, in real-time, the planned schedules of the resources. The determination of optimal changes in such cases was said to involve solving difficult combinatorial problems. Re-scheduling in real-time, referred to as day-to-day resource management, was described as entailing four steps, namely: (i) event recognition, (ii) affected component identification, (iii) solution generation, and (iv) best solution selection.

Due to the changeable nature of engineering design, it has been recognised that, potentially, there is a requirement for plans and schedules to be changed [Dellen & Maurer, 1996; Goldmann, 1996; Maurer, 1996], the need for which can be detected through monitoring [Duffy et al., 1993; Thrampoulidis et al., 1997; Bendeck et al., 1998]. The issue of monitoring is discussed in Section 3.3.5. With respect to the need to change schedules, i.e. re-assign tasks to resources, dynamic scheduling is identified as a key issue of operational design co-ordination, and, further, the management of this process.

In the context of a computing environment, dynamic scheduling has been described as postponing the assignment of tasks to processors until run time [Hamidzadeh & Lilja, 1996]. Further, scheduling decisions were said to be "adjusted to match the dynamically changing conditions encountered at run time". As such, a variety of dynamic scheduling algorithms have been developed [Hamidzadeh & Lilja, 1994; Hamidzadeh & Lilja, 1996; Hamidzadeh & Atif, 1998]. Each of these algorithms was described as addressing the problem of dynamic scheduling such that the act of scheduling and its duration is controlled and co-ordinated with task execution. As in the context of project management [Goldmann, 1996], scheduling was reported as being performed concurrently with task execution. Specifically, the search for the next partial schedule occurred simultaneously with the execution of tasks previously assigned to processors in accordance with the previous schedule. Batches of tasks, which were not defined in terms of being either independent or inter-dependent, were scheduled in phases such that each task was only ever scheduled once. A characteristic of each algorithm, which was reported as being ignored by many scheduling algorithms, is that they employed a tuning and prediction technique such that the scheduling duration could be adjusted to account for the relationship between tasks and processors, i.e. affinity. Longer scheduling times were said to enable greater optimisation durations resulting in higher quality schedules. Similarly, Garvey et al. presented an approach to design-to-time real-time scheduling, which was described as using all the available time to produce the best possible solution [Garvey et al., 1993]. The scheduler employed within the algorithm developed was said to "be able to trade-off the quality of its schedules as a function of the time devoted to scheduling". That is, the scheduler was able to control its own performance by dynamically modifying the task structure being scheduled.

Previously, the management of activities/tasks, was discussed leading to the recognition that in order to structure activities/tasks appropriately, consideration must be given to the dependencies between them. Further, it was suggested that the management of tasks/activities must also involve the simultaneous consideration of resources. That is, the assignment of tasks to resources has been identified as a key issue of operational design co-ordination. In addition, in order to ensure the appropriate assignment of tasks to resources throughout a changeable process or environment, dynamic scheduling has been identified as an extension of this issue. Further, it has been identified that planning and schedule enactment must also be managed. Due to the recognised importance of the resources that tasks are assigned to, it is postulated that attention must be afforded to the management of resources, which includes monitoring.

3.3.5 Managing Resources

With regard to design co-ordination, the allocation of resources has been identified as an important task within design management [Andreasen et al., 1996]. "The focus for supporting design co-ordination is directed at the effective utilisation and integration of resources in order to optimise design activity" [Duffy et al., 1993]. Design co-ordination has similarly been described as covering aspects of organisation and management of resources, and control of the use of resources [MacCallum & Carter, 1991]. Likewise, Carter identified requirements of design co-ordination as including the integration of resources, and organisation and control of expertise and knowledge [Carter, 1991]. Integration of resources was reported as enabling interaction across boundaries allowing different functional areas to perform meaningful work on a design. Organisation and control was described as being aimed at the large number of various kinds of knowledge and expertise to be managed such that a design solution could be obtained. That is, an organisational structure should be provided to allow the identification, maintenance and application of resources with communication where needed.

In agreement with Carter, although with regard to distributed artificial intelligence, Nwana et al. cited organisational structuring as a classic co-ordination technique, which was described as implicitly defining agent responsibilities, capabilities, connectivity and control flow [Nwana et al., 1996]. On this theme, Durfee and So viewed run-time co-ordination strategies as transforming the configuration of an organisation, with principled effects on the expected performance of the agent system, where agents were described as human or computational

[Durfee & So, 1997]. A run-time co-ordination strategy was described as ensuring that, under normal conditions, agents work on complementary tasks. However, in the event of agent failure, the surviving agents were applied most effectively. Role re-allocation and local task re-ordering were named as two main co-ordination strategies, although it was accepted that such strategies have an associated cost that may outweigh their benefits.

In this thesis, resources are viewed as entities, actors, agents, people capable of performing activities in order to complete tasks that accomplish goals. The use of many resources to facilitate the efficient performance of activities is an approach that has been reported as having benefits such as speeding up a process [Smith, 1980; Findler & Elder, 1995]. However, with regard to computing environments, Nguyen recognised that the reduction in duration of many parallel applications is not proportional to the increase in the number of processors [Nguyen et al., 1996a]. Thus, a technique was proposed to automatically regulate the number of processors used in the execution of an individual parallel program so as to maximise speed-up, which was defined as the time taken to solve a particular problem using a single processor divided by the time taken using a number of processors [Nguyen et al., 1996a]. On a related theme, Coates et al. presented a methodology for design co-ordination implemented within an agent-oriented system in a distributed computing environment [Coates et al., 1999b]. The key observation reported was that committing greater resources to a problem would not necessarily result in a proportional reduction of time to complete tasks. Rather, "it is the capacity to co-ordinate the activity performed by each team member, taking into account the available resources and knowledge of their roles and effects, that enables a measured reduction in the duration of those activities to be achieved".

In Section 3.3.4, monitoring was identified as an issue of co-ordination. Specifically, monitoring was discussed in the context of plans and schedules [Duffy et al., 1993; Thrampoulidis et al., 1997; Bendeck et al., 1998]. The requirement for monitoring exists since "the design of complex products involves the co-ordinated organisation of multi-disciplinary groups, activities and information which continually evolve and change during the design process" [Andreasen et al., 1996; Duffy, 1998]. Thus, monitoring is thought of as facilitating the detection of change such that, if appropriate, corrective action may be taken by performing re-scheduling.

Distributed computing systems need resource management capabilities that can allocate resources to applications, monitor and control the use of resources, and re-allocate resources due to anomalies [Davis & Sydir, 1996]. Thus, a need was identified for research to develop new techniques that will manage resources in a uniform and co-ordinated way within a dynamic environment. Kim and Lilja recognised that while resource scheduling has been the focus of much research over recent years, network monitoring has been largely neglected [Kim & Lilja, 1998]. Furthermore, it was understood that the dynamic varying nature of network load can substantially impact resource performance. Musliner et al. also recognised the need to be able to detect and recover from discrepancies between the expected state and actual state during execution [Musliner et al., 1991]. Indeed, Ranganathan et al. indicated that deciding which resource to run particular applications can be based on monitoring variations in network characteristics [Ranganathan et al., 1996]. Nguyen et al. indicated that despite the inherent inaccuracies of runtime measurements, and the added overhead of more frequent re-allocations, schedulers using them can significantly outperform those that do not [Nguyen et al., 1996b]. In addition, Garvey and Lesser considered monitoring as almost always providing a reduction in missed deadlines [Garvey & Lesser, 1994]. A concern voiced by Wolski was that monitoring should be non-intrusive, i.e. not compromise performance [Wolski, 1997].

The Distributed Resource Management System (DRMS) has been developed to support dynamic reconfiguration of data parallel applications in an environment of unpredictable and varying workload [Moreira & Naik, 1997]. The DRMS incorporates entities such as a job scheduler and analyser, task co-ordinator and run-time monitor to ensure the co-ordinated execution of re-configurable applications. Komodo [Ranganathan et al., 1996], the Network Weather Service (NWS) [Wolski, 1997], and the Network Status Predictor (NSP) [Kim & Lilja, 1998] are stand-alone computer network monitoring systems, the latter two of which have been described as supporting dynamic network resource scheduling. In each of the three systems, network load was detected using the technique of sample message sending between two nodes to determine the round trip time. Whereas Komodo only detected network load, the NWS and NSP have been described as enabling predictions to be made regarding future performance. The NWS has been used to provide dynamic system information for an application specific approach to scheduling individual parallel applications on a heterogeneous system [Berman et al., 1996]. Distributed sensors periodically accumulated instantaneous conditions, which were used with a number of numerical methods to project future conditions. Thus, the NWS was described as sensing resource performance, forecasting future performance, and disseminating forecasts to the schedulers concerned. Kim and Lilja criticised the NWS since only a single number was used to predict future performance, whereas within the NSP upper and lower bounds were used [Kim & Lilja, 1998].

3.4 Summary

This chapter has presented a review of the nature of operational design co-ordination and, hence, identified the key issues involved. A number of the publications in the literature reviewed have previously been discussed in more detail [Coates et al., 2000b].

The key issues of operational design co-ordination have been identified as:

- ***coherence***, i.e. integrating, or linking together, resource effort and tasks within an organisation in a harmonious manner to avoid chaos,
- ***communication / interaction***, i.e interaction involving the exchange of structured and meaningful data, information and knowledge,
- ***task management***, i.e. the organisation and control of tasks, and the dependencies between them, such that they can be undertaken and completed in a structured manner,
- ***schedule management***, i.e. managing the planning and dynamic assignment of tasks to resources, and the enactment of the resulting schedules, throughout a changeable design development process, and,
- ***resource management***, i.e organising and controlling resources to enable their continuous optimised utilisation throughout a changeable design development process.

With regard to the key issues of *schedule management* and *resource management*, it has been recognised that engineering design is changeable due to the evolution of the multi-disciplinary groups, activities and information involved [Andreasen et al., 1996; Duffy, 1998]. Thus, a further key issue of operational design co-ordination is identified as:

- ***real-time support***, i.e. how to manage and adapt to a changeable, i.e. dynamic and unpredictable, design development process.

The key issues identified in this chapter provide the basis (i) for a critique of existing related approaches presented in Chapter 4, and (ii) to identify the requirements of operational design co-ordination as discussed in Chapter 5.

4 A Critical Review of Existing Approaches

The aim of this chapter is to present a critical review of existing approaches related to operational engineering management with respect to the key issues of operational design co-ordination that were identified in Chapter 3. The outcome will be the identification of limitations of these approaches that will need to be overcome in order to more comprehensively support operational design co-ordination.

In Section 4.1, an overview of the scope of the review is presented. In Sections 4.2 and 4.3, approaches related to operational engineering management within relevant research areas are summarised and critically reviewed. Finally, the chapter is summarised in Section 4.4.

4.1 Scope of the Review

Approaches in two areas are considered to be related to operational engineering management, namely ***design management*** and ***project management***. The literature reviewed in this chapter considers the most relevant approaches within these two areas that are identified as being related to operational design co-ordination. A number of these approaches and others have been discussed by Coates et al. [Coates et al., 2000b]. Table 4.1 indicates the review areas, general features of approaches in these areas, and relevant work that is reviewed.

In Sections 4.2 and 4.3, summaries and critical reviews of relevant existing approaches are presented in the areas of *design management* and *project management* respectively. The approaches are critically reviewed with respect to the key issues of operational design co-ordination identified in Chapter 3, namely: (i) *coherence*, (ii) *communication/interaction*, (iii) *task management*, (iv) *resource management*, (v) *schedule management*, and (vi) *real-time support*. Furthermore, when critically reviewing an approach against the key issues, where appropriate, it is indicated whether or not support to address the key issue is claimed, and if operational knowledge is provided, i.e. within the public domain, to provide the said support.

Review Area	General Features of the Approaches	Relevant Work
Design Management	Organisation and Control of Resources	HOBS [Carter, 1991]
	Product Decomposition to Organisation of Tasks	Design Management Strategy [Eppinger et al., 1990] Decomposition Methodology / Schedule and Management Approach [Kusiak & Park, 1990] A Design Activity Management Model [Pourbabai & Pecht, 1994]
	Product Decomposition to Schedule Development	Design-Development Modelling Strategy [Scott, 1999]
	Process Management	Design-Development Process Management [Lewis & Cangshan, 1997] Concurrent Workflow Management Process [Prasad et al., 1998] Knowledge-Based Process Modeller [KTI, 1999]
Project Management	Concurrent Planning, Scheduling and Enactment	CoMo-Kit [Dellen & Maurer, 1996] Procura [Goldmann, 1996] An Approach to Co-ordinating Management Activities [Bendeck et al., 1998]
	Distributed Agenda Management	A Distributed, Co-operative Work Support Tool [Decker & Lesser, 1995b] COFCAST-RU [Liu & Sycara, 1996] PACT [Cleetus et al., 1996]
	Resource Relationship Management	A Co-ordination Structure Approach [Bailetti et al., 1994]

Table 4.1 Review Areas, General Features of the Approaches, and Relevant Work

4.2 Design Management

Approaches to operational design management are sparse. However, the 1990s has seen the emergence of a number of approaches, the most relevant of which are summarised and critically reviewed in this section.

4.2.1 Existing Approaches

Organisation and Control of Resources

Carter presented a software architecture for supporting engineering design co-ordination of diverse resources undertaking co-operative and distributed design activity [Carter, 1991]. The Hierarchical Object Oriented Blackboard System (HOBS) is described as a computer-based support system. It is stated that "the central concept in the HOBS architecture is that the segments of design expertise or resources are organised into a hierarchy of objects (or Knowledge Sources), which are controlled through a blackboard mechanism (the Executive), and communicate with one another about the product through a common area referred to as the Workspace". Figure 4.1 presents the information links between the various components of HOBS.

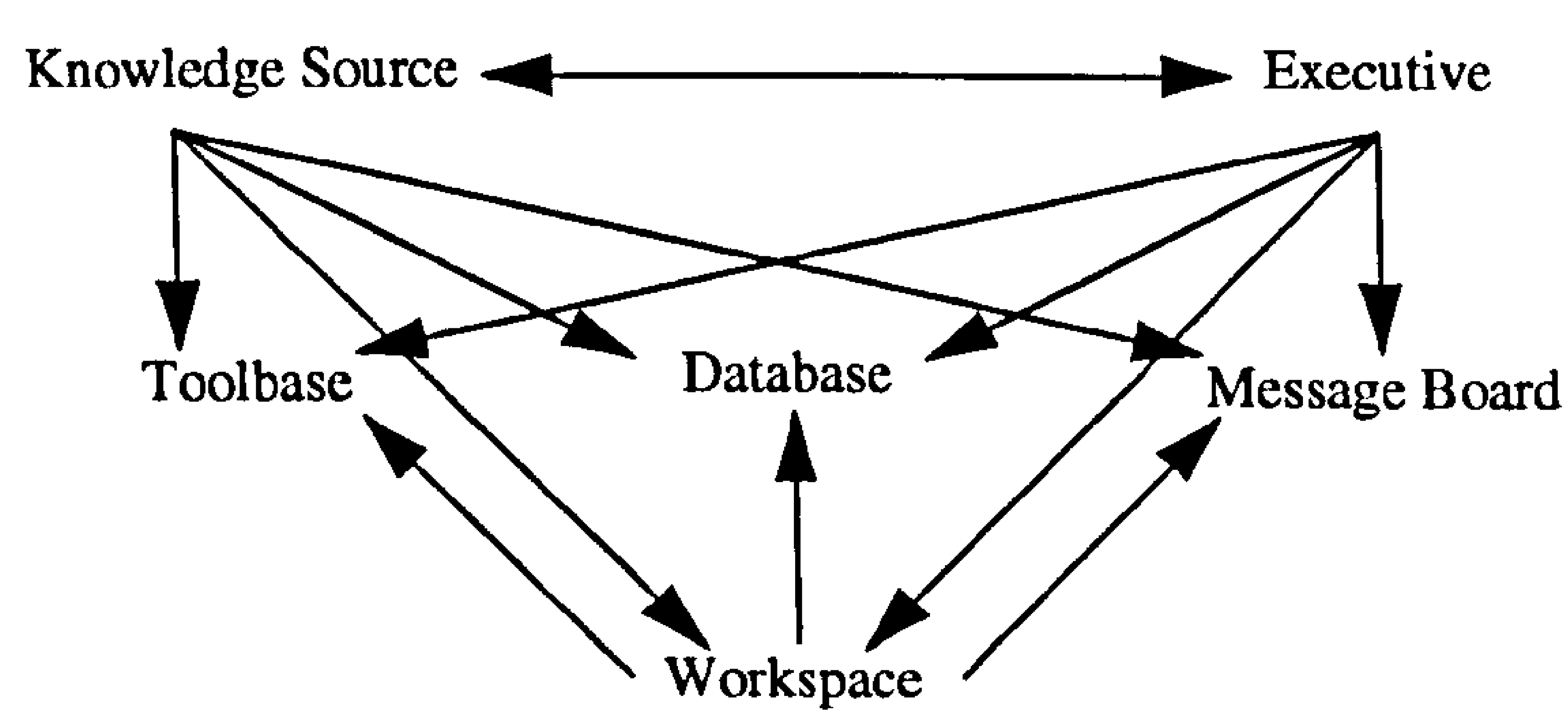

Figure 4.1 Information Links between Components of HOBS [Carter, 1991]

The Executive is the control mechanism that elects the next action or operation to be carried out by knowledge sources. Communication between knowledge sources regarding the product occurs through a Workspace, which is described as a general resource area for the system, handling data, tools and messages. For each resource type, the Workspace comprises the Database, the Toolbase and the Message Board.

Product Decomposition to Organisation of Tasks

Eppinger et al. presented a design management strategy concerned with organising design tasks in order to reduce complexity and product development time [Eppinger et al., 1990]. The design structure matrix representation is used to model the relationships between design tasks [Steward, 1981]. Indeed, the matrix representation is said to capture both the sequence of and technical relationships among the many design tasks to be performed [Eppinger et al., 1994]. Once constructed, the matrix is partitioned through re-arranging / inter-changing rows and columns such that a more organised sequence of tasks could be found. Parallelisation, artificial decoupling, and increased coupling are named as strategies for improving the design process once re-sequencing is completed.

Kusiak and Park proposed a decomposition methodology coupled with an approach to schedule and manage design activities [Kusiak & Park, 1990]. The methodology focuses on decomposing a product or system into modules that each involves a set of activities. A non-structured incidence matrix is used to represent the interactions between modules and activities. Subsequently, cluster analysis techniques are used to transform the matrix to enable the detection of potential groups of activities that may be scheduled simultaneously. The approach to schedule and manage design activities is achieved through the application of a knowledge-based system. Prior to the application of the system, network analysis is used to represent precedent constraints between groups of activities. An analysis of these constraints then enables the identification of the inter-group links requiring to be weakened in order to execute groups of activities concurrently.

Pourbabai and Pecht presented a model for managing design activities [Pourbabai & Pecht, 1994]. The model comprises three functions:

- decompose a product into its smallest elements, i.e. components,
- according to the components, represent activities in a network diagram, and,
- assign activities amongst operating groups at various working shifts.

Product Decomposition to Schedule Development

Scott identified time compression as a driving factor of modern business and, thus, recognised concurrent engineering as the basis for a "strategy for modelling the design-development phase of a product" [Scott, 1999]. The strategy involves five stages that are performed sequentially:

- create a product design-work breakdown structure involving the decomposition of a product system leading to a set of discrete activities,
- model design-development activities and their data-dependencies using a design structure matrix,
- derive a near-optimal schedule of activities, based on objectives of minimising iteration and maximising concurrency,

- derive an activity network diagram based on the design structure matrix, and,
- derive a resource-constrained schedule of activities using a multi criteria genetic algorithm.

Process Management

Lewis and Cangshan described the management of the design-development process as involving three stages, namely (1) describing the process, (2) modelling the process, and (3) identification and management of design resources [Lewis & Cangshan, 1997]. Firstly, the process is described as being characterised by (i) inputs of information, (ii) outcomes in the form of plans and product specifications, and (iii) the array of decisions to transform inputs into outcomes. Secondly, the process is modelled using design management tools, such as the design structure matrix and strategic information flow, in order to reveal the strategic ordering of key design decisions. Finally, a *design resources chart* is presented that encapsulates the knowledge and skill base required to support decisions. The chart is said to identify "the resources (other than time) to be marshalled by the design manager and includes the knowledge generated and utilised during the process of product design and development". As such, the chart is described as providing a design manager with critical information in a visual format, i.e. the resources required for successful design-development.

Prasad et al. described a "systematic concurrent workflow management process for integrated product development" [Prasad et al., 1998]. The combination of concurrent engineering and workflow management is said to be "essential to achieve time compression and optimal performance of the product's design and development". Furthermore, it is stated that "the best performance (of the product development process) is usually realised by scheduling the identified activities or workflow in parallel and by maximising the utilisation of the available talents/resources". The process comprises four stages:

- work process modelling, which is described as modelling the concatenation of four sub-models, i.e. product, workflow, organisational, and resource,
- workflow performance analysis, involving teams understanding dependencies and constraints among identified activities,
- work process re-engineering, described as being realised by organisation re-engineering, resource re-engineering, and workflow re-engineering, and,
- work process activity management, said to "start when a set of tasks for each activity is well established and a member of the workgroup for each task is identified".

The Knowledge-based Process Modeller (KPM) is described as an integrated set of modules that provide an environment for knowledge-based process design, management, and execution [KTI, 1999]. The integrated software environment of KPM comprises five modules:

- Server, where process definition, instantiation, execution, and change occur, and the management of user performed tasks takes place. The server includes a dynamic scheduling system.
- Developer, a graphical environment in which process designers create and maintain process definitions.
- Execution Manager, the environment where process instantiators instantiate process execution and process managers monitor and control execution.
- User Assistant, a browser-based environment that notifies users of tasks that have been assigned to them. Furthermore, the user assistant assists the user in keeping track of tasks and reporting to the server on the completion of tasks.
- Execution Monitor, a graphical environment for use by individuals needing to track process progress, but who cannot alter the process.

Further, the Developer, Execution Manager, User Assistant, and Execution Manager are said to be "user-interface environments for performing the wide range of activities associated with process management".

4.2.2 Critique

Prior to critically reviewing the approaches to design management summarised in Section 4.2.1, each respective key issues of operational design co-ordination is stated as defined in the summary of Chapter 3.

<u>Coherence</u>

Coherence has been described as "integrating, or linking together, resource effort and tasks within an organisation in a harmonious manner to avoid chaos". In order to achieve coherence, operational management activities must be performed in an appropriate manner.

All of the approaches to design management summarised in Section 4.2.1 give no consideration to performing operational management activities appropriately such that resource effort and tasks can be linked together harmoniously [Eppinger et al., 1990; Kusiak & Park, 1990; Carter, 1991; Pourbabai & Pecht, 1994; Lewis & Cangshan, 1997; Prasad et al., 1998; KTI, 1999; Scott, 1999]. Thus, these approaches do not address the issue of coherence.

With regard to KPM, this system is described as a software environment that provides a generic process model template that can be used to manage design. In order to be flexible and have a broad commercial application base, KPM has been developed such that it can be tailored to the specific needs of an organisation. This has been achieved by not coupling KPM with any specific engineering management philosophy. Thus, KPM is groupware (See Chapter 2, Section 2.2.8) and, as a result, does not support the appropriate performance of operational management activities to facilitate coherent working.

Communication / Interaction

Communication/interaction was offered as "interaction involving the exchange of structured and meaningful data, information and knowledge". In the context of operational design co-ordination, communication/interaction concerns exchanges between the various parts of an approach. More specifically, in non-software environments, the parts of an approach relate to the techniques used. Within software environments, it is the entities, e.g. actors or agents, that employ the techniques that participate in exchanges.

Three of the approaches to design management do not give consideration to communication/ interaction [Eppinger et al., 1990; Pourbabai & Pecht, 1994; Lewis & Cangshan, 1997].

The five stages in Scott's strategy for modelling the design phase of a product are performed sequentially with an indication given as to the information being passed between each stage. Thus, it is considered that communication/interaction is supported and operational knowledge provided.

Kusiak and Park's decomposition methodology is applied followed by the approach to schedule and manage design activities. The communication/interaction between the methodology and the approach is the groups of activities that can be scheduled simultaneously. As such, while communication/interaction is trivial in this case, nevertheless, it is supported although operational knowledge is not provided. Similarly, communication/interaction between the four stages of Prasad et al.'s approach are represented, however, operational knowledge is only limited.

In Carter's user-interactive HOBS, resources, i.e. knowledge sources, communicate through a common area called the *workspace*, which is said to provide overall data management. As shown in Section 4.2.1, Figure 4.1 presents the information links between the components of HOBS, each of which has specific responsibilities. These components are said to "interact with one another, with the fundamental mechanism for interacting being that of passing messages". Considering each component in turn, including the user, Carter presents an interaction specification that provides knowledge of the types and recipients of messages, and their effects. Further, Carter uses a product description language to ensure the avoidance of inconsistency in communications. Thus, HOBS provides support and operational knowledge regarding communication/interaction.

Within KPM, the user-interface environments are described as sharing information with one or more Servers in order to manage a process. As such, while KPM does support communication/interaction, only limited operational knowledge is provided with regard to how the modules communicate/interact.

<u>Task Management</u>

Task management has been defined as "the organisation and control of tasks, and the dependencies between them, such that they can be undertaken and completed in a structured manner".

Two of the design management approaches summarised in Section 4.2.1 do not consider task management [Carter, 1991; Lewis & Cangshan, 1997]. However, four of the approaches that are based on the concurrent engineering philosophy, focus on the sequencing of activities [Eppinger et al., 1990; Kusiak & Park, 1990; Pourbabai & Pecht, 1994; Scott, 1999]. These approaches concentrate on managing tasks and their dependencies, although they do not consider the undertaking of tasks.

In a similar fashion to those discussed, the second stage within Prasad et al.'s approach, i.e. *workflow performance analysis*, involves the use of a relationship matrix to analyse the interdependencies among activities. In addition, reference is made to the *parallel distribution of tasks* such that work groups can work concurrently. With regard to these aspects of the approach, operational knowledge is not provided regarding how tasks are managed. Again, as with the approaches discussed, managing the undertaking of tasks is not supported.

Within KPM, two modules are described as being involved with task management. The Server is said to be where the management of user performed tasks take place. In addition, a User Assistant is described as keeping track of the completion of tasks. In KPM, tasks to be executed are contained within a task structure. Thus, in summary, KPM does support task management in the sense that the software modules are in place to manage tasks and they are formally represented. However, operational knowledge of how this is achieved is not provided.

<u>Resource Management</u>

Resource management has been termed as "organising and controlling resources to enable their continuous optimised utilisation throughout a changeable design development process".

Resource management is an issue that has not been considered by four of the approaches to design management [Eppinger et al., 1990; Kusiak & Park, 1990; Pourbabai & Pecht, 1994; Scott, 1999]. Eppinger et al., and Kusiak and Park indicate that the design of complex products can involve co-ordinating hundreds or thousands of engineers, however, this recognition is not discussed further. In addition, Eppinger et al. stated that "with no limitations on resources" undertaking tasks concurrently could be completed more quickly. Pourbabai and Pecht only gave a brief mention to resources when discussing the assignment of activities. Scott only accounted for resources in so far as they are considered when performing static scheduling. Thus, the four approaches mentioned do not address the issue of resource management.

Prasad et al. named the first of their four stage process approach as *work process modelling*, which is said to contain resource information captured within a sub-model. A matrix of teams are included within the sub-model, however, knowledge of such a representation, or operational knowledge of managing resources, is not provided.

Lewis and Cangshan claimed that one of three steps to managing the design development process is the identification and management of design resources. However, the design resources chart discussed did not provide knowledge of how resources are identified such that they can be "marshalled by the design manager".

Within KPM, resources are only considered when scheduling tasks for execution. That is, resource information is contained within *resource sets* that are allocated to task structures. Resource sets are said to hold documentation describing the resources although no further information is provided. In addition, knowledge of how resources are managed is not provided.

Within Carter's HOBS, resources are organised in a hierarchical arrangement such that they could be controlled in a fashion that enables problems to be decomposed. An explanation of how resources are controlled and selected to perform operations is given in the discussion regarding schedule management.

<u>Schedule Management</u>

Schedule management was expressed as "managing the planning and dynamic assignment of tasks to resources, and the enactment of the resulting schedules, throughout a changeable design development process".

Schedule management was not considered by two of the approaches to design management summarised [Eppinger et al., 1990; Lewis & Cangshan, 1997].

Despite claiming to schedule design activities, Kusiak and Park only went as far as identifying potential groups of activities that could be scheduled simultaneously. Similarly, Pourbabai and Pecht merely indicate that the activities resulting from decomposition need to be assigned amongst operating groups. As such, these approaches do not support the development or management of a schedule. Within the final stage of Prasad et al.'s approach, i.e. *work process activity management*, the need is recognised to "schedule tasks among the team members so that they can be executed concurrently". However, Prasad et al. did not develop or manage a schedule. Thus, these three approaches do not address the issue of schedule management.

The final stage of Scott's strategy did involve planning and the development of a static schedule. However, the subsequent management of the enactment of the schedule is not considered. As such, this approach does not address the issue of schedule management.

In Carter's HOBS architecture, rather than scheduling in the traditional sense, the Executive, which contains the control mechanism, accepts bids from resources, i.e. knowledge sources, and selects the most suitable one to perform the operation under consideration. Due to the hierarchical organisation of the knowledge sources, once the Executive selects a knowledge source, bids can then be accepted from its children such that the problem can be decomposed. As such, HOBS does not provide support for dynamic scheduling and, thus, does not address the issue of schedule management.

Within the KPM software environment, the Server module is said to "include a dynamic scheduler that supports a variety of scheduling and re-scheduling strategies". Knowledge of the dynamic scheduler and strategies employed by the Server is not provided. A reason for this may be that due to KPM being commercial software, detailed dissemination would provide competitors with knowledge that may serve to undermine its commercial competitiveness. As such, knowledge regarding how schedules are produced within KPM is not within the public domain. Further, the management of the enactment of a schedule is not discussed.

<u>Real-Time Support</u>

Real-time support was stated as "how to manage and adapt to a changeable, i.e. dynamic and unpredictable, design development process".

In six of the approaches to design management summarised, the changeable nature of the design development process is not considered and, thus, real-time support is not provided [Eppinger et al., 1990; Kusiak & Park, 1990; Carter, 1991; Pourbabai & Pecht, 1994; Lewis & Cangshan, 1997; Scott, 1999]. That is, the various steps or stages in these approaches are only performed once, thus neglecting the need to adapt in real-time due to unforeseen circumstances. As such, the design development process is implicitly assumed to be static. Failure to address the issue of real-time support conflicts with the true essence of design and, thus, these existing approaches do not reflect design practice.

Prasad et al. did recognise the need to manage the non-deterministic nature of design. Monitoring the status of tasks is cited as a means of recognising the need for real-time task adjustment as a result of the occurrence of unexpected situations. However, no knowledge is offered regarding the process of monitoring tasks nor how or when to adjust the workplan or schedule to account for unexpected situations.

KPM is stated as being "well suited to domains such as engineering design, in which the dynamic and uncertain nature of the design process present complex management challenges". However, operational knowledge regarding real-time support was not provided.

4.3 Project Management

In contrast to the majority of the design management approaches discussed in Section 4.2, most of the approaches to project management summarised and critically reviewed in this section have placed an emphasis on co-ordination [Bailetti et al., 1994; Decker & Lesser, 1995b; Cleetus et al., 1996; Dellen & Maurer, 1996; Liu & Sycara, 1996; Bendeck et al., 1998]. These approaches, and one other, are summarised and critically reviewed in this section.

4.3.1 Existing Approaches

Concurrent Planning, Scheduling and Enactment

CoMo-Kit is described as supporting project planning and co-ordination for complex, distributed design projects / design development processes [Dellen & Maurer, 1996]. The computer-based system is said to allow the interlocking of planning and enactment. The CoMo-Kit architecture comprises three main parts, i.e. a Modeller, a Scheduler, and an Information Assistant as shown in Figure 4.2.

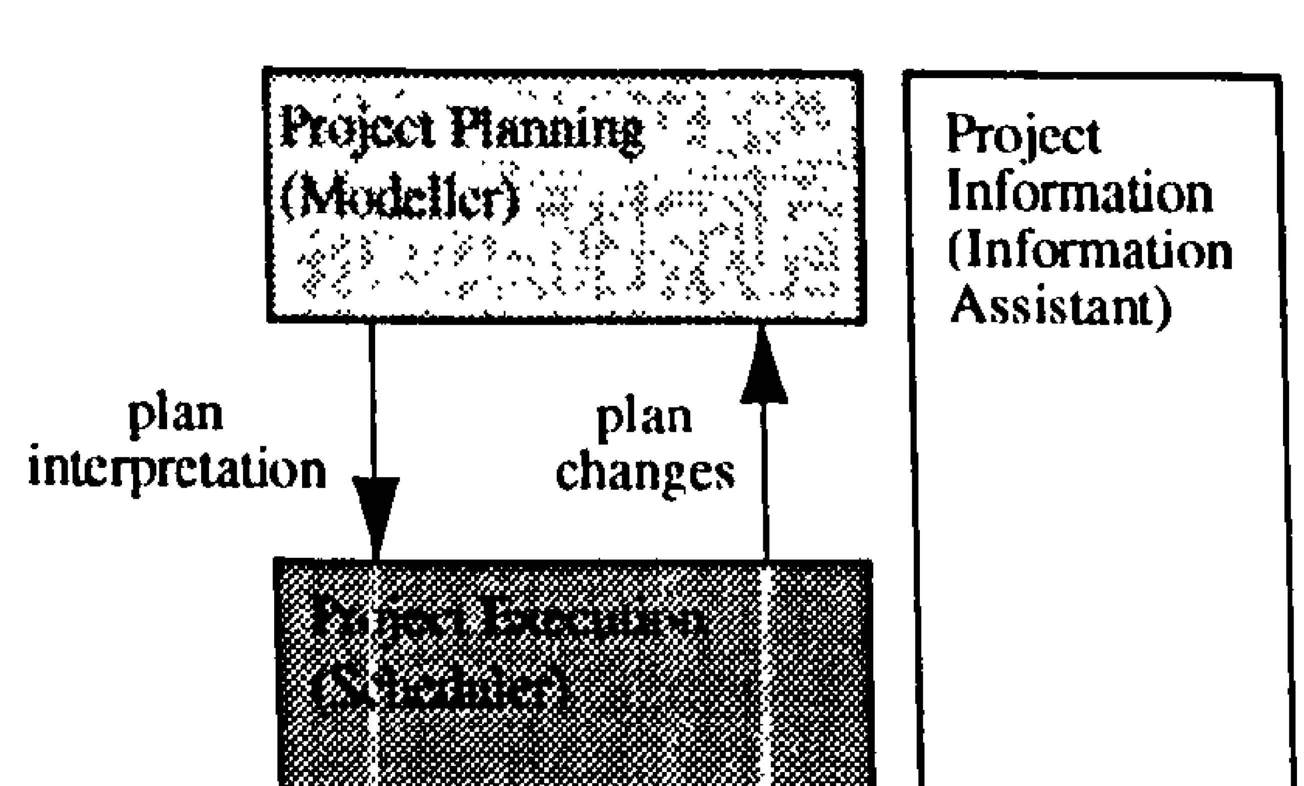

Figure 4.2 The Architecture of the CoMo-Kit System [Maurer, 1996]

The Modeller describes project plans using tasks, methods, products, and resources. The Scheduler is said to interpret the plans and manage the process information necessary to give useful planning and execution support. The Information Assistant is described as allowing access to the current state of the project.

Procura is described as a project management model that allows planning and scheduling agent-based design projects in a hierarchical top-down approach [Goldmann, 1996]. In Procura, planning, scheduling and plan execution are said to be interleaved, i.e. take place concurrently. Planning is described as the division of tasks into subtasks. Scheduling is indicated to be the assignment of resources and designation of task start and end times. Plan execution is stated as the assignment of values to design variables. The plan and schedule are incrementally revised during the design and progressively become more detailed. That is, re-planning and re-scheduling are supported. Procura's system architecture is shown in Figure 4.3.

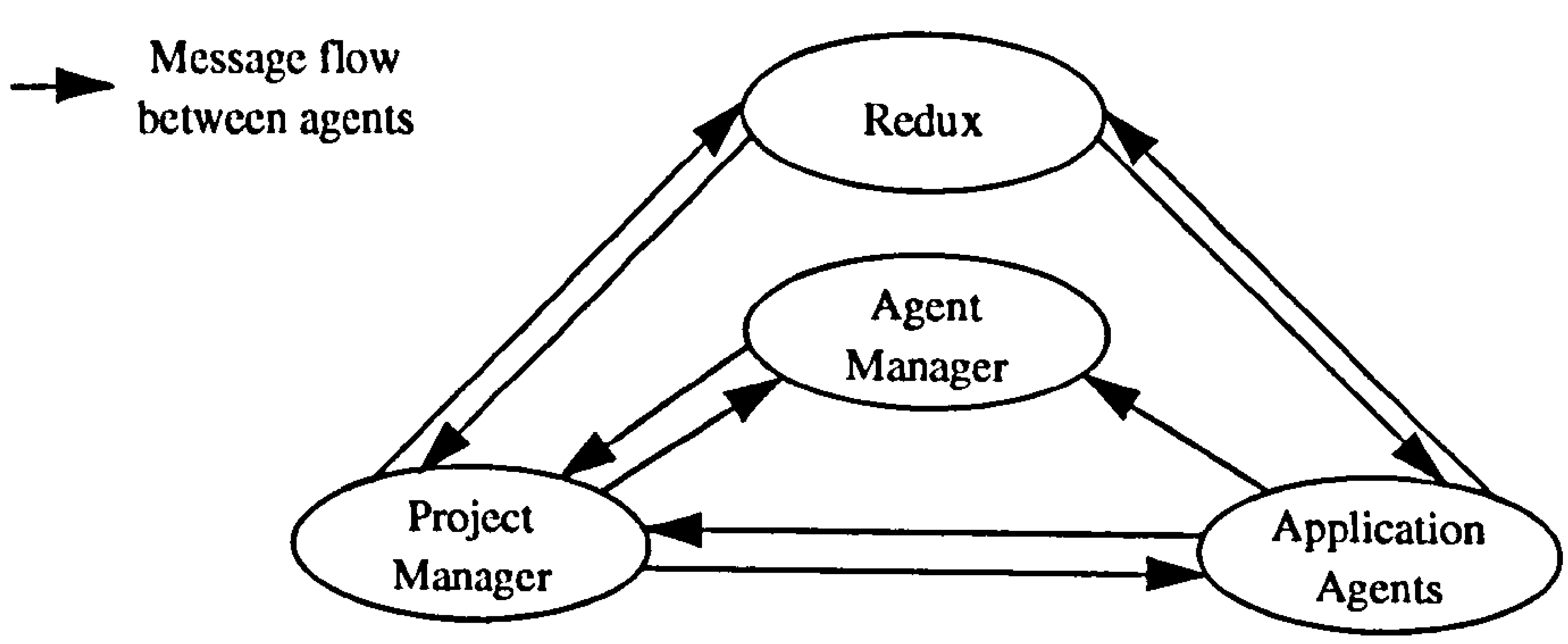

Figure 4.3 Procura System Architecture [Goldmann, 1996].

Procura comprises a Project Manager and Agent Manager that are supported by Redux and Application Agents. The Project Manager constructs the plan and schedule, although it is stated that "the original decision about who is going to do what, and when, is made by the human user". The Agent Manager controls the utilisation and availability of agents and resources. Redux is a conflict management model that supports Procura by providing a notification mechanism for conflicts. Application Agents, i.e. humans or computers that use interfaces to Procura, solve tasks according to the plan using equipment and workers, defined as humans with no link to Procura.

Bendeck et al. considered the co-ordination of management activities, i.e. project planning and scheduling, and monitoring during execution [Bendeck et al., 1998]. Thus, a system architecture is proposed to address the issues of co-ordination and notification in the context of a distributed software development design process, as shown in Figure 4.4.

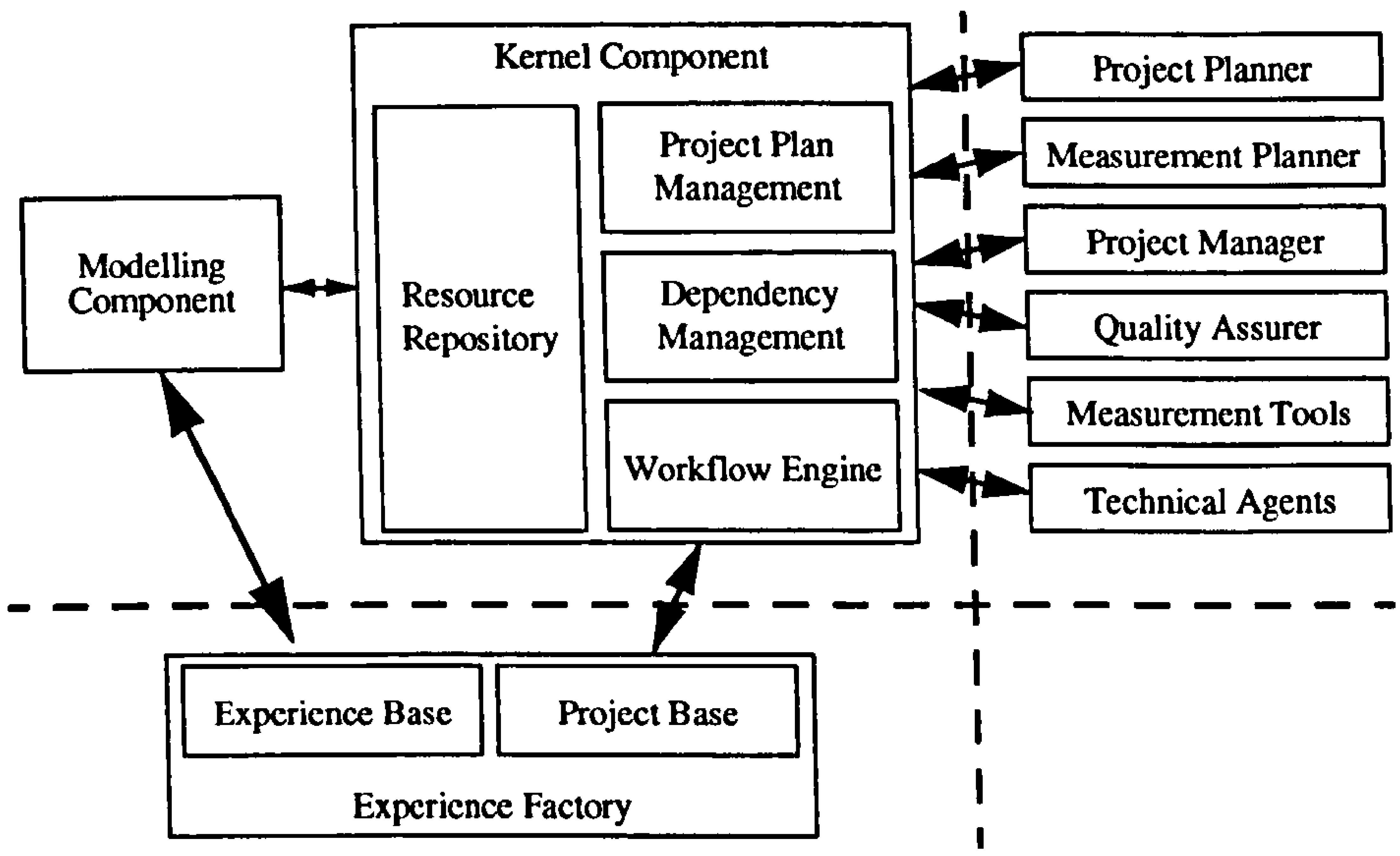

Figure 4.4 System Architecture [Bendeck et al., 1998]

The system architecture includes modelling and kernel components, and an experience factory, along with process agents. The modelling component is said to be a store for process, product, and quality models retrieved from the experience base. The kernel component is composed of several sub-components: Project Plan Management (maintains the plan and schedule), Resource Repository (provides a resource system that represents agent attributes), Dependency Management (implements the notification mechanism), and Workflow Engine (manages project's execution plan). The experience factory stores general models (Experience Base) and project data (Project Base). During a software development process, the process agents are said to perform the management activities such as create and change (Project Planner), measure (Measurement Planner) and ensure the correct and timely execution (Project Manager) of the project plan.

Distributed Agenda Management

Decker and Lesser presented a support tool for distributed, co-operative work by groups of humans and computational agents [Decker & Lesser, 1995b]. Specifically, the support tool involves agents assisting people in co-ordinating their activities by helping the management of their agenda. As shown in Figure 4.5, the tool comprises two types of computational agents, namely a *User Coordination Assistant Agent* (UCAA) and an *Agent Coordination Module* (ACM). Situated at a user's workstation, the responsibilities of a UCAA include keeping track of current tasks and offering task schedules, i.e. orderings, according to user preferences. An ACM can provide agenda management to co-ordinate computational agents according to a human's task-order preference. All instances of both types of agent are linked such that a distributed co-ordination process occurs and agendas are produced in a collaborative manner.

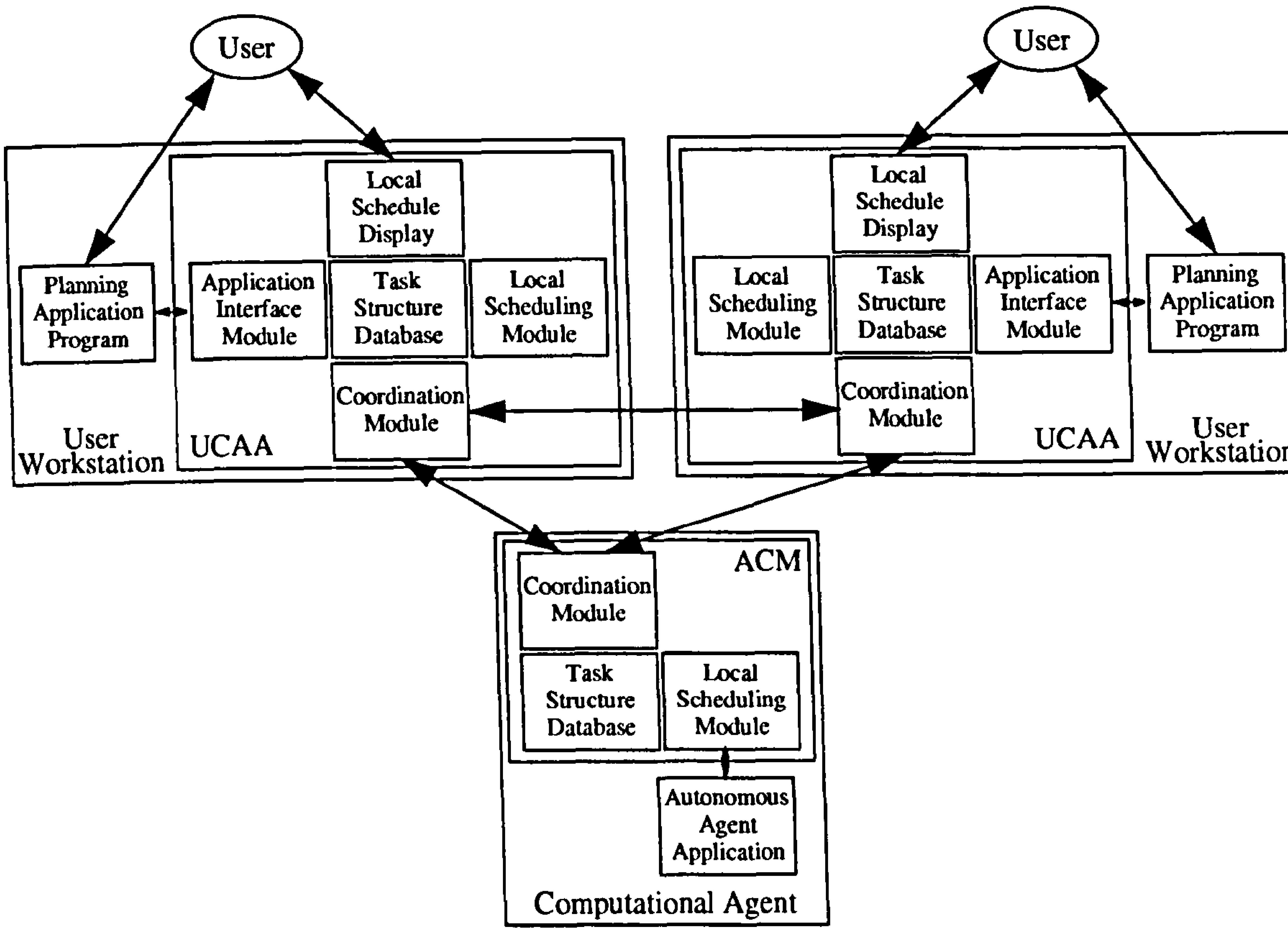

Figure 4.5 Architectural Overview of Agent-based System [Decker & Lesser, 1995b]

A UCAA is described as consisting of five modules: (i) the *Local Schedule Display* is an interactive window showing user tasks and a suggested schedule, (ii) a *Local Scheduling Module* to develop potential user task schedules, (iii) a *Coordination Module* to implement various co-ordination mechanisms via communication with other UCAAs and ACMs, (iv) an *Application Interface Module* for the workstation application(s) that records the current tasks the user is working on, (v) a *Task Structure Database* shared by all the modules. The modules described in (ii), (iii) and (v) are common to an ACM, which is said to work in conjunction with an autonomous computational agent. The TÆMS framework (Task Analysis, Environment Modelling, and Simulation), which represents co-ordination problems in a formal domain independent manner, is said to be stored in the *Task Structure Database* of the UCAAs and ACMs. The framework is described as being used by the *coordination modules* to choose appropriate co-ordination mechanisms, called Generalised Partial Global Planning (GPGP), and by the *local scheduling modules* to make appropriate scheduling decisions.

Liu and Sycara presented an approach to multi-agent co-ordination aimed at reducing the short-sightedness of decisions being made in real-time, dynamic environments [Liu & Sycara, 1996]. More specifically, the approach is described as addressing the problem of distributed agenda ordering. The approach consists of two parts, namely a standard operating procedure and look-ahead co-ordination. The standard operating procedure, i.e. despatch scheduling, involves jobs being sequentially passed to buffers of agents who, based on some local prioritising, perform some operation of the job. However, system performance, in terms of solution quality, is described as suffering from agent's myopic decisions based on only local and current conditions. Thus, in order to improve solution quality, the need is recognised to increase agent visibility and provide cues for decision adjustment by providing useful indicative information based on global and future conditions. The look-ahead co-ordination mechanism, called co-ordinated forecasts with relaxed urgency (COFCAST-RU), is said to operate on top of dispatch scheduling in order to improve performance. At each point of scheduling an operation, an agent is said to perform four actions:

- schedule an operation, i.e. select an operation based on a priority rule using relaxed due dates, and assign its start and end times,
- forecast future processing, i.e. based on a priority rule, assign predicted start times and predicted end times of a partial set of unprocessed operations that are in view,
- update relaxed due dates, i.e. adjust job's relaxed due dates based on the prediction, and,
- co-ordinate future forecasts by adjusting operation's predicted ready times.

Cleetus et al. presented PACT (Project Assessment and Coordination for Teams), which is said to manage projects and co-ordinate people [Cleetus et al., 1996]. PACT is described as attempting to marry project management and groupware (See Chapter 2). The single-user commercial software Microsoft Project is said to be extended into multi-user operating software that keeps project team members constantly aware of each other's activities. The use of the word *co-ordination* is said to be deliberate in order to stress the connectivity between groups of people rather than a single manager controlling the complete project. Initially, a hierarchical structure of tasks is described as being decomposed as the project progressed and team members work on the details of tasks. A project database is said to then support the assignment of tasks to individuals who are able to view tasks that others are working on. Once assigned to individuals, tasks cannot be delegated and are only able to be updated when completed. Further, the assignment of tasks to individuals is acknowledged by stating expected completion time before work commences. Based on this acknowledgement, each project team member can then plan their own work. PACT is also said to make data available to those who need it, i.e. the project database stored (i) actual documents that are input needed to perform a task, and (ii) output resulting from the performance of a task. PACT includes a communication infrastructure enabling any worker to notify anyone else or ask questions related to tasks. The communication infrastructure also enables workers to ascertain whether tasks on which they are dependent have been completed. This facility is said to avoid the need for human chasers, i.e. people who expedite activities by following up with numerous departments, contractors and individuals.

Resource Relationship Management

Bailetti et al. presented a co-ordination structure approach to the management of projects [Bailetti et al., 1994]. A co-ordination structure is stated as being “a system level view of the entire set of inter-related inter-dependencies between all of the individuals and groups that are involved in the project”. A co-ordination structure comprises of diagrammatic representations called co-ordination ensembles, which correspond with each stage of the design of the artefact under consideration. A co-ordination ensemble is defined as “a configuration of actors that interact by creating, modifying and using an array of shared objects”. Each co-ordination ensemble, i.e. object based model of a co-ordination structure, is said to form a base layer supporting a complex set of inter-dependent activities. As such, they are described as forming a front-end for conventional activity based project management.

4.3.2 Critique

Coherence

All seven of the approaches to project management summarised in Section 4.3.1 do not consider coherence [Bailetti et al., 1994; Decker & Lesser, 1995b; Cleetus et al., 1996; Dellen & Maurer, 1996; Goldmann, 1996; Liu & Sycara, 1996; Bendeck et al., 1998].

Dellen and Maurer's CoMo-Kit is described as integrating planning and plan execution. Similarly, Goldmann's Procura is indicated as enabling concurrent planning, scheduling, and plan execution. Also, Bendeck et al.'s software system is reported as co-ordinating planning, scheduling and monitoring during execution. In actuality, within these three user-interactive software systems, the management activities mentioned are *interleaved* due to the occurrence of changes or decisions being made at certain points in time during the software development process. As such, these project management systems are aimed at enabling the incremental revision/development of plans and schedules rather than coherence. In addition, with regard to each system architecture, only limited operational knowledge is provided as to how these management activities should be interleaved.

Communication / Interaction

Six of the approaches to project management are incorporated within software systems [Decker & Lesser, 1995b; Cleetus et al., 1996; Dellen & Maurer, 1996; Goldmann, 1996; Liu

& Sycara, 1996; Bendeck et al., 1998]. In the context of these systems, the emphasis in on communication/interaction between entities, such as actors and agents, that use techniques.

Despite indicating links between the Modeller and Scheduler within the system architecture, as shown in Figure 4.2, no indication is given regarding the consideration of communication/ interaction [Dellen & Maurer, 1996]. In addition, no links are shown to or from the Information Assistant. Thus, while communication/interaction is assumed to be supported, operational knowledge is not provided.

Both Bendeck et al.'s and Goldmann's software project management tools are said to provide a notification mechanism/system that keeps all agents informed of the current project state/ occurring changes. Similarly, Cleetus et al.'s PACT is described as a multi-user operating software that has a communication interface built into the software system enabling any worker to notify or query anyone else regarding tasks. In these systems, only brief explanations were provided as to the communication/interaction between the (i) agents responsible for performing management activities [Goldmann, 1996; Bendeck et al., 1998] or (ii) the workers undertaking tasks [Cleetus et al., 1996]. Thus, it is concluded that these tools do support communication/interaction, however, operational knowledge is limited.

Decker and Lesser's tool includes two agent types, i.e. a UCAA and an ACM. Multiple instances of these agents can exist, each of which contain and are connected by their respective *coordination modules* (See Figure 4.5). Co-ordination mechanisms are employed by the *coordination modules* in order to organise the workload of their respective agents. Thus, communication/interaction is supported between the agents, however, operational knowledge is encapsulated within the *coordination modules* and, as such, is not provided.

Within Liu and Sycara's COFCAST-RU, agents are not described as communicating with one another directly, but rather surveying information in order to make better decisions regarding the sequencing of job operations they perform. At the point of scheduling each operation, a four-step procedure is performed with the links between them explained. As such, Liu and Sycara, do support communication although it is unconventional. In addition, operational knowledge is provided regarding the interactions regarding the procedural steps within COFCAST-RU.

Bailetti et al.'s approach does not consist of parts that interact as such, but rather the co-ordination ensembles, i.e. diagrammatic representations, that indicate how shared objects link two actors. The content of the interaction between actors is described as being founded on the shared object that links them. Thus, in the context of operational design co-ordination, communication/interaction is not supported.

Task Management

Within their approach, Bailetti et al. do not consider tasks or their management. Three of the approaches to project management only consider tasks at the point of scheduling [Cleetus et al., 1996; Dellen & Maurer, 1996; Liu & Sycara, 1996]. Failure to organise tasks, and their dependencies, prior to scheduling prevents them from being controlled such that they can be undertaken and completed in a structured manner. Thus, the three approaches mentioned do not provide support for task management.

Bendeck et al. concentrate on management activities rather than technical tasks and, as such, do not support task management. Despite this, only when summarising the functionality of the dependency management component within the proposed architecture, Bendeck et al. stated that it "manages the dependencies between technical activities". However, operational knowledge of this support is not provided.

Goldmann does organise tasks although this is discussed in the context of planning. That is, it is stated that "by determining which of the task's inputs have to be in place before work on it can be started, and by finding out which tasks produce the required parameters or features, the precedence relationships between the tasks is determined, and a plan can be stated". As such, Procura supports the organisation of tasks and their dependencies such that they can be controlled.

Decker and Lesser's agenda management tool comprises a task structure database that is said to be shared by all the UCAAs and ACMs (See Figure 4.5). It is indicated that the database consists of, amongst other information, "how tasks interrelate". Further it is stated that the contents of the database are "used by the *coordination modules* to choose appropriate co-ordination mechanisms, and by the local scheduling modules to make appropriate scheduling decisions". However, knowledge of the contents of the database are not provided. Thus, the organisation of tasks, and their dependencies, is supported although operational knowledge is not provided.

Resource Management

The focus of Bendeck et al.'s approach is said to be "co-ordinating the management activities that accompany the technical software design process". Consequently, the resources, i.e. design team, are only mentioned in that the system architecture comprises of a resource repository, which is said to "represents roles, properties and skills of agents and their work load". Specific operational knowledge of resources and how such representations are able to be used to enable resources to be managed during a project is not provided.

Dellen and Maurer indicated that CoMo-Kit holds properties regarding actors, namely qualifications, roles and organisation [Maurer, 1996]. Further, it is stated that the "system compares the required properties of a task with the properties an agent possesses" and "this allows to compute the set of agents which is able to solve the task". Similarly, within Goldmann's Procura, resources are only considered when tasks are being assigned to them, i.e. scheduling. As such, in both of these systems, resource management is not addressed.

Three of the approaches summarised are oriented toward managing task agendas / to-do lists of agents, i.e. human and/or computational, rather than directly managing the agents themselves [Decker & Lesser, 1995b; Cleetus et al., 1996; Liu & Sycara; 1996]. As such, resource management is not considered.

Bailetti et al.'s co-ordination structure approach focused on diagrammatically representing actor configurations and shared objects. However, the co-ordination structure does not offer any knowledge of managing resources in an operational sense.

<u>Schedule Management</u>

Of all the approaches to project management summarised, only that of Bailetti et al. did not consider schedule management.

Dellen and Maurer's CoMo-Kit focuses on alternating planning and enactment, which are described as being supported by the Modeller and Scheduler respectively. Despite incorporating a Scheduler, CoMo-Kit does not support scheduling. Knowledge is not provided regarding how a plan is constructed by the Modeller. The Scheduler is described as providing project agents with process information for undertaking tasks, i.e. the next task to do, input data, and applicable methods. It is indicated that project agents decide on one of several methods in order to solve a task. However, operational knowledge of how plan enactment is managed is not provided.

In Goldmann's Procura, "planning, scheduling and plan execution are interleaved". Planning is said to be "the division of tasks into subtasks", and, by means of an example, it is shown how planning is performed. With regard to scheduling, it is stated that "the original decision about who is going to do what task, and when, is made by the human user, but the propagation of changes through the schedule can be automated". As such, scheduling is not supported. Further, application agents are said to be responsible for solving the plan's tasks, however, only limited operational knowledge is provided as to how this is achieved.

Bendeck et al. indicated that a general requirement needing to be met to support the co-ordination of management activities in the software development process, is that "planning, scheduling and enactment have to be interleaved". As such, the system architecture presented includes a project planner to "create a project plan" and a project manager who "ensures the correct and timely execution of the project". Further, with regard to the project manager, it is stated that "his/her responsibilities are to assign agents and other resources to the processes prescribed in the plan, determine the processes' start and end times in accordance with milestones and deadlines dictated by the plan". The technical roles are described as being responsible for the execution of the processes in the project plan. In addition, it is indicated that co-ordinating these roles during project execution is an issue still not solved. Further, it is stated that they "concentrate on management-oriented roles, and omit the requirements that arise from co-ordinating the technical roles in a software engineering environment". In summary, despite claiming to plan, schedule and enact, Bendeck et al. provide no operational knowledge for any of these and, indeed, do not support enactment.

Within Decker and Lesser's support tool for helping people manage their agenda, each person's UCAA comprised several modules including a *local scheduling module* that is said to "develop potential user task schedules" based on their preferences. Despite these schedules being developed collaboratively, the user is still said to have "significant freedom in the ordering of their activities". Thus, although each schedule is constructed in a collaborative manner via the *coordination module* of each user's UCAA, the support tool does not offer support or operational knowledge with regard how schedules are developed or managed during enactment.

Liu and Sycara employed despatch scheduling as a standard operating procedure, however, the focus of their work is overcoming myopic decisions being made by agents regarding the tasks to be undertaken. Specifically, COFCAST-RU is described as overcoming this short-sightedness by enabling improvements to be made in the decisions of agents as to what tasks they should undertake. Since schedules are simply the next task selected to be undertaken, schedule enactment is not supported.

Within Cleetus et al.'s PACT, the static assignment of tasks to individuals is achieved using the project database, of which no explanation is given. In addition, once assigned tasks they must be completed. Further, the communication infrastructure is described as enabling each individual to communicate the expected completion times for each task they had been assigned such that others could plan their own respective work. Thus, dynamic scheduling is not supported. The enactment of a schedule is indicated as being supported through the communication infrastructure. However, operational knowledge is limited.

<u>Real-Time Support</u>

The approaches implemented within project management systems gave indications that they provide real-time support, however, this is not always explicitly stated [Decker & Lesser, 1995b; Cleetus et al., 1996; Dellen & Maurer, 1996; Goldmann, 1996; Liu & Sycara, 1996; Bendeck et al., 1998].

Liu and Sycara stated that they "considered an environment where agent's tasks are tightly coupled and require real-time scheduling and execution". In terms of a requirement of project management, Cleetus et al. stated that "it must take place in real-time and must involve every member of the project". With regard to their agenda management support tool, Decker and Lesser stated that "problems are solved in efficient ways that are dynamically adapted to the current situation". Despite alluding to real-time support, these approaches only provide limited operational knowledge regarding how this is achieved.

Dellen and Maurer recognised the need to modify planning since: (i) the design process depends on a changing conditions forcing re-planning, and (ii) some planning decisions can only be reached based on knowledge resulting from the development process. Similarly, Goldmann recognised that re-planning and re-scheduling are required since decisions made as a result of high-level planning and scheduling would need to be changed as soon as more information became available causing conditions to change. In agreement, Bendeck et al. indicated that management activities need to be interleaved to allow detailed planning to occur after project enactment has already started. Thus, each of these approaches indicates that real-time support is provided, although, in alignment with the communication/interactions between their agents discussed previously, operational knowledge is limited [Goldmann, 1996; Bendeck et al., 1998] or not provided [Dellen & Maurer, 1996].

With regard to their co-ordination ensembles, Bailetti et al. stated that "they can be used in the initial work breakdown structure and task allocation, and for subsequent adjustments during a project". However, operational knowledge is not provided as to how this is achieved.

4.4 Summary

This chapter has presented a critical review of existing approaches related to operational engineering management with respect to the key issues of operational design co-ordination. Table 4.2 presents a matrix summarising the critical review.

Key Issues of Operational Design Co-ordination		Approaches to Operational Engineering Management																													
		Design Management																Project Management													
		[Carter, 19991]		[Eppinger et al., 1990]		[KTI, 1999]		[Kusiak & Park, 1990]		[Lewis & Cangshan, 1997]		[Pourbabai & Pecht, 1994]		[Prasad et al., 1998]		[Scott, 1999]		[Baiketti et al., 1994]		[Bendeck et al., 1998]		[Cleetus et al., 1996]		[Decker & Lesser, 1995]		[Delen & Maurer, 1996]		[Goldmann, 1996]		[Liu & Sycara, 1996]	
		S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K	S	K
Coherence		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Communication / Interaction		✓	✓	×	×	✓	×	✓	×	×	×	×	×	✓	×	✓	✓	×	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	✓
Task Management	Organisation and Control	×	×	✓	✓	✓	×	✓	✓	×	×	✓	✓	✓	×	✓	✓	×	×	×	×	×	×	✓	×	×	×	✓	✓	×	×
	Dependency Management	×	×	✓	✓	×	×	✓	✓	×	×	✓	✓	✓	×	✓	✓	×	×	✓	×	×	×	✓	×	×	×	✓	✓	×	×
	Structured Undertaking	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Resource Management	Organisation and Control	✓	✓	×	×	✓	×	×	×	✓	×	×	×	✓	×	×	×	✓	×	✓	×	×	×	×	×	✓	×	×	×	×	×
	Optimised Utilisation	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Schedule Management	Planning	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	×	✓	×	✓	✓	×	×
	Dynamic Scheduling	×	×	×	×	✓	×	×	×	×	×	×	×	✓	×	×	×	×	×	✓	×	×	×	✓	×	×	×	✓	×	✓	×
	Schedule Enactment	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	✓	×	✓	×	×	×	✓	×	✓	×	×	×
Real-Time Support		×	×	×	×	✓	×	×	×	×	×	×	×	✓	×	×	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×

Table 4.2 Support and Operational Knowledge provided by the Approaches

With regard to Table 4.2, for each approach, a tick indicates that the key issue, or an associated aspect, is claimed to be supported (S) and, operational knowledge (K) is provided. Conversely, a cross indicates that support is not claimed and operational knowledge is not provided.

The approaches critically reviewed in this chapter provide valuable contributions in the field of operational engineering management. However, from Table 4.2, it can be seen that no single approach addresses all of the key issues by incorporating the appropriate techniques. Thus, by implication, all of the techniques have not been integrated, i.e. linked together, within a unified approach. As such, there is scope for an approach that addresses all of the key issues by incorporating the appropriate techniques and, in addition, providing the linkages between them. Indeed, Harrison recognised that it is the notion of an encompassing approach that is actually more important than the specific groups of techniques used [Harrison, 1992]. Similarly, with regard to the Design Co-ordination Framework, while the framework models are identified as important, Duffy et al. recognised linking them together as a main goal of future research [Duffy et al., 1999].

Further, limitations of existing approaches have been identified since they do not provide operational knowledge with regard to:

- how to perform management activities appropriately to enable coherent working,
- how to manage tasks to enable their structured undertaking,
- how to manage resources such that their utilisation can be optimised,
- how to manage dynamic scheduling,
- how to manage the enactment of schedules, and,
- how to enable real-time support.

Thus, the main outcome of the critical review is that there is scope for an integrated and holistic approach that addresses the key issues of operational design co-ordination and overcomes the limitations of existing approaches.

5 Requirements of Operational Design Co-ordination

The aim of this chapter is to identify the requirements of operational design co-ordination based on the key issues identified in Chapter 3 and aimed at overcoming the limitations of existing approaches discussed in Chapter 4.

In Section 5.1, an overview of the chapter is presented. In Section 5.2, 5.3 and 5.4, key issues of operational design co-ordination are discussed in terms of requirements. Finally, Section 5.5 summarises the requirements of an approach to operational design co-ordination and closes the chapter.

5.1 Overview

In Chapter 3, the nature of operational design co-ordination was discussed leading to the identification of the key issues needing to be addressed. In Chapter 4, consideration of these key issues enabled existing approaches related to operational engineering management to be critically reviewed. Consequently, these existing approaches were shown to exhibit a number of limitations. As a result of the critical review, it was stated that there is scope for an integrated and holistic approach to operational design co-ordination. More specifically, an approach that is more comprehensive than existing approaches by incorporating the appropriate techniques in order to address the key issues of operational design co-ordination, but more significantly, integrates them in unified manner. Further, an approach must overcome the limitations of existing approaches, thus, enabling design to be managed coherently in real-time such that inter-related tasks can be undertaken in a structured manner while resource utilisation is optimised in accordance with the enactment of dynamically generated schedules. Such an approach will provide an original and significant contribution to knowledge in the field of operational engineering management, specifically operational design co-ordination.

In Sections 5.2, 5.3 and 5.4, the key issues of coherence, communication/interaction and real-time support are not covered explicitly but, rather, discussed in the context of task, resource, and schedule management.

5.2 Task Management

Aspects of the management of tasks have been identified as central to co-ordination [Fayol, 1949; Duffy et al., 1994; Perrin, 1997]. In Chapter 3, a key issue of operational design co-ordination was described as organising and controlling tasks, and the dependencies between them, such that they can be undertaken and completed in a structured manner.

Management of Task Dependencies

The design-development of large complex made-to-order products involves the need to undertake and complete many inter-related tasks. The relationships between tasks, i.e. dependencies, can significantly increase the complexity of co-ordination [Kusiak & Wang, 1991; Eppinger et al., 1994]. Indeed, co-ordination has been defined as the process of managing dependencies between tasks [Malone & Crowston, 1994]. In order to facilitate the co-ordinated undertaking of tasks in a structured and natural order, their dependency relationships need to be established, maintained, and managed. With regard to operational design co-ordination, an emphasis is placed on managing dependencies between tasks to ensure the preservation of the natural order that they should be undertaken and completed. Thus, problems and difficulties, such as re-work, that are encountered using techniques to induce concurrency, for example artificial de-coupling and increased coupling [Eppinger et al., 1990], are avoided. Consequently, the overall integrity of the design development process is preserved.

Knowledge of the dependencies between tasks needs to be represented such that, once established, they can be maintained and managed. That is, tasks can only be undertaken appropriately if all tasks they are dependent on have been completed. Thus, for each task, there is a requirement for knowledge of the number of tasks it is dependent on and their identification.

Information Management

In addition to managing the dependencies between tasks, where appropriate, there is also a need to manage the flow of information between tasks. That is, there is a requirement for the relevant information to be made available at the appropriate time to the right resource such that the associated task can be undertaken. Also, on the completion of a task, any resulting information must be preserved and stored accordingly such that, if subsequently required by another task, it can be provided.

Due to the requirement to manage information flow between tasks, there is a need to establish what specific information must be provided prior to tasks being undertaken and stored upon their completion. Thus, for each task there is a requirement for knowledge of input and output information.

Indexing of Tasks

In Chapter 3, tasks were declared as being undertaken to accomplish or achieve goals. In order to co-ordinate tasks at an operational level, tasks corresponding to each goal need to be distinguishable, i.e. uniquely identifiable. Pourbabai and Pecht discussed the concept of identifying activities through the assignment of indices, i.e. an index denotes a particular activity [Pourbabai & Pecht, 1994]. Similarly, although with regard to design cases rather than design tasks, Manfaat used indices, described as labels, as a means of differentiating between cases [Manfaat, 1998]. Further, using indices was described as being necessary given a large number of design cases since search efficiency becomes critical. In this research, indexing tasks is required to ensure consistency by enabling tasks to be uniquely identified, thus, avoiding the inadvertent consideration of the incorrect task and/or its associated knowledge.

With regard to an approach to operational design co-ordination, in order for tasks to be identified, knowledge of each task should comprise an index signifying the goal with which it is associated. Task knowledge should also comprise a local identification index to enable a task to be distinguished from other tasks associated with the same goal. In addition, since tasks could potentially be dynamically scheduled, they must be uniquely identifiable in terms of all tasks. Thus, task knowledge should also comprise a global identification index.

5.3 Resource Management

The management and effective utilisation of resources have been identified as requirements of design co-ordination [Carter; 1991; MacCallum & Carter, 1991; Duffy et al., 1993]. It is argued in this thesis that, in terms of operational design co-ordination, there is a requirement to manage resources in order to create the opportunity for the available resources to be continuously allocated and utilised in an optimised fashion in real-time throughout a changeable design development process.

Resource Performance

Resources can be skilled in a single or a range of disciplines and, as such, may only be able to undertake particular tasks. Furthermore, resources skilled in the same discipline may exhibit varying proficiency with regard to undertaking the same tasks. Thus, the expected performance of each resource needs to be modelled and established in terms of each task they are capable of undertaking. Knowledge of expected performance is required for scheduling purposes to ensure the optimised allocation and utilisation of resources with respect to the outstanding tasks.

In order to reflect the variations in the expected performance of different resources with regard to the duration to complete a task, each task should include knowledge of a datum duration. Thus, once a task is assigned to a resource the expected duration to complete the task can be established reflecting expected resource performance.

Resource Monitoring

Throughout the design development process, resources may not perform as intended. That is, resources may be susceptible to fluctuations in performance, the occurrence and magnitude of which are unpredictable. As such, there is a requirement for monitoring resources to enable the detection of differences between actual and expected resource performance. Failure to detect such performance deviations and, thus, adjust accordingly may lead to delays in meeting critical deadlines. Conversely, if the actual resource performance exceeds expectations, such that they can be utilised more effectively than intended, then advantage should be taken of this situation.

In the event of the detection of a departure between actual and expected resource performance, there may be a need to adjust the allocation and utilisation of the resources, i.e. re-schedule, in order to adapt to the prevailing circumstances such that their performance remains optimised. As such, in addition to the requirement for monitoring, there is a need for a mechanism that activates the consideration of re-scheduling and, also, a means of establishing whether or not re-scheduling should be performed (See Section 5.4).

Forecasting / Re-assignment of Expected Resource Performance

If re-scheduling is to be considered, an estimate must be predicted regarding the future expected performance of a resource. Forecasting expected resource performance is aimed at reducing the risk of allocating and utilising resources in a sub-optimised manner. The timely use of forecasted expected resource performance knowledge, with regard to planning and scheduling, will contribute to providing the opportunity for the future optimised allocation and utilisation of resources, in addition to that during the process of re-scheduling.

Resource Improvements

In terms of resource management, the discussion so far has been concerned with providing the capability to continuously create the opportunity for the optimised allocation and utilisation of resources in real-time. Further to engineering design being co-ordinated in real-time, it is considered that operational design co-ordination should be prospective. That is, there is also a requirement to be able to look forward to determine how best to dynamically adjust the available resources such that the performance of the design development process can be further improved. In addition, in the event of foreseeing the slippage of a deadline, it would be useful to establish what additional or improvement in resources would be required in order to maintain the intended deadline.

Table 5.1 summarises the various static-dynamic combinations with respect to process and resources. Case I is concerned with both a static process and resources. Operational design co-ordination in real-time can be considered as corresponding to Case II, i.e. a dynamic process and a static number of resources, although their performance is dynamic. Complementing real-time operational design co-ordination with prospective operational design co-ordination can be viewed as corresponding to Case III. As such, not only are the complexities of a dynamic process and dynamic resource performance managed but also the number of resources is dynamic.

Case	Process	Resources
I	Static	Static
II	Dynamic	Static
III	Dynamic	Dynamic

Table 5.1 Static-Dynamic Combinations of Process and Resources

To facilitate the identification of possible improvements to the available resources, existing deficiencies need to be recognised such that appropriate changes can be recommended and assessed. This could be achieved by analysing the in-work schedule and establishing where investment in new resources or development of existing resources would offer the most significant benefits in terms of, say, time and cost. The use of time as the primary factor is shared by a number of authors [Clark & Fujimoto, 1991; Cleetus et al., 1996; Scott, 1999]. Clark and Fujimoto indicated that the elapsed time taken to get a new product to market is the primary focus of contemporary strategies aimed at gaining competitive advantage. Similarly, as a result of intense competition in the marketplace, Cleetus et al. stated that "time is recognised as the most important of the three cardinal variables in projects: time, cost and quality". Scott described time reduction in getting a product to market as a priority objective.

In summary, rather than only aiming to facilitate the improvement of the performance of the design development process through operational design co-ordination in real-time, an insight of how to achieve further increases in performance could be gained by considering possible improvements to the available resources.

<u>**Indexing of Resources**</u>

In a similar manner to that as discussed in Section 5.2. with regard to tasks, indexing is required such that resources can be uniquely identified.

5.4 Schedule Management

Enabling the operational co-ordination of the design development process involves the appropriate resources being allocated and utilised in an optimised manner to undertake and complete inter-related tasks in the proper order at the right time. The complexity of this problem is exacerbated by the fact that there are multiple resources with varying proficiency and multiple tasks of varying difficulty. Task and resource management have been discussed in terms of coping with the complexities described and, thus, creating the opportunity for the design development process to be co-ordinated such that it can be performed in an improved fashion. Schedule management can be thought of as the realisation of this opportunity.

Planning

In this thesis, planning is considered to be a pre-requisite and preparation for scheduling. Planning involves establishing (i) what tasks need to be undertaken and completed, (ii) what resources are available to be allocated and utilised, and (iii) the associated knowledge regarding each task and resource. For example, for scheduling purposes, knowledge is required regarding the dependencies between tasks and the expected performance of resources with regard to those tasks.

In order to ensure that only outstanding tasks are considered for scheduling, task knowledge must account for the progress of a task. Thus, only the tasks yet to be undertaken or with a proportion outstanding will be re-scheduled.

Similarly, throughout the design development process resources may or may not be available for allocation and utilisation. Thus, resource knowledge must include the status of a resource such that only those available can be considered for the purpose of re-scheduling.

Dynamic Scheduling

Scheduling can be viewed as involving tasks being assigned to resources. More specifically, in this thesis, the view of scheduling is shared with that offered by Duffy et al. and Goldmann, i.e. scheduling involves the assignment of resources and start and end times to tasks [Duffy et al., 1993; Goldmann, 1996]. The order in which a resource can undertake tasks is implicit within the allocation of start and end times.

Due to the changeable nature of the design development process, at times there may be a need to re-schedule. Thus, there is a requirement for dynamic scheduling to ensure that tasks are undertaken appropriately and resources remain utilised in an optimised manner. In order for dynamic scheduling to be effective, tasks and resources must be managed appropriately as discussed in Sections 5.2 and 5.3 respectively.

Operational design co-ordination requires the use of an optimisation algorithm/technique to enable the optimised allocation and utilisation of resources in order to complete their assigned inter-related tasks. As such, scheduled tasks should be allocated a start and end time that ensures the preservation of dependency relationships between them while accounting for the expected performance of the resources to be utilised.

<u>Schedule Enactment / Dynamic Management of Scheduled Task Dependencies</u>

On the completion of scheduling or re-scheduling, resources need to undertake their assigned tasks in accordance with the respective designated start and end times. However, due to the possibility of variations between the actual and expected performance of resources, the start and end times of tasks may not be able to be adhered to. As such, a schedule should not be thought of as a static time-based sequence to be followed, but rather a guide for undertaking tasks. This view concurs with that of Goldmann who considered scheduling as a prediction [Goldmann, 1996].

A consequence of failing to adhere to the start and end times allocated to a task may result in a domino effect in that subsequent tasks may not be able to proceed in accordance with their respective start and end times, and so on. Thus, the complexity of managing dependencies between tasks, as discussed in Section 5.2, is further complicated with regard to schedule enactment in real-time. As such, knowledge of scheduled tasks should comprise dependency knowledge such that checks can be made as to whether it is appropriate to undertake them, i.e. all of the tasks that a task is dependent on have been completed. In addition, if it is inappropriate to undertake certain tasks and, as such, they become pending, then they need to be managed accordingly such that they are only undertaken when possible. As discussed in Section 5.2, indices can be used for purposes of checking dependencies between tasks.

<u>Schedule Monitoring</u>

As with resources, schedules need to be monitored such that any discrepancies between actual and expected progress can be detected and, if appropriate, adaptive measures can be taken, i.e. re-scheduling. Deviations in the progress of a schedule can occur due to (i) differences between actual and expected resource performance, and/or (ii) inaccurate estimates of the duration to complete a task causing the actual progress of a task to deviate from that expected. Differences in actual and expected resource performance have been discussed in Section 5.3. As a result of (ii), there may be a need to re-assign the datum duration of a task.

Decision-Making with regard to Re-Scheduling

In the event of deviations between actual and expected schedule progress, there may be a need to adjust the schedule, i.e. re-schedule, such that optimised utilisation of resources and the structured undertaking of tasks can be resumed. However, re-scheduling should only be performed if an advantage would be gained over the continuation of the existing schedule. That is, the duration of re-scheduling and enacting the newly derived schedule is less than that to complete the enactment of the existing schedule. As such, there is a requirement to establish and compare these durations in order to determine whether or not re-scheduling should be performed.

Optimised Concurrent Re-Scheduling and Undertaking Tasks

With regard to project management [Goldmann, 1996] and computing environments [Hamidzadeh & Lilja, 1994], the concept of concurrently re-scheduling and undertaking tasks has been recognised. Furthermore, in order to control the quality of the schedule produced, the duration of re-scheduling has been adjusted [Garvey et al., 1993; Hamidzadeh & Lilja, 1994].

In this thesis, it is viewed that rather than just concurrently re-scheduling and undertaking tasks, the objective should be to optimise this opportunity for concurrency. That is, determine and undertake the appropriate number of tasks while the remainder are re-scheduled such that resources utilisation is optimised during and after this period. Meeting this objective will contribute to improving the performance of the design development process. As such, there is a requirement to ensure that the utilisation of resources is optimised during the period of time between the current schedule expiring and the derivation of the new schedule by considering knowledge of expected resource performance. In addition, there is a need to simultaneously optimise the number of tasks to be undertaken and completed with respect to the duration of re-scheduling. Selecting and managing the appropriate outstanding tasks to undertake and complete concurrently, and those outstanding tasks to re-schedule, will ensure the timely transition between an expiring schedule and emerging schedule such that resource idle time is minimised.

5.5 Summary

Based on the discussions in Sections 5.2, 5.3 and 5.4, an approach to operational design co-ordination should comprise:

- A *methodology* that should exercise:
  - ***real-time operational design co-ordination*** to achieve the coherent, timely and

appropriate structured undertaking of inter-related tasks while continuously optimising the utilisation of the resources, in accordance with dynamically derived schedules, within a changeable design development process, and,

- *prospective operational design co-ordination* to enable the recognition of deficiencies in terms of resources in the in-work schedule and, consequently, the proposal and assessment of improvements to the available resources.

- A *knowledge modelling formalism* able to represent task, resource, and schedule knowledge such that the methodology can be supported.

The specific requirements of the methodology and knowledge modelling formalism components of the approach can be viewed as:

<u>Methodology</u>

- **Task Management**
  - support the establishment, maintenance, and management of tasks, and the dependencies between them,
  - support the organisation and provision of information to enable the undertaking of tasks, and the storage of information produced on the completion of tasks for use with other tasks, and,
- **Resource Management**
  - support the assignment of expected performance of each resource with regard to the range of tasks able to be undertaken,
  - support the monitoring of resources and, thus, the detection of any significant discrepancies between actual and expected performance in order to activate the consideration of re-scheduling,
  - support the forecasting and re-assignment of expected resource performance to aid the derivation of more appropriate schedules such that the optimised use of resources can be maintained,
  - support the identification of deficiencies in the available resources with respect to the existing schedule such that possible improvements can be proposed and assessed, and,
- **Schedule Management**
  - support planning and dynamic scheduling in real-time such that resources are able to be allocated and utilised continuously in an optimised manner with respect to

completing the outstanding inter-related tasks, thus, contributing to the improved performance of the design development process,

- support the enactment of schedules, while managing and maintaining dependencies between scheduled tasks in order to facilitate their co-ordinated undertaking and completion,
- support the monitoring of schedules in order to detect any significant discrepancies between actual and expected progress in order to activate the consideration of re-scheduling,
- support decision-making to ensure that re-scheduling only occurs if appropriate, i.e. will lead to a reduction in time to complete the design development process, and,
- support the optimised concurrent re-scheduling and undertaking of tasks, such that their completion is near co-incident facilitating minimum transition delay between adjacent schedules, and, in addition, resource idle time is minimised.

<u>Knowledge Modelling Formalism</u>

- Tasks
    - formal representation of knowledge, i.e.
        - indexing such that tasks can be uniquely identified in order for them to be considered for scheduling/re-scheduling and, also, undertaken in a structured manner.
        - time such that the datum duration to complete a task may be adjusted to account for the resource to be utilised.
        - progress such that tasks, or the appropriate proportions of tasks, can only be considered for re-scheduling.
        - dependencies so that given the input and output for each task, then the number and identification of tasks they are dependent on can be established.
- Resources
    - formal representation of knowledge, i.e.
        - indexing of resources such that they can be uniquely identified for allocation and utilisation.
        - status such that only available resources may be considered for allocation and

utilisation.

- performance in order to model the efficiency of resources with respect to the tasks they can be utilised to undertake.
- cost to enable resource improvements to be assessed from a financial perspective.

- **Schedules**
  - formal representation of scheduled task knowledge, as described previously for tasks, including start and end times such that the progress of a task can be monitored.

An integrated and holistic approach to operational design co-ordination is developed in the work presented in this thesis, that aims to provide the required support as established in this chapter. Specifically, an overview of the approach is presented in Chapter 6 followed by the knowledge modelling formalism and methodology in Chapters 7 and 8 respectively.

6 An Approach to Operational Design Co-ordination

The aim of this chapter is to present an overview of a novel, integrated and holistic approach to operational design co-ordination. The approach exercises real-time operational design co-ordination such that the dynamic and unpredictable design development process can continuously be performed in an improved manner. Furthermore, the approach exercises prospective operational design co-ordination, which enables the identification and evaluation of possible improvements to the available resources such that further improvements to the performance of the design development process can be achieved.

In Section 6.1, an overview of the approach to operational design co-ordination is presented. In Sections 6.2 and 6.3, the components of the approach are introduced, namely the operational design co-ordination methodology and knowledge modelling formalism respectively. Finally, Section 6.4 summarises the chapter.

6.1 An Overview of the Approach

An original approach has been developed to enable the management of the design development process by exercising operational design co-ordination of tasks, resources and schedules.

The approach has two components, i.e. ***an operational design co-ordination methodology*** and ***a knowledge modelling formalism***. The main component of the approach is the methodology, which is supported by the knowledge modelling formalism. An overview of the approach is presented in Figure 6.1.

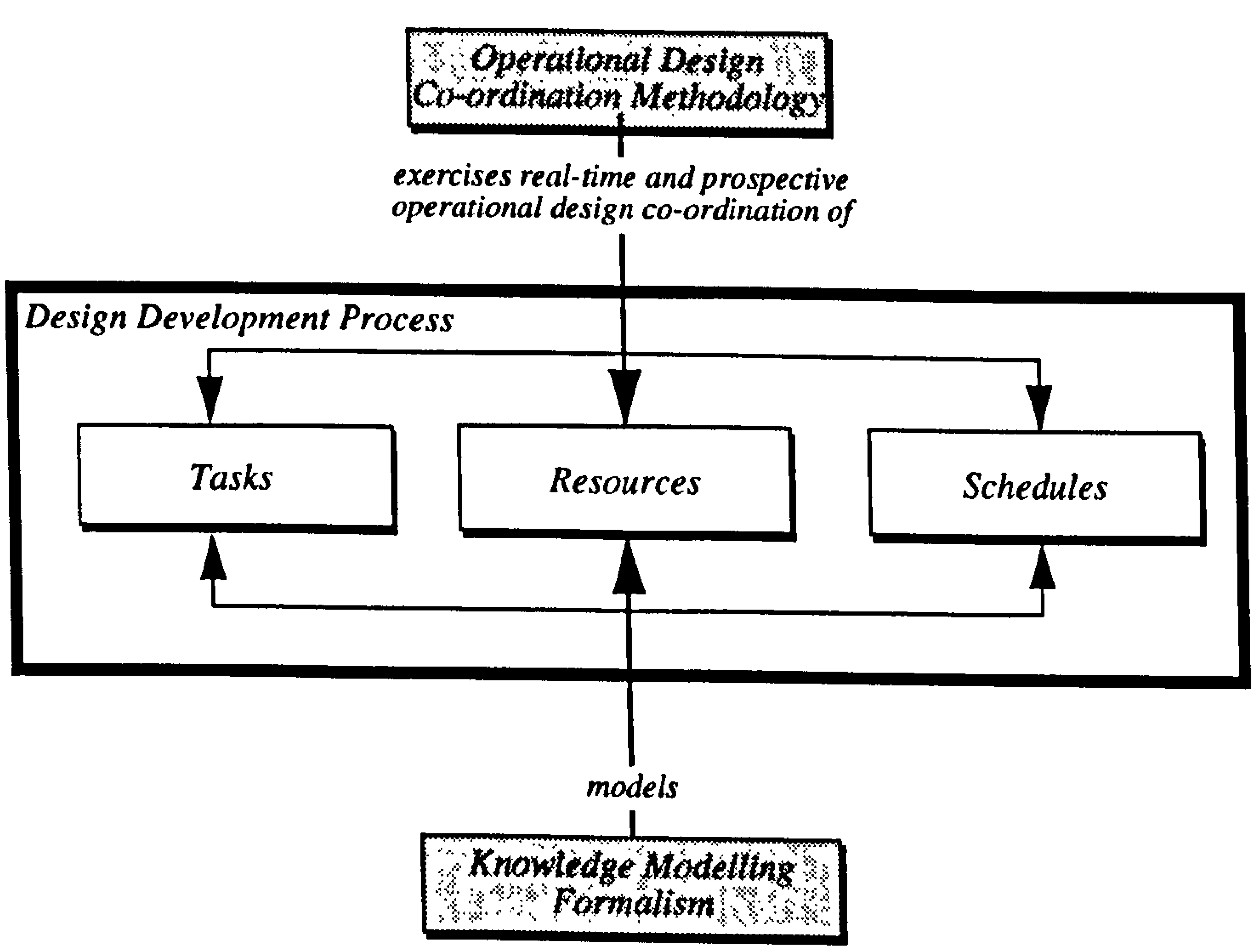

Figure 6.1 An Overview of the Approach to Operational Design Co-ordination

As indicated in Figure 6.1, the methodology exercises real-time and prospective operational design co-ordination of the design development process. The knowledge modelling formalism represents knowledge of the tasks, resources, and schedules that are operationally co-ordinated.

6.2 Operational Design Co-ordination Methodology

The methodology comprises two parts, i.e. *real-time* and *prospective operational design co-ordination.* A distinction is made between the real-time and prospective parts of the methodology since the former enables *as-is* operational design co-ordination whereas the latter permits *what-if* operational design co-ordination. That is, the real-time part of the methodology is aimed at coping with the occurrence of events as and when they arise during the design development process such that its performance can be improved. The prospective part of the methodology allows an off-line assessment to be conducted regarding enhancements to the resources such that further improvements in the performance of the design development process can be achieved.

Real-Time Operational Design Co-ordination

Real-time operational design co-ordination enables multiple inter-related tasks to be undertaken and completed by allocating and utilising multiple resources, of varying proficiency, in an optimised fashion in accordance with multiple schedules in a coherent, appropriate and timely manner, within the dynamic and unpredictable design development process. Furthermore, real-time operational design co-ordination facilitates the improved performance of the design development process to be achieved and, in addition, sustained. The term *real-time* is used since this part of the methodology involves in-situ operational design co-ordination continuously being in operation. Thus, when an event occurs that causes the performance of the design development process to be degraded, the appropriate adjustments can be made to resume improved performance. This involves resource allocation and utilisation being adjusted and tasks being re-arranged and re-distributed appropriately. As a result, the improved performance of the design development process can be maintained. Real-time operational design co-ordination also ensures that adjustments only occur if appropriate and, if so, periods of resource adjustment and task re-arrangement are utilised effectively.

An overview of the real-time operational design co-ordination part of the methodology is presented in Figure 6.2. This part of the methodology provides a systematic means of simultaneously co-ordinating the various management activities such that resources utilisation can be optimised and design tasks are undertaken and completed in accordance with schedules in a coherent manner.

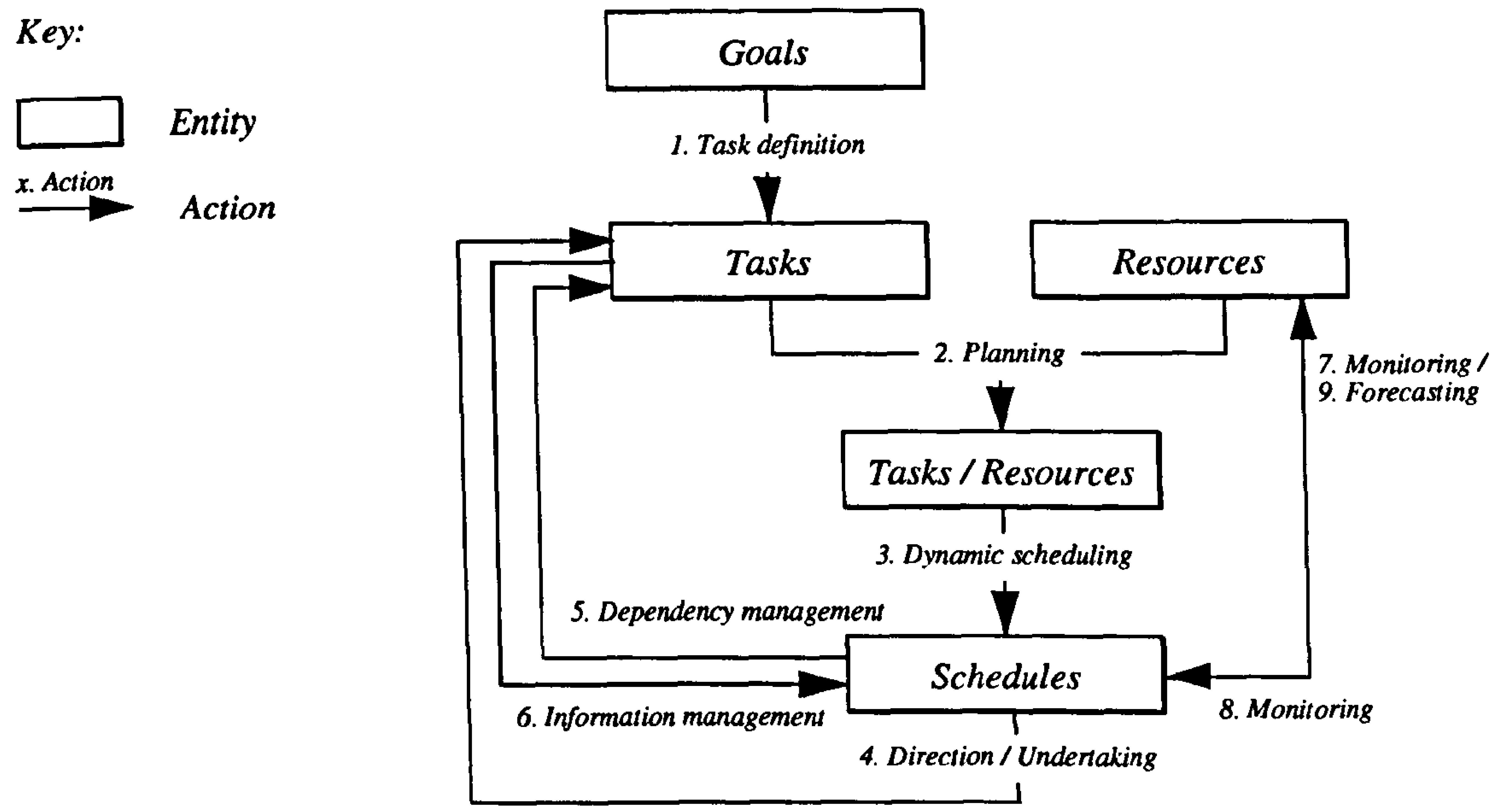

Figure 6.2 An Overview of Real-Time Operational Design Co-ordination

A more detailed illustration of this part of the methodology can be found in Section 8.1 of Chapter 8.

With regard to Figure 6.2, initially, operational tasks are defined based on the goals required to be accomplished *(Action 1)*. Planning *(Action 2)* enables knowledge of the outstanding tasks and the resources available to be considered for scheduling. As a result of scheduling, a schedule is derived *(Action 3)*, which is the basis for the direction and undertaking of tasks *(Action 4)*. Prior to a task being undertaken, dependency relationships must be satisfied *(Action 5)*. In addition, any necessary information must be managed such that it is made available to allow the task to be completed *(Action 6)*. Monitoring facilitates the detection of deviations between the actual and expected performance of a resource *(Action 7)*. Similarly, monitoring enables deviations in the progress of schedules to be detected *(Action 8)*. If the deviation in resource performance or schedule progress significantly degrades the performance of the design development process, forecasts are made for expected resource performance *(Action 9)* and/or task durations are revised. In addition, and only if appropriate, planning *(Action 2)* and scheduling *(Action 3)* are repeated in order to produce a more suitable schedule. In periods of transition between successive schedules, tasks continue to be completed and resources utilised in an optimised manner. Monitoring is conducted throughout the duration of the design development process such that at any time, and if appropriate, the operational course of action can be adapted with respect to the prevailing circumstances.

Prospective Operational Design Co-ordination

Prospective operational design co-ordination enables the identification and evaluation of proposed enhancements to the resources given the actual tasks to be undertaken such that the affect on the performance of the design development process can be assessed. That is, the existing resources can be assessed for deficiencies such that recommendations can be made regarding possible changes, which if implemented, will improve the performance of the design development process.

An overview of the prospective operational design co-ordination part of the methodology is illustrated in Figure 6.3.

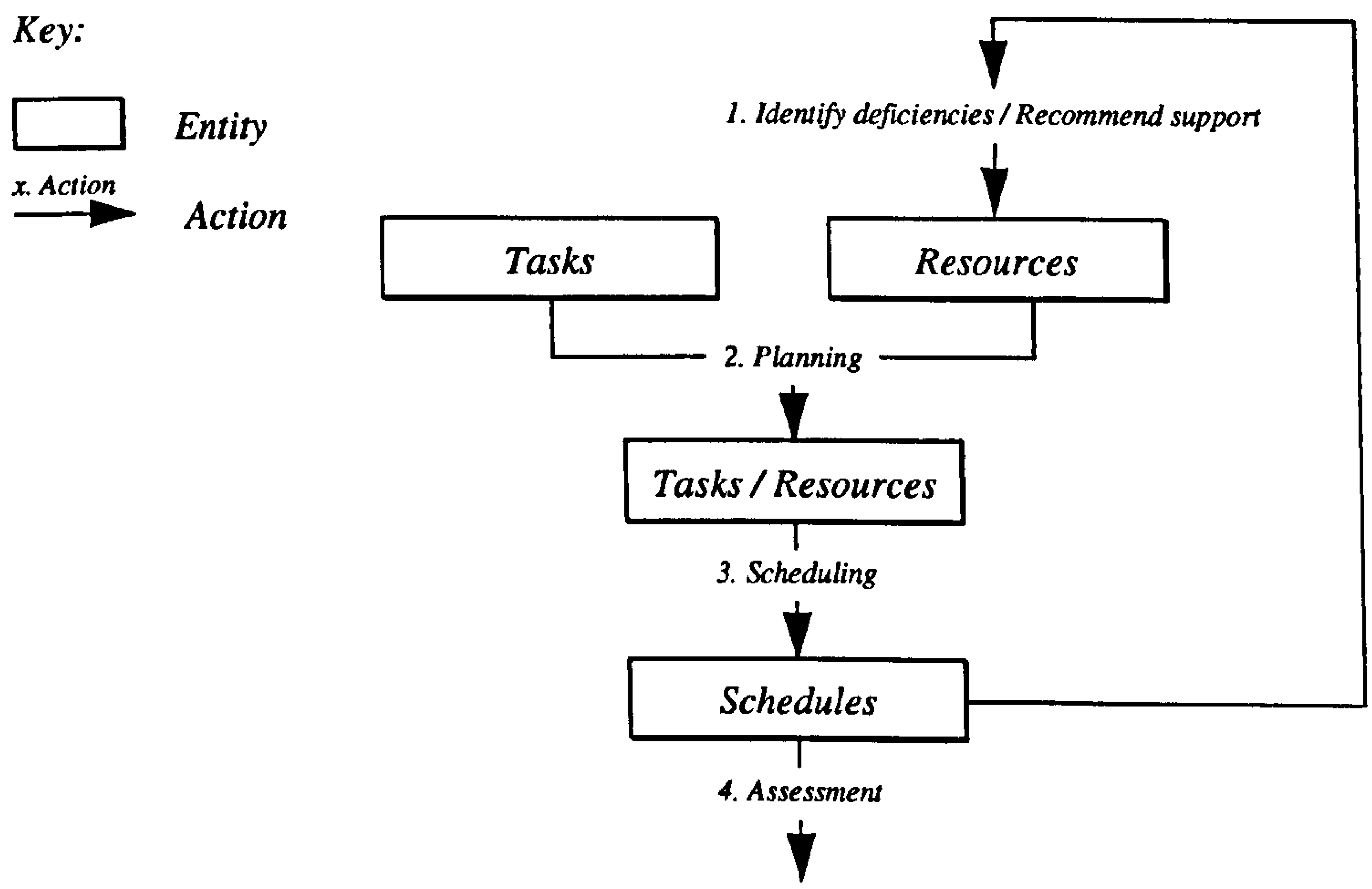

Figure 6.3 An Overview of Prospective Operational Design Co-ordination

With respect to the tasks to be undertaken according to the existing schedule being used within the design development process, deficiencies are identified in the resources *(Action 1)*. Thus, recommendations, in terms of improvements to the resources, are made aimed at redressing any imbalance in the resources and/or reducing the time to complete the outstanding tasks *(Action 1)*. Planning is conducted in order to prepare knowledge of the outstanding tasks, and the proposed changes in the resources *(Action 2)*. Scheduling is performed in order to create off-line optimised schedules that correspond to the proposed changes in resources *(Action 3)*. An assessment is made of the schedules in terms of time to complete the specified tasks and the cost to do so with the resources utilised *(Action 4)*. If applied in conjunction with the real-time part of the methodology, prospective operational design co-ordination is exercised each time re-scheduling is performed.

6.3 Knowledge Modelling Formalism

The knowledge modelling formalism component of the approach enables the appropriate representation of tasks, resources and schedules within the operational design co-ordination methodology. That is, task, resource, and schedule knowledge must be modelled in such a way that enables tasks to be undertaken and completed in an structured manner while resource utilisation is optimised in accordance with the derived schedules.

An overview of the knowledge modelling formalism component of the approach is shown in Figure 6.4.

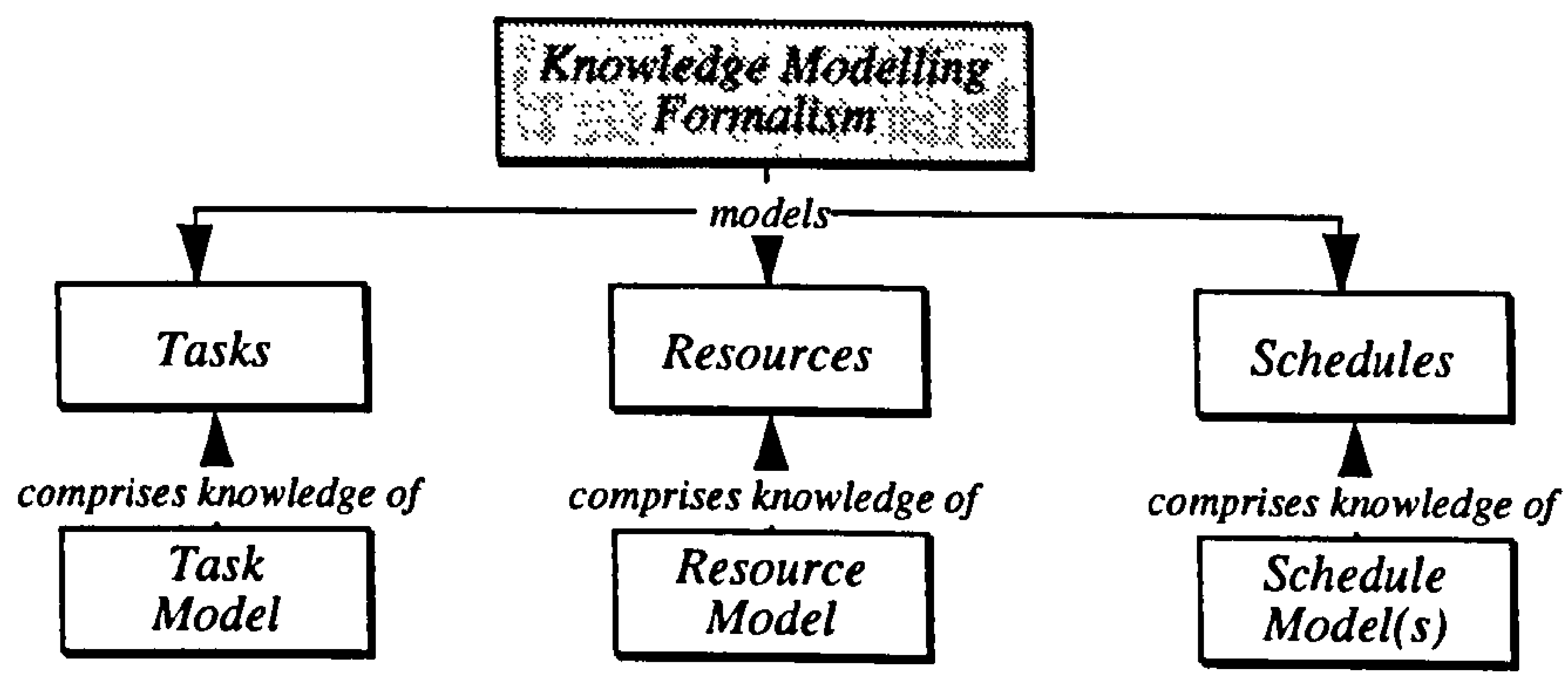

Figure 6.4 An Overview of the Knowledge Modelling Formalism

As shown in Figure 6.4, knowledge of tasks, resources, and schedules is held within their respective model. Schedule knowledge is derived from knowledge within the task model and resource model, using a suitable optimisation algorithm.

A schedule model exists for each resource allocated to be utilised according to a schedule. Such a model comprises knowledge of the associated resource to be utilised and knowledge of the tasks to be undertaken. A schedule model can be classified as either original/revised or interim. Schedule models are classified as original/revised if they are directly obtained from an optimised schedule that is derived from using a suitable optimisation algorithm. Interim schedule models are obtained directly from original/revised schedule models and are used to ensure the completion of the appropriate tasks by allocating and utilising the appropriate resources during the period of re-scheduling.

6.4 Summary

This chapter has presented an overview of a novel, integrated and holistic approach to operational design co-ordination. The approach consists of an operational design co-ordination methodology and a knowledge modelling formalism.

In Section 6.2, the main component of the approach was introduced, i.e. the methodology involving real-time and prospective operational design co-ordination. Both parts of the methodology are aimed at improving the performance of the design development process. Modelling of task, resource, and schedule knowledge, required to support the operational design co-ordination methodology, was introduced in Section 6.3.

The knowledge modelling formalism and the operational design co-ordination methodology are presented in Chapters 7 and 8 respectively. The knowledge modelling formalism is used within the operational design co-ordination methodology, and, thus is presented prior to the methodology.

7 Knowledge Modelling Formalism

The aim of this chapter is to present the knowledge modelling formalism component of the approach to operational design co-ordination. In Chapter 6, it was indicated that the knowledge modelling formalism is required to support the methodology within the approach.

Formalisms of task, resource, and schedule modelled knowledge are presented in Sections 7.1, 7.2 and 7.3 respectively. Finally, Section 7.4 summarises the chapter.

7.1 Task Knowledge

A task is considered as that which can be managed and undertaken at an operational level, which when completed will accomplish, or contribute to the accomplishment, of its associated goal.

Within the knowledge modelling formalism component of the approach, initially, tasks are defined by the designer and, as such, are represented in a form that cannot be managed within the operational design co-ordination methodology. That is, designer defined tasks have not been assigned values for each of the required knowledge attributes. Once tasks are assigned values to all knowledge attributes they are included within a task model such that they can be managed within the methodology.

The representation of modelled knowledge of a task is shown in Figure 7.1.

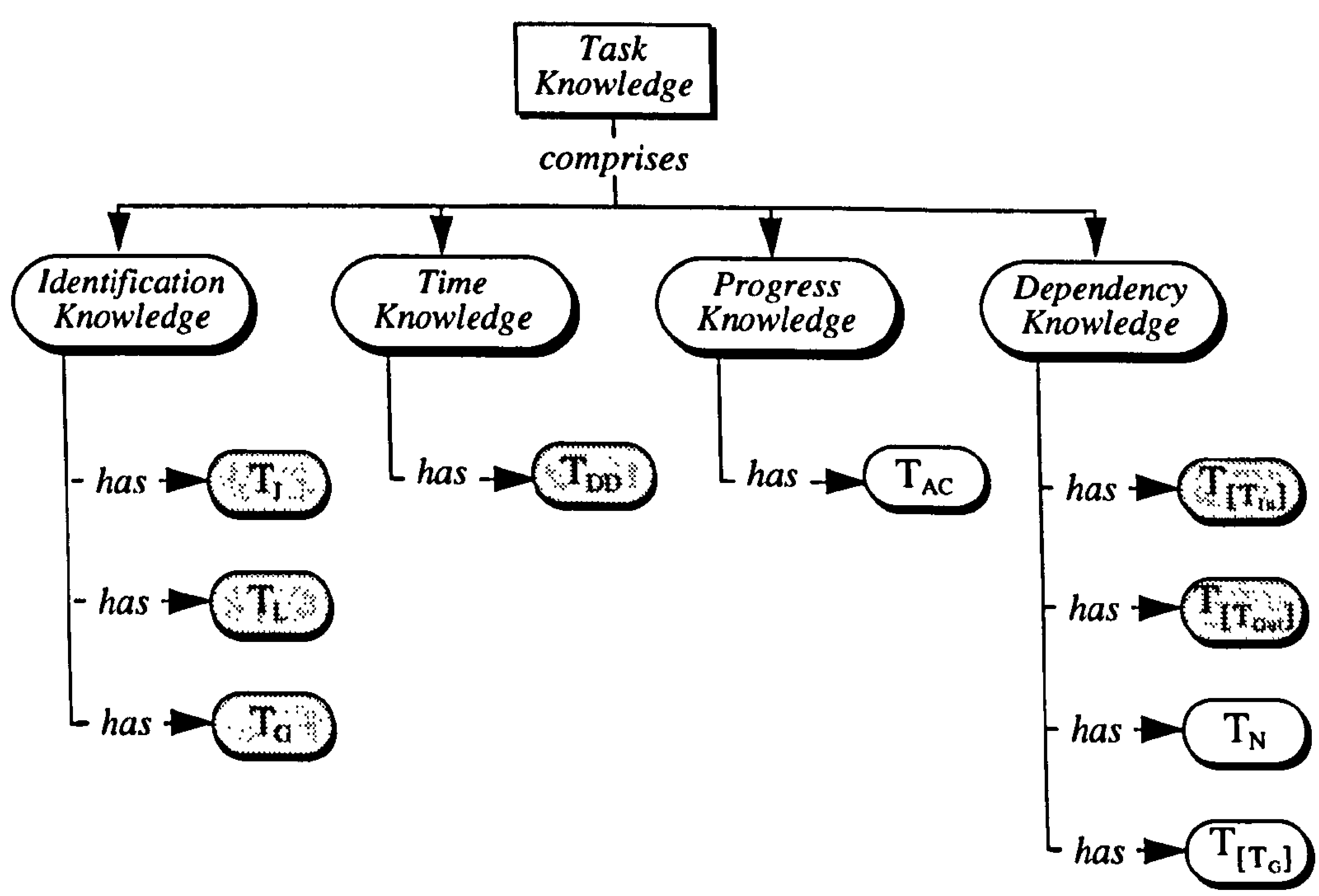

Figure 7.1 Modelled Knowledge of a Task

With regard to Figure 7.1, designer defined tasks are assigned values to those attributes that are shaded only. Tasks able to be managed within the methodology are assigned values to all attributes shown.

Identification Knowledge

Identification knowledge comprises static and dynamic knowledge attributes, which are used to identify a task.

Static identification knowledge attributes enable a task to be identified with respect to its associated goal, which is required during the undertaking and completion of tasks. The identification of each task comprises a goal identification index, T_I, and local task identification index, T_L. T_I refers to the goal to which the task is associated. T_L is an identifier assigned to a task within the context of its associated goal.

The dynamic identification knowledge attribute permits a task to be identified within the context of all tasks to be completed for all goals to be accomplished. The global task identification index, T_G, is used for the purposes of scheduling/re-scheduling.

Time Knowledge

Time knowledge entails the duration of a task, T_{DD}, that acts as a datum for comparative purposes, i.e. when considering resources of varying efficiency to undertake the task. That is, T_{DD} is required when a task is considered for scheduling/re-scheduling such that its duration can be adjusted to take into account the resource to be utilised.

Progress Knowledge

Progress knowledge comprises T_{AC}, which is a measure of the degree of completion of a task. The values that can be assigned to T_{AC} depend on whether the task is either:

- pre-emptive, i.e. once started can be interrupted, or,
- non pre-emptive, i.e once started cannot be interrupted.

For pre-emptive tasks, T_{AC} is the actual percentage completion of a task, i.e.

$$0 \leq T_{AC} \leq 100$$

T_{AC} is used to indicate whether or not a task has been completed such that the task is only considered for re-scheduling if $T_{AC} < 100\%$. Furthermore, in the event of re-scheduling, T_{AC} enables the appropriate proportion of the task to be re-scheduled.

For non pre-emptive tasks, $T_{AC} = \{0,1\}$, where 0 indicates that a task has not been completed and 1 signifies that it has been completed.

Dependency Knowledge

Dependency knowledge comprises a number of attributes that enable the relationship between the task under consideration and related tasks to be managed. This knowledge is required to establish knowledge of relationships with other tasks, which is then used when a task is being considered for scheduling/re-scheduling and, subsequently, being undertaken. Dependency knowledge consists of:

- an input requirements matrix, $T_{[T_{In}]}$,
- an output requirements matrix, $T_{[T_{Out}]}$,
- the number of tasks that a task is dependent on, T_N, and,
- a global task identification index matrix, $T_{[T_G]}$, which is comprised of the global task identification index of each task dependent on.

Specifically,

$$T_{[T_{In}]} = \begin{bmatrix} T_{In,1} \\ \dots \\ T_{In,T_{NIn}} \end{bmatrix} \qquad T_{[T_{Out}]} = \begin{bmatrix} T_{Out,1} \\ \dots \\ T_{Out,T_{NOut}} \end{bmatrix} \qquad T_{[T_G]} = \begin{bmatrix} T_{G,1} \\ \dots \\ T_{G,T_N} \end{bmatrix}$$

where T_{NIn} is the number of task input requirements, and T_{NOut} is the number of task output requirements.

$T_{[T_{In}]}$ defines the information needed to be available prior to the task being undertaken, whereas $T_{[T_{Out}]}$ defines the information produced on the completion of the task. Furthermore, by comparing $T_{[T_{In}]}$ of each task with $T_{[T_{Out}]}$ of all other tasks, T_N and $T_{[T_G]}$ can be established. Before a task can commence, all the tasks it is dependent on must have been completed. Thus, for each task to be undertaken, knowledge of the global task identification index of tasks it is dependent on enables a check on T_{AC} of those dependent tasks to be made in order to determine whether or not it is appropriate to commence.

7.2 Resource Knowledge

Knowledge of resources is modelled in a form to enable their optimised allocation and utilisation throughout the design development process. Resource knowledge is held within a resource model, which is maintained throughout the design development process.

Each resource has knowledge modelled as illustrated in Figure 7.2.

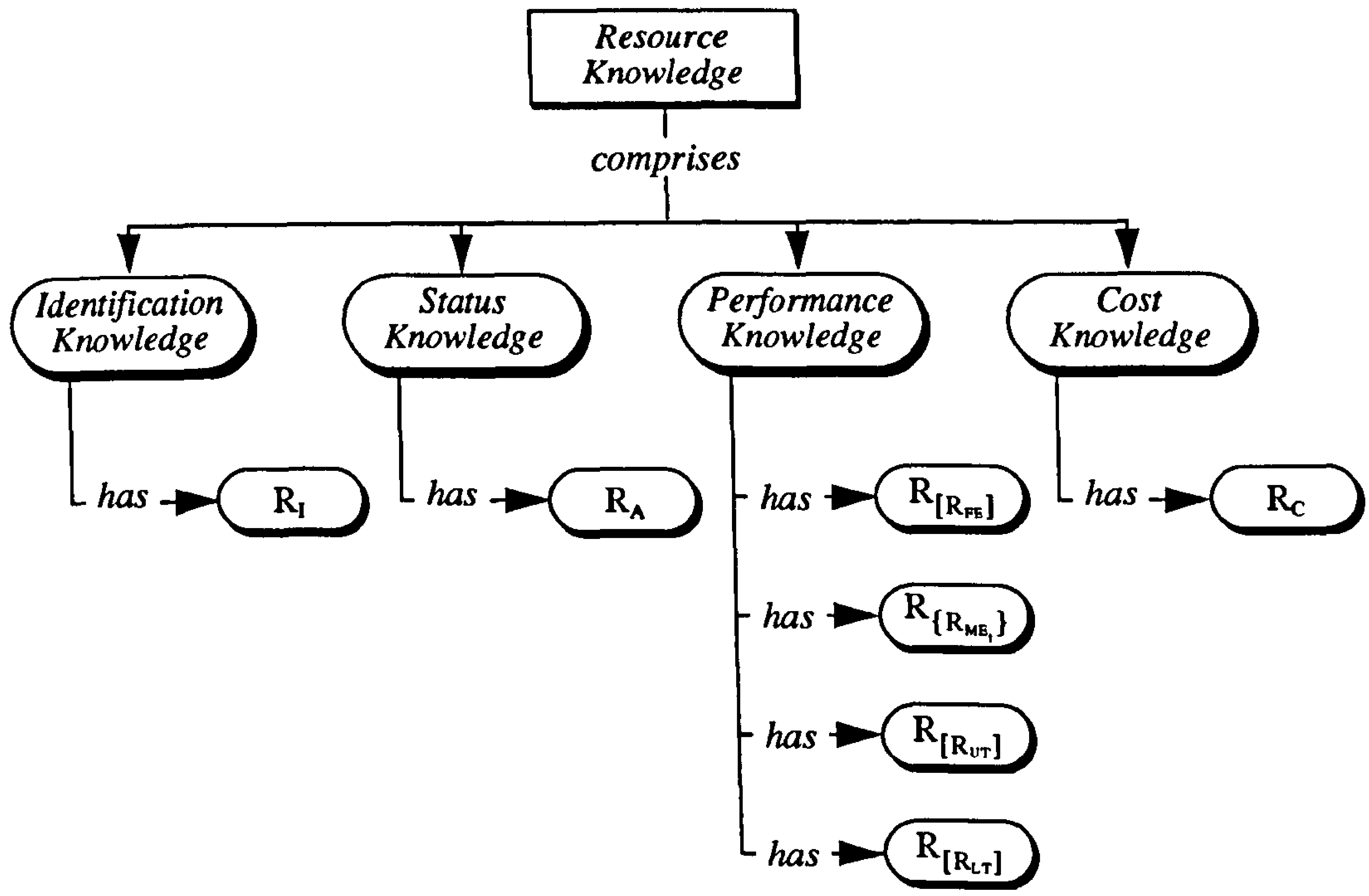

Figure 7.2 Modelled Knowledge of a Resource

Identification Knowledge

R_I is a unique identifier which can be used to differentiate a resource from others. This is required to distinguish the resource that tasks have been assigned to in order to be completed.

Status Knowledge

R_A is an indication of whether or not a resource is available to be allocated for utilisation. Thus, R_A is required to determine whether a resource may be considered for scheduling, i.e. $R_A = \{0,1\}$, where 0 indicates that a resource is unavailable for use and 1 signifies that it is available for use.

Performance Knowledge

Performance knowledge comprises attributes that govern the utilisation of a resource with respect to completing tasks. Performance knowledge is required to permit the appropriate allocation and utilisation of a resource, and consists of:

- a forecasted efficiency matrix, $R_{[R_{FE}]}$,
- a monitored efficiency time series, $R_{\{R_{ME_t}\}}$, where $t = \{1,2,...,n\}$ and n is the number of time steps,
- an upper monitored efficiency threshold matrix, $R_{[R_{UT}]}$, and,

- a lower monitored efficiency threshold matrix, $R_{[R_{LT}]}$.

A time series is a sequence of observations on a variable of interest [Montgomery & Johnson, 1976]. Further, the variable is observed at discrete time points, usually equally spaced.

Forecasted efficiency indicates how efficient a resource is predicted to be with regard to the completion of a particular task. Monitored efficiency represents the actual efficiency of a resource at various points in time during the completion of a task. A resource is assigned a forecasted efficiency for each different type of task it is capable of completing. Initially, the forecasted efficiencies of a resource regarding tasks can be assigned based on historical information from previous design development processes. If no historical information is available, as in the case of a new recruit to be utilised within the design development process, estimates of forecasted efficiency must be made. During the course of the design development process, and based on monitored efficiencies over a period of time, forecasted efficiencies can be revised to account for variability in resource performance. Monitored efficiency thresholds are a measure of the permitted deviation between monitored and forecasted efficiency of a resource for each task that can be undertaken. The designer defines the upper and lower monitored efficiency threshold values, which may be particular to the individual resources and tasks to be completed. If either threshold is exceeded at any point during the design development process, a decision must be made regarding re-scheduling in order to adapt to the new forecasted efficiency of a resource such that they remain utilised in an optimised manner.

Cost Knowledge

Cost knowledge, R_C, refers to the financial cost of utilising a resource per unit time. As such, R_C is necessary to establish the total financial cost as a result of utilising a resource within a schedule.

7.3 Schedule Knowledge

Schedule knowledge is obtained from scheduling, which uses task and resource knowledge. As a result of scheduling, tasks are allocated additional knowledge attributes, which are assigned values. These knowledge attributes enable tasks to be undertaken and completed in a certain order using a specified resource.

Schedule knowledge is contained within schedule models, which exist for each resource allocated to be utilised and are categorised as either original, revised, or interim. Original schedule models are obtained from the schedule produced as a result of scheduling prior to any tasks being undertaken at the outset of the design development process. If the original schedule models become inappropriate due to a significant deviation in progress, re-scheduling is performed to produce more suitable revised schedule models. If appropriate, during the period of re-scheduling, i.e. during the elapsed time between the cancellation of the original and derivation of the revised schedule models, interim schedule models can be constructed and enacted. That is, if it is possible to complete tasks from the original schedule models during the period of re-scheduling then they can be included within the corresponding interim schedule models. In addition to constructing and enacting interim schedule models between the original and first revised schedule models, if appropriate, they can also be constructed and enacted between subsequent successive revised schedule models.

Figure 7.3 shows an example sequence of schedule models during the design development process.

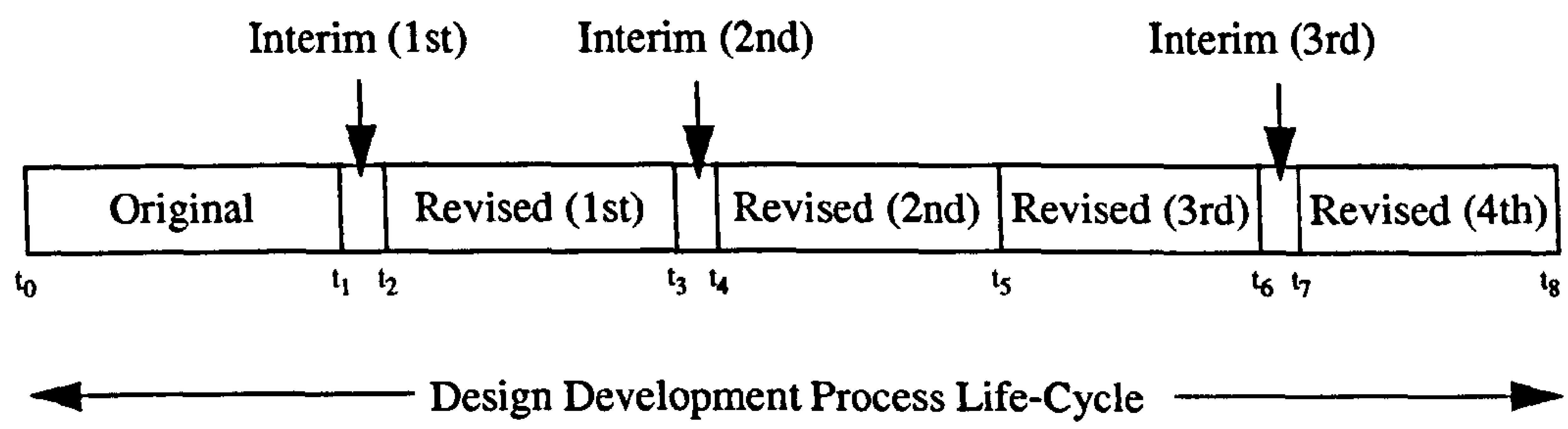

Figure 7.3 A Sequence of Schedule Models

Initially, prior to any tasks being undertaken, scheduling is performed in order to create a schedule from which the original schedule models are obtained. If the original schedule models are enacted at time t_0, and at some time later t_1 they become inappropriate due to circumstances such as a significant deviation between expected and actual resource performance, then re-scheduling is required. As a result, the first revised schedule models are derived, which can be enacted at time, t_2. While re-scheduling is performed, and based on the original schedule models, the first interim schedule models are enacted. The existence of the interim schedule model is dependent upon attributes of the outstanding tasks that a resource would have been utilised to undertake and complete in accordance with its original schedule model. Specifically, only outstanding tasks within the original schedule model, which have all the tasks they are dependent on completed, are permitted to be included within the corresponding interim schedule model. Furthermore, the tasks to be completed according to the first interim schedule model are selected such that their overall completion will as near as possible coincide with the end of re-scheduling. This enables the enactment of the first revised schedule models to commence with minimal delay. In the event that no tasks are appropriate for inclusion within interim schedule models, as between the second and third revised schedule models shown in Figure 7.3, no tasks can be completed during re-scheduling.

As mentioned at the beginning of Section 7.3, as a result of scheduling, for each resource allocated to be utilised, schedule models are obtained that contain schedule knowledge, i.e. knowledge of the scheduled tasks to be completed. Knowledge of each scheduled task contained within a schedule model is illustrated in Figure 7.4.

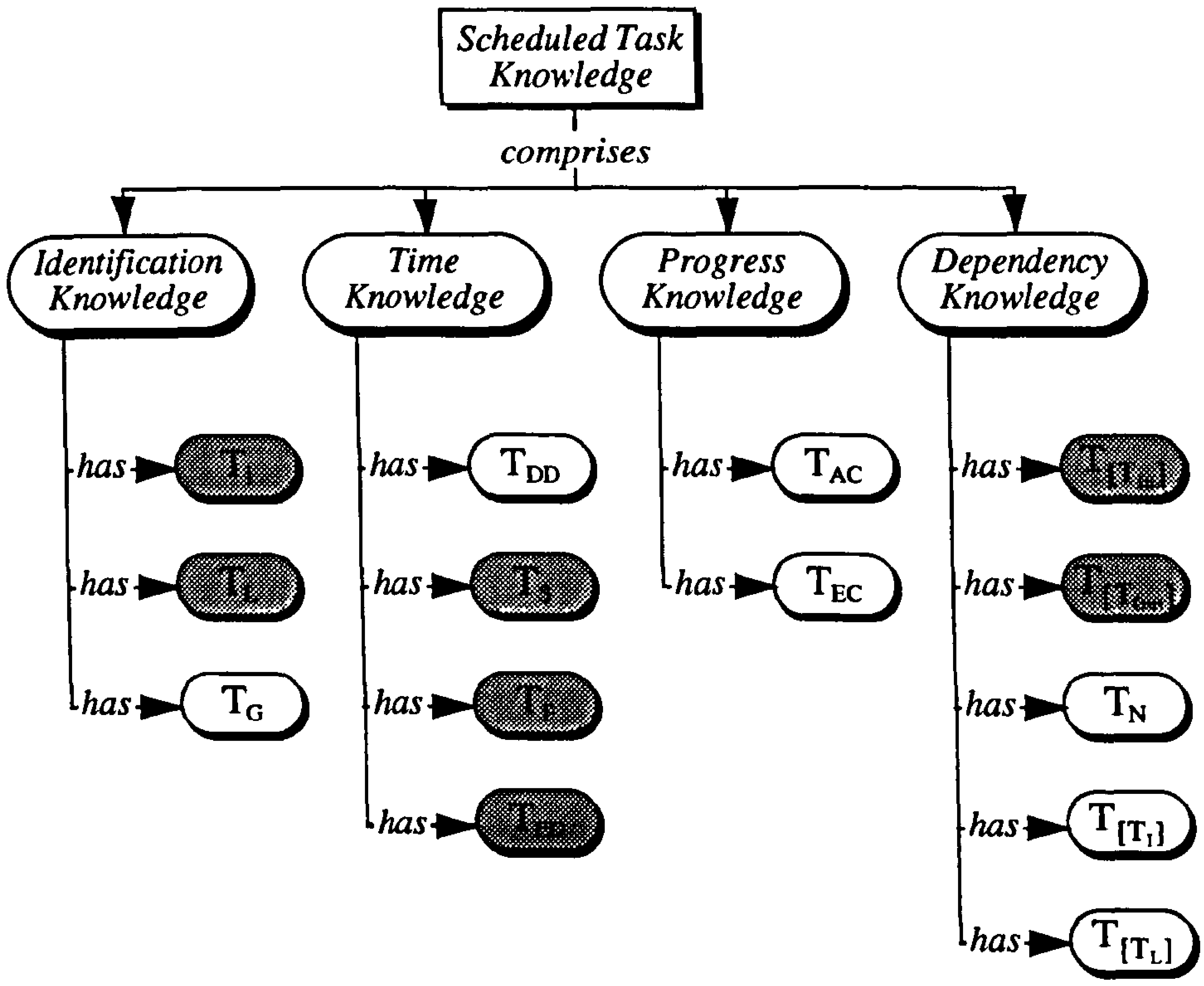

Figure 7.4 Modelled Knowledge of a Scheduled Task within a Schedule Model

With regard to Figure 7.4, within original/revised schedule models, values are assigned to all scheduled task attributes shown. Within interim schedule models, values are only assigned to the attributes shown as shaded, since dependency checks and progress checks are not conducted. These checks are not required due to all scheduled tasks being independent within interim schedule models.

In the remainder of this section, only those scheduled task knowledge attributes not described in Section 7.1 are discussed, i.e. time knowledge (T_S, T_F, T_{ED}), progress knowledge (T_{EC}), and dependency knowledge ($T_{[T_I]}$, $T_{[T_L]}$).

Time Knowledge

As a result of scheduling, within its associated original/revised schedule model, each task to be undertaken is allocated additional time knowledge attributes, i.e. start time, T_S, finish time, T_F, and estimated duration, T_{ED}. T_S indicates the time at which a task is scheduled to commence, whereas T_F denotes the time at which a task is scheduled to be completed. T_{ED} is the difference between T_S and T_F, i.e. $T_{ED} = |T_S - T_F|$. Furthermore, T_{ED} is calculated by dividing

T_{DD} by the allocated resource's value of R_{FE} for the task to be undertaken, i.e. $T_{ED} = T_{DD}/R_{FE}$. This calculation is incorporated within a suitable optimisation algorithm.

T_{DD} is contained within an original/revised schedule model since, if the need arises to re-schedule, it is used to re-calculate the estimated duration of the task to be held within the corresponding interim schedule model. The reason for re-calculating the estimated duration of a task is due to the possibility of a change in resource forecasted efficiency for that task.

Progress Knowledge

Only for a pre-emptive task, additional progress knowledge is represented by an estimated completion measure, T_{EC}. Expressed as a percentage, T_{EC} is an indication of how much a task is estimated to have been completed at periods of time over which it is undertaken.

Dependency Knowledge

With regard to dependency knowledge, $T_{[T_G]}$ from the task model is used to obtain the corresponding goal identification index matrix, $T_{[T_I]}$, and local task identification index matrix, $T_{[T_L]}$, i.e. the goal identification index and local task identification index of each task that a task is dependent on. These matrices are required for the purpose of undertaking tasks.

7.4 Summary

This chapter has presented the knowledge modelling formalism component of the approach to operational design co-ordination.

Task, resource, and schedule knowledge has been modelled in the manner presented to enable the operational design co-ordination methodology to be implemented. That is, the knowledge modelling formalism component of the approach supports the operational design co-ordination methodology. The manner in which modelled knowledge is used within the methodology is described in Chapter 8.

8 Operational Design Co-ordination Methodology

The aim of this chapter is to present the methodology of the approach to operational design co-ordination.

The real-time and prospective parts of the methodology are presented in Sections 8.1 and 8.2 respectively. A summary of the methodology is presented in Section 8.3. Finally, Section 8.4 summarises the chapter.

In Chapter 7, the modelling of task, resource and schedule knowledge has been formalised. This chapter describes the methodology of how this modelled knowledge is acquired, derived, maintained and used in order to enable the real-time and prospective operational design co-ordination of the design development process.

As stated in Chapter 6, the methodology consists of two parts, namely real-time and prospective operational design co-ordination, as shown in Figure 8.1.

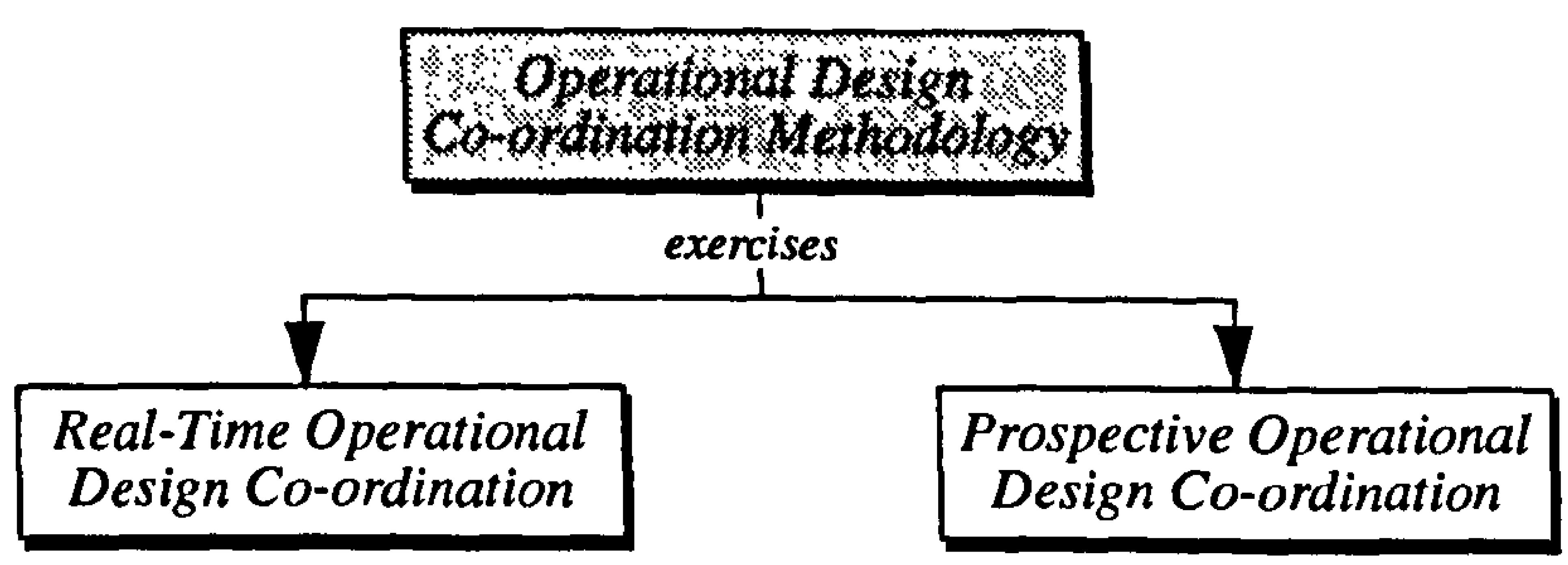

Figure 8.1 Parts of the Operational Design Co-ordination Methodology

8.1 Real-Time Operational Design Co-ordination

As indicated in Chapter 6, real-time operational design co-ordination enables multiple inter-related tasks to be undertaken and completed by allocating and utilising multiple resources, of varying efficiency, in an optimised fashion in accordance with multiple schedules in a coherent, appropriate and timely manner, such that the improved performance of the dynamic and unpredictable design development process can be achieved and sustained. As such, the real-time part of the methodology developed provides a systematic means of simultaneously co-ordinating the various management activities such that resource utilisation may be optimised and tasks undertaken and completed in a structured manner.

8.1.1 Initialisation

The first stage of the real-time operational design co-ordination part of the methodology is the initialisation of task and resource knowledge, which involves eight interactions.

<u>Designer Defined Tasks</u> *(Interactions 1 and 2)*

Knowledge of tasks is acquired from the designer *(Interaction 1)* and/or the resource/task history repository *(Interaction 2)*, as illustrated in Figure 8.2. The key presented in Figure 8.2 is applicable to other figures in this chapter related to the interactions of the methodology.

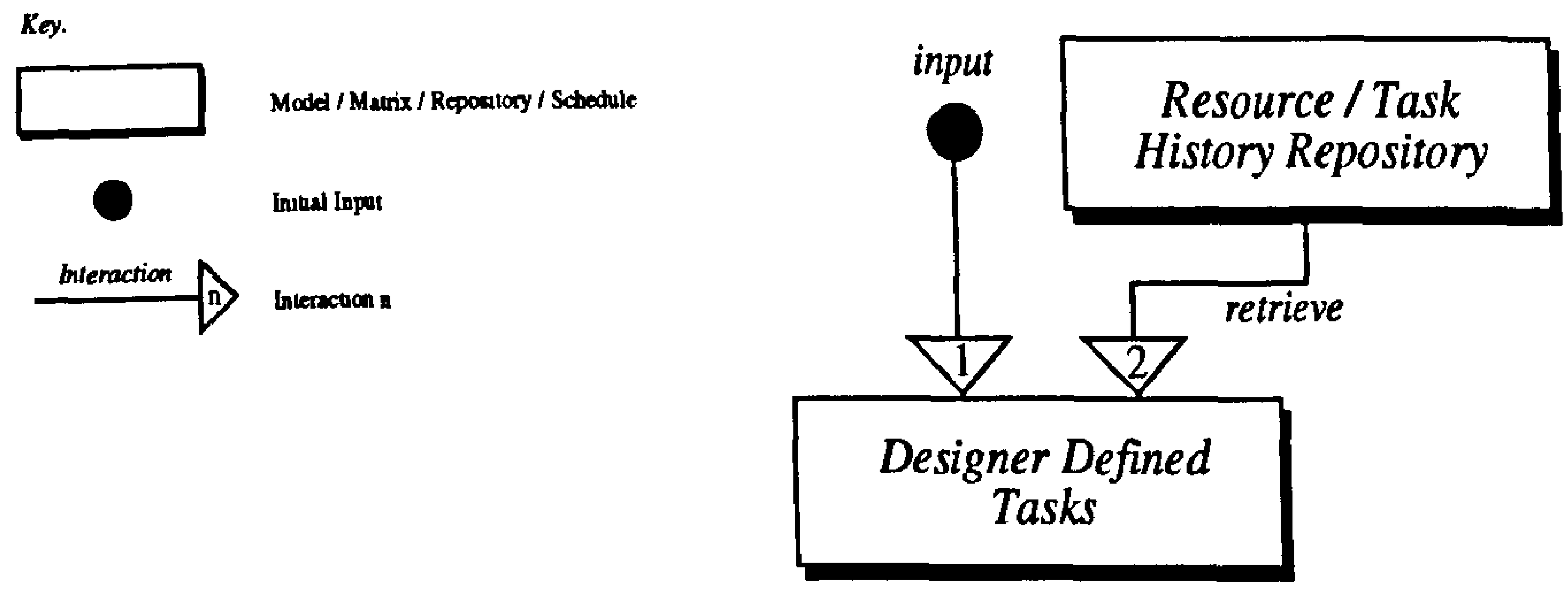

Figure 8.2 Definition of Tasks

Each task defined by the designer is assigned a goal identification index, T_I, a local task identification index, T_L, and a global task identification index, T_G. These three indices are incremented appropriately as tasks are defined.

Task datum duration, T_{DD}, is either provided by the designer or retrieved from the resource/task history repository. If the task has been completed in a previous design development process, datum duration knowledge is retrieved from the resource/task history repository. However, if a task has not been completed previously then the designer must exercise judgement and experience to estimate the datum duration. This estimate is not only assigned to the task but also recorded in the resource/task history repository. Thus, this knowledge may be retrieved in the event of it being required at any time in the future, rather than the designer providing an estimate.

Dependency knowledge, i.e. task input requirement matrix, $T_{[T_{In}]}$, and task output requirement matrix, $T_{[T_{Out}]}$, are either provided by the designer or retrieved from the resource/ task history repository.

<u>Resource Model</u> *(Interactions 3, 4 and 5)*

As shown in Figure 8.3, the construction of the resource model involves designer input *(Interaction 3)*, the resource/task history repository *(Interaction 4)*, and/or designer defined tasks *(Interaction 5)*.

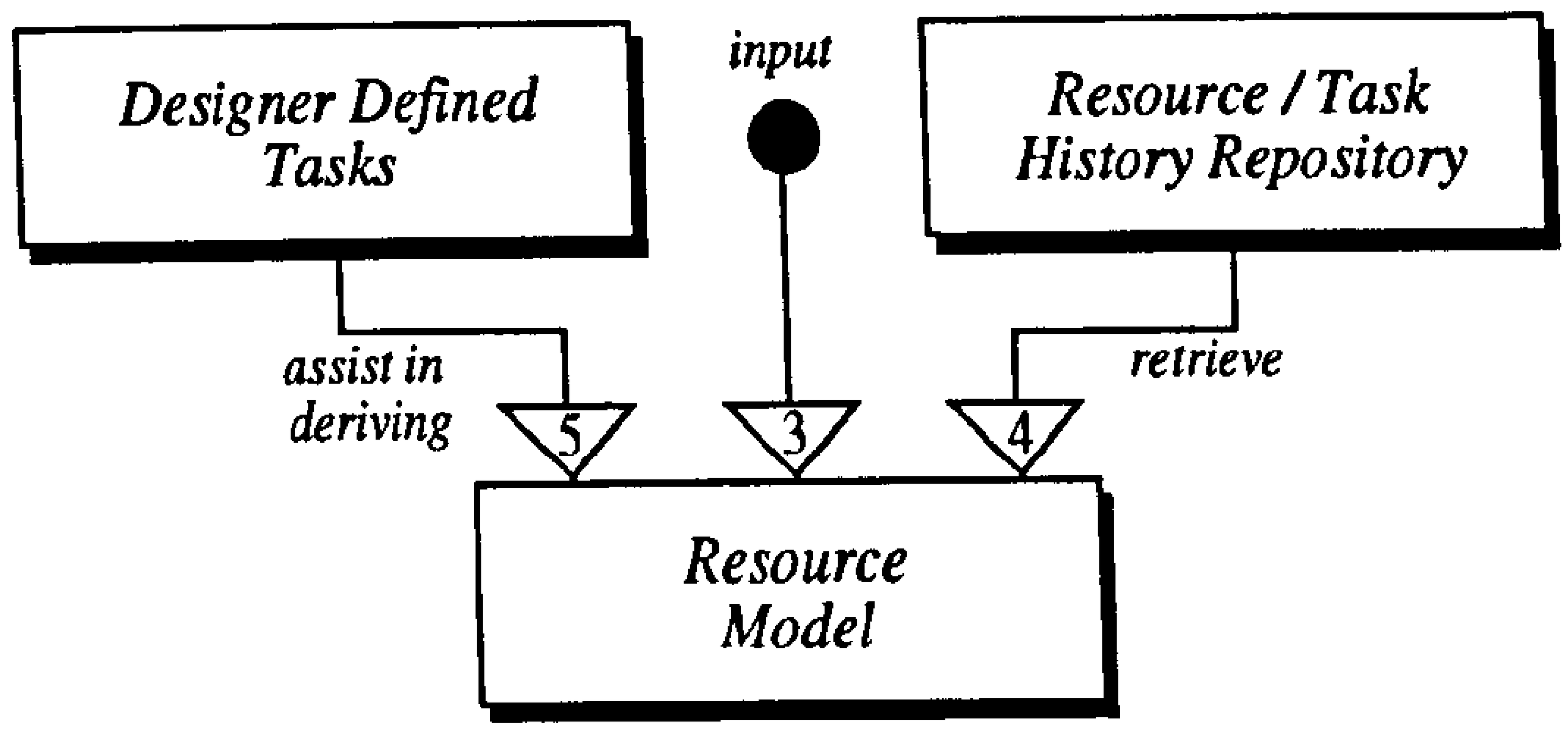

Figure 8.3 Construction of the Resource Model

For each resource, the identification index, R_I, and availability, R_A, are supplied by the designer *(Interaction 3)*. The first resource included within the resource model is arbitrarily assigned $R_I = 0$ or 1. As other resources are added, R_I is incremented accordingly.

Performance knowledge consists of forecasted efficiency, R_{FE}, upper and lower monitored efficiency thresholds, R_{UT} and R_{LT}, for each task able to be completed utilising the resource. Specifically, R_{FE} assigned to a resource for each particular task that it can be used to complete, can be obtained from:

- input based on the judgement and experience of the designer *(Interaction 3)*
- retrieved from the resource/task history repository *(Interaction 4)*
- considering task knowledge regarding designer defined tasks *(Interaction 5)*

In the event of R_{FE} not being known for the resources able to be utilised to complete particular tasks within the design development process, the designer must supply this knowledge based on judgement and experience *(Interaction 3)*. For example, the designer may assign R_{FE} based on the designation of the resource to be utilised. Given that resources have been utilised previously to complete particular tasks needing to be completed, historical knowledge can be retrieved from the resource/task history repository *(Interaction 4)*, which holds knowledge from previous design development processes. Using T_{DD}, as assigned to the tasks, R_{FE} can be tailored with respect to each particular task to reflect the variation in the estimated duration of a task, T_{ED}, for the different resources *(Interaction 5)*. For example, given that a task has a datum duration of 20 units of time and two resources are estimated to be able to complete the task in 25 and 36 units of time, then the corresponding efficiencies forecasts of the resources for that particular task are 0.80, i.e. 20/25, and 0.56, i.e. 20/36, respectively. These values are calculated by dividing the datum duration by the respective estimated duration.

In the case of the estimated duration to complete a task for a particular resource being less than the existing datum duration, then the datum duration is assigned the value of the estimated duration. That is, the datum duration equals the lowest estimated duration of all resources capable of undertaking the task. As a result, the forecasted efficiency of the resource able to undertake the task in the lowest estimated duration will be 1, since $R_{FE} = T_{DD}/T_{ED}$ and $T_{DD} = T_{ED}$. In addition, existing forecasted efficiencies of resources must be determined based on the newly assigned datum duration, i.e. the lowest estimated duration. Due to the datum duration of a task being equal to the lowest estimated duration of all resources capable of completing the task, forecasted efficiencies are always less than or equal to unity.

With regard to the previous example, if a resource was estimated as being able to complete the task, with a datum duration of 20 units of time, in 15 units of time, then the datum duration is changed and assigned the value 15. As such, with respect to the task, the forecasted efficiency of the resource is set at 1. Furthermore, the forecasted efficiencies of the resources able to complete the task in 25 and 36 units of time would be re-calculated to be 0.60 (15/25) and 0.42 (15/36) respectively.

In Table 8.1, for an example design development process, resource forecasted efficiencies, R_{FE}, are shown for six resources and eight tasks. The shaded cells highlight the non-zero values for R_{FE}.

		Task							
		1	2	3	4	5	6	7	8
Resource	1	0	0.25	0.3	0.1	0.8	0	0.4	0.65
	2	0.7	0	0.68	0	0.92	0	0	0.1
	3	0	0.56	0.58	0	0	0.34	0	0.45
	4	0.78	0	0.58	0.21	0	0.66	0.5	0
	5	0.67	0	0	0.8	0	0	0.2	0.24
	6	0	0.44	0	0.9	0.6	0.8	0.4	0

Table 8.1 Resource Forecasted Efficiencies

For example, resource 4 has been assigned $R_{FE} = 0.66$ for task 6. Similarly, resource 4 has an $R_{FE} = 0$ for task 8 indicating that the task cannot be undertaken by the resource.

Depending on the nature of the resources to be used and the tasks they can complete, R_{UT} and R_{LT} will be supplied by the designer *(Interaction 3)* based on permissible deviations between the monitored and forecasted resource efficiency. In addition, monitored efficiency thresholds may be particular to the design development process in order to account for variations in sensitivity to the consideration of re-scheduling.

In situations where the cost of utilising resources is to be calculated, cost knowledge, R_C, is also provided by the designer *(Interaction 3)* or retrieved from the resource/task history repository *(Interaction 4)*.

<u>Task Dependency Matrix</u> ***(Interaction 6)***

A task dependency matrix is a means of presenting the input/output relationships between tasks, as discussed in Section 2.2.3 of Chapter 2. The design structure matrix modelling tool is used within this approach since it fulfils the requirement of representing relationships between tasks, in addition to being suitable for use within a software implementation of the real-time part of the methodology, i.e. the Design Co-ordination System, presented in Chapter 9.

As shown in Figure 8.4, the task dependency matrix is derived from knowledge of designer defined tasks, specifically by comparing each input requirement within $T_{[T_{In}]}$ against each output requirement within $T_{[T_{Out}]}$ of all other tasks.

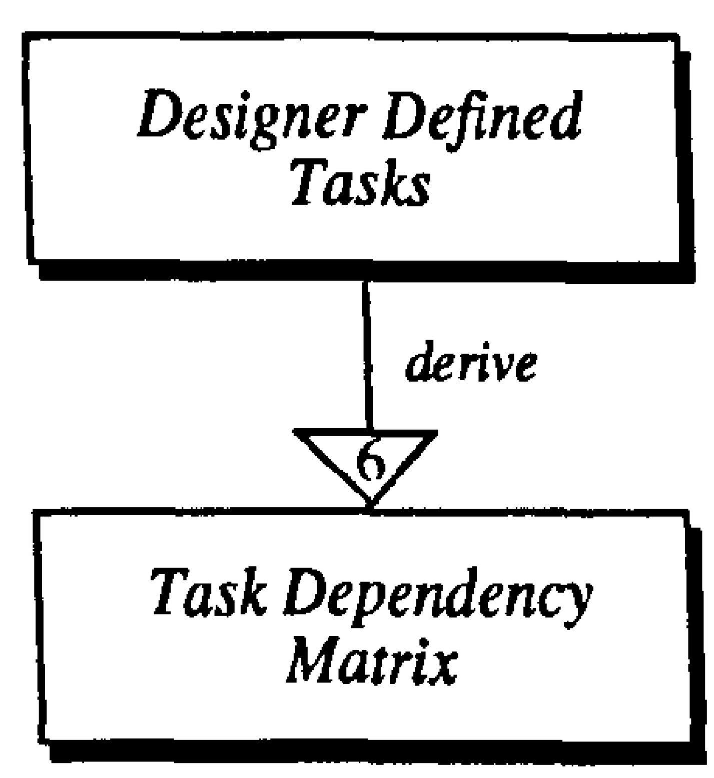

Figure 8.4 Construction of the Task Dependency Matrix

If an input requirement within $T_{[T_{In}]}$ for one task is common with an output requirement within $T_{[T_{Out}]}$ of another task, then a relationship exists between the tasks. Specifically, the task with an input requirement is dependent on the task with the common output requirement.

A non-diagonal element of unity within the task dependency matrix indicates that the task represented in the particular column must precede the task represented in the corresponding row. An element equal to zero indicates that no dependency relationship exists between the respective tasks. For example, with respect to the task dependency matrix shown in Table 8.2, the output requirement of task T_G=4 constitutes part of the input requirement of task T_G=6 indicating that T_G=6 is dependent upon T_G=4. This dependency relationship represents that T_G=4 needs to be completed prior to the commencement of T_G=6.

		Inputs							
	T_G	1	2	3	4	5	6	7	8
Dependents	1	6	0	0	0	0	0	0	0
	2	1	20	0	0	0	0	0	0
	3	0	0	14	0	0	0	0	0
	4	1	1	0	29	0	0	0	0
	5	0	1	1	0	19	0	0	0
	6	0	0	0	1	1	16	0	0
	7	0	0	1	0	0	0	27	0
	8	0	0	0	0	0	1	1	6

Table 8.2 Task Dependency Matrix

Values of T_{DD} for the task associated with the corresponding row and column are shown in the diagonal elements of the matrix.

<u>Task Model</u> *(Interactions 7 and 8)*

Each task defined by the designer is represented in the task model. Knowledge held in the task model is constructed based on knowledge regarding the tasks defined by the designer *(Interaction 7)* and the task dependency matrix *(Interaction 8)* as illustrated in Figure 8.5.

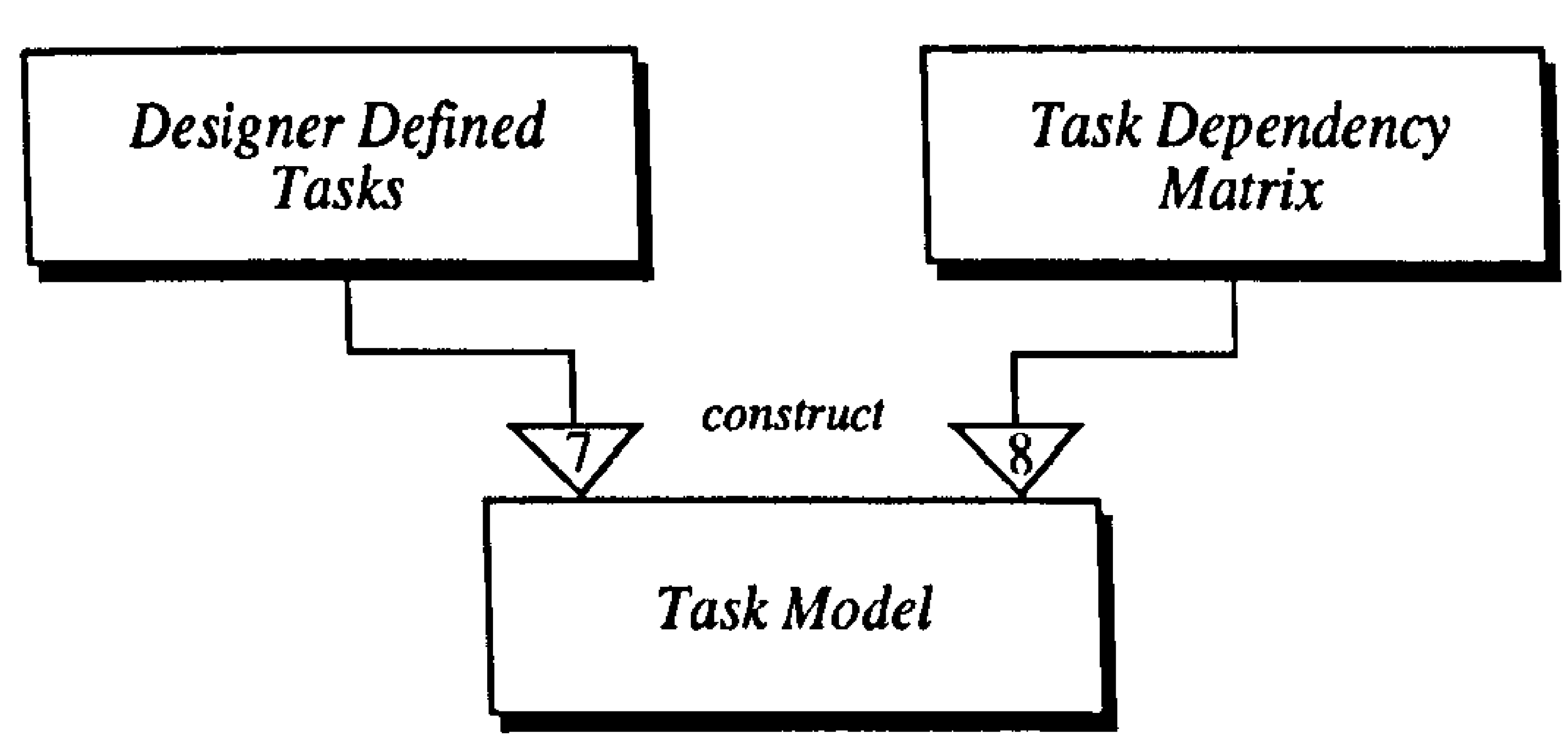

Figure 8.5 Construction of the Task Model

The task model is a representation of the tasks required to be completed in the design development process. The task model is used to assist scheduling (*Interaction 9, page 97*), and enable dependency checking (*Interaction 13, page 101*) such that tasks can be directed (*Interaction 14, page 101*), undertaken (*Interaction 15, page 101*) and completed (*Interaction 16, page 101*).

For each task to be completed, knowledge regarding identification, time, progress and dependencies is contained within the task model.

Certain knowledge of each task defined by the designer is mapped directly to the task model, namely T_I, T_L, T_G, T_{DD}, $T_{[T_{In}]}$ and $T_{[T_{Out}]}$.

Progress knowledge, T_{AC}, for each task is introduced in the task model, which is initially set to zero indicating that the task has yet to be undertaken.

For each task, using T_G, dependency knowledge for inclusion within the task model is extracted from the task dependency matrix, i.e. the number of tasks that the task to be undertaken is dependent on, T_N, and the global task identification matrix, $T_{[T_G]}$. T_N is the sum of the elements of the corresponding row in the task dependency matrix. For example, with regard to Table 8.2, for T_G=5 their are two tasks which it is dependent upon, namely T_G=2 and T_G=3. If a task is dependent on other tasks, i.e. $T_N > 0$, the global identification index of each of those tasks are obtained by identifying the corresponding column of the task dependency matrix.

<u>Summary of Initialisation</u> ***(Interactions 1 to 8)***

The initialisation stage of real-time operational design co-ordination, involves *Interactions 1 to 8*, as illustrated in Figure 8.6.

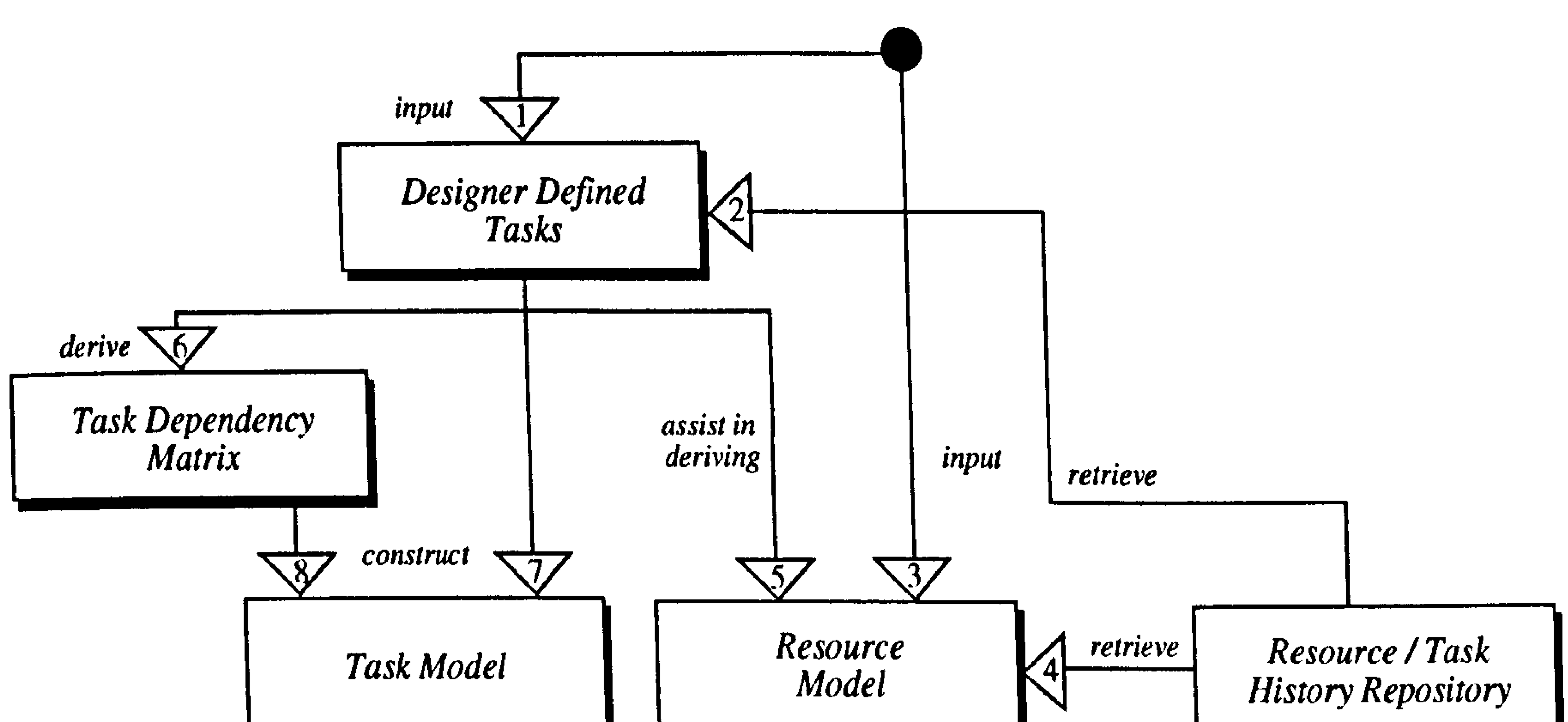

Figure 8.6 Real-Time Operational Design Co-ordination - Initialisation

Table 8.3 summarises the involvement of modelled knowledge in the interactions shown in Figure 8.6.

Interaction	Knowledge Modelled	
	Task	Resource
1	$T_I, T_L, T_G, T_{DD}, T_{\{T_{In}\}}, T_{\{T_{Out}\}}$	n/a
2	$T_{DD}, T_{\{T_{In}\}}, T_{\{T_{Out}\}}$	n/a
3	n/a	$R_I, R_A, R_{\{R_{FE}\}}, R_{\{R_{UT}\}}, R_{\{R_{LT}\}}, R_C$
4	n/a	$R_{\{R_{FE}\}}, R_C$
5	T_{DD}, T_{ED}	$R_{\{R_{FE}\}}$
6	$T_G, T_{\{T_{In}\}}, T_{\{T_{Out}\}}$	n/a
7	$T_I, T_L, T_G, T_{DD}, T_{\{T_{In}\}}, T_{\{T_{Out}\}}, T_{AC}$	n/a
8	$T_N, T_{\{T_O\}}$	n/a

Table 8.3 Summary of Involvement of Modelled Knowledge

8.1.2 Operation

Once the initialisation of task and resource knowledge has been completed in accordance with *Interactions 1* to 8, the operation stage of the real-time part of the methodology can be enacted as described in *Interactions 9 to 32*.

Derive an Optimised Original Schedule *(Interaction 9)*

Within the real-time part of the methodology, the objective of scheduling is viewed as minimising the total time to complete a given number of tasks with interdependencies between them by assigning them to an optimum number of resources with varying performance efficiencies. Furthermore, real-time operational design co-ordination is aimed at ensuring this objective is satisfied at all times throughout a dynamic and unpredictable design development process.

Two scenarios exist where there is a requirement to derive an optimised schedule. Firstly, an optimised schedule must be created at the outset of the design development process prior to any tasks being completed. Secondly, during the design development process there may be a requirement to re-schedule in the event that the current schedule becomes inefficient due the detection of any significant deviations in resource monitored efficiency *(Interaction 23, page 105)* with regard to the current tasks being completed *(Interaction 24, page 105)*. That is, in the situation where completing the current schedule would take more time than the act of re-scheduling and enacting the revised schedule derived *(Interaction 27, page 107)*. However, prior to re-scheduling, in order to derive an optimised schedule, if appropriate, the resource model and task model may be revised *(Interactions 25 and 26, page 106)*.

In both scenarios, i.e. at the outset of the design development process or in the event of re-scheduling, the relevant resource and task knowledge is used with an appropriate optimisation algorithm such that an optimised schedule can be derived, as illustrated in Figure 8.7.

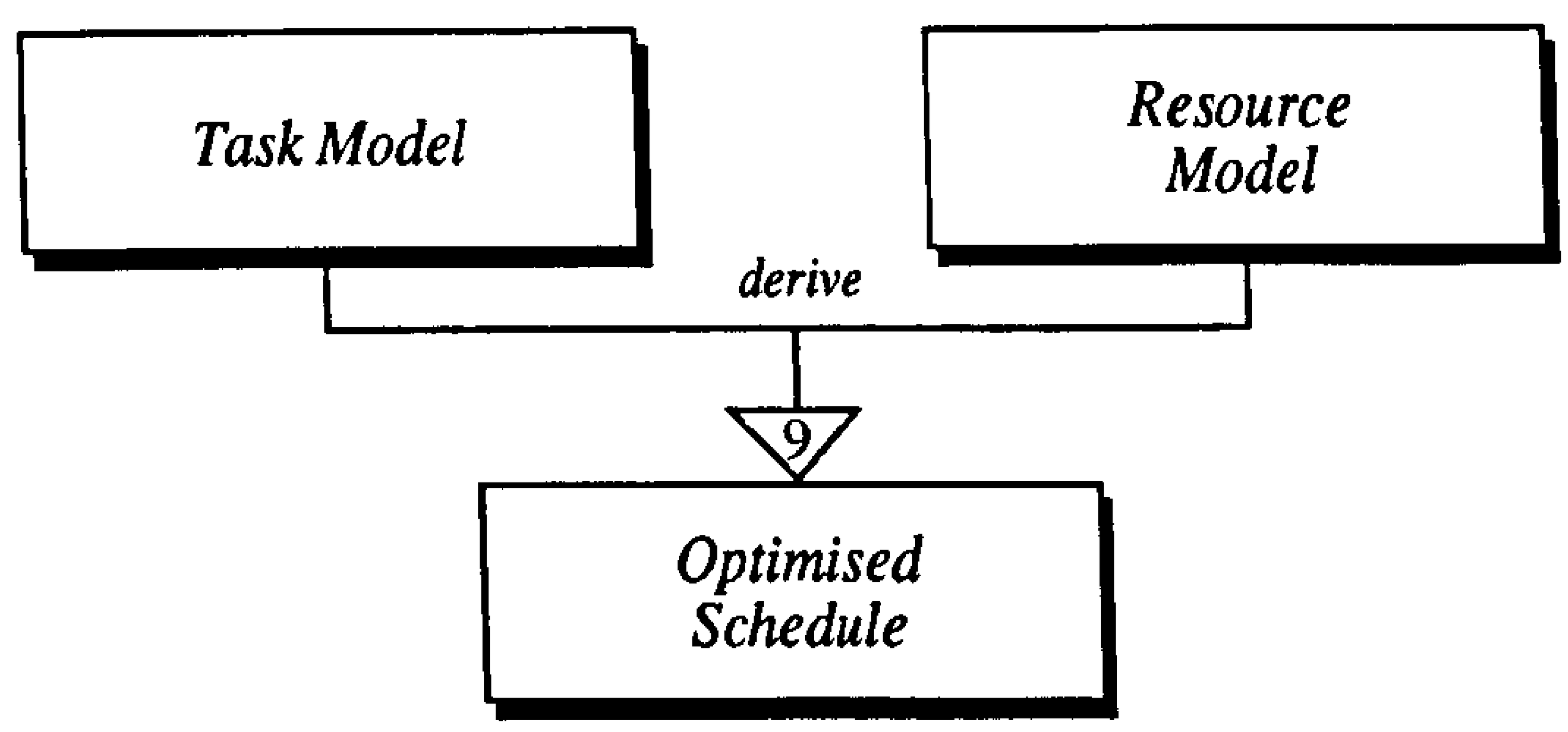

Figure 8.7 Deriving an Optimised Schedule

Tasks are selected for scheduling/re-scheduling only if T_{AC} indicates that they have not been completed, i.e. $T_{AC} < 100\%$ for pre-emptive tasks or $T_{AC}=0$ for non pre-emptive tasks. The knowledge of each task required for scheduling/re-scheduling comprises of T_G, T_{DD}, T_N, and $T_{[T_G]}$.

The total number of tasks to be scheduled, n_{TS}, and the total number of tasks that each task to be scheduled is dependent on, n_{TD}, are also needed, where:

$$n_{TD} = \sum_{i=1}^{n_{TS}} T_{N,i}$$

and $T_{N,i}$ is the number of tasks that the ith task is dependent on.

Only those resources available to be utilised are considered for scheduling/re-scheduling, i.e. those resources with $R_A = 1$. For each resource able to be utilised, R_I and R_{FE} for each task able to be completed using the resource are required. In addition, the number of resources available for consideration to be scheduled, n_{RAS}, is also required.

The result of using the optimisation algorithm with the relevant task and resource knowledge is the derivation of an order in which to complete tasks for each resource allocated to be utilised. For each scheduled task, identified by T_G, new knowledge is derived, i.e. start time, T_S, finish time, T_F, and estimated duration, T_{ED}.

The optimised schedule derived from the use of the optimisation algorithm, along with task and resource knowledge, satisfies the scheduling objective stated earlier.

<u>Construct Original/Revised Schedule Models</u> *(Interactions 10, 11 and 12)*

Original/revised schedule models are constructed by extracting derived knowledge from the optimised schedule *(Interaction 10)* and obtaining knowledge from the task model *(Interactions 11 and 12)*, as shown in Figure 8.8. In addition, new knowledge is assigned as tasks are added to their respective original/revised schedule model.

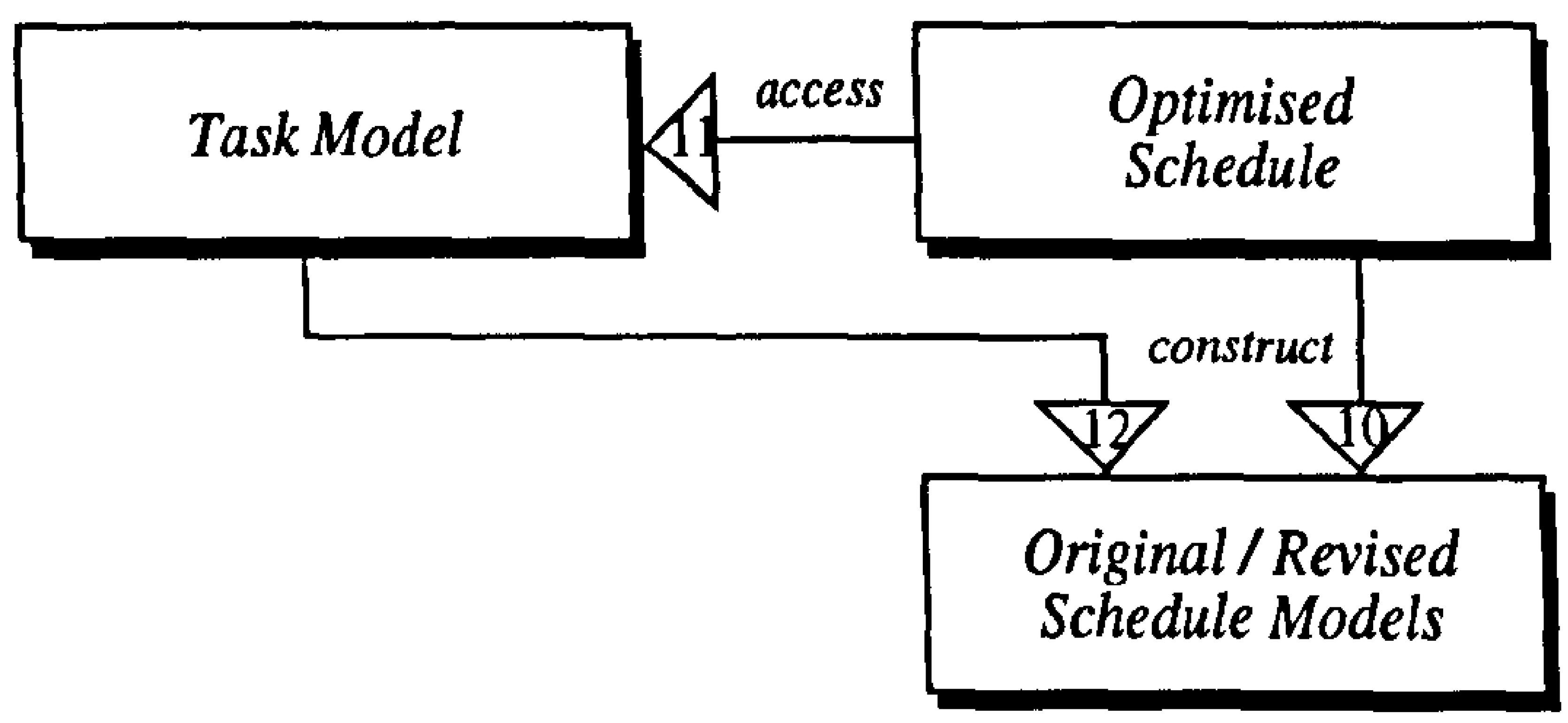

Figure 8.8 Construction of Original/Revised Schedule Models

An optimised schedule comprises knowledge of the tasks to be undertaken and completed for each resource to be utilised in the form of schedule knowledge. Once an optimised schedule has been derived, knowledge for inclusion within the original/revised schedule models is extracted such that each resource to be utilised can undertake and complete the assigned tasks in a co-ordinated manner. As an example, Figure 8.9 illustrates that the optimised schedule shown has knowledge of the tasks to be completed for each of the resource to be utilised, n_{RUS}.

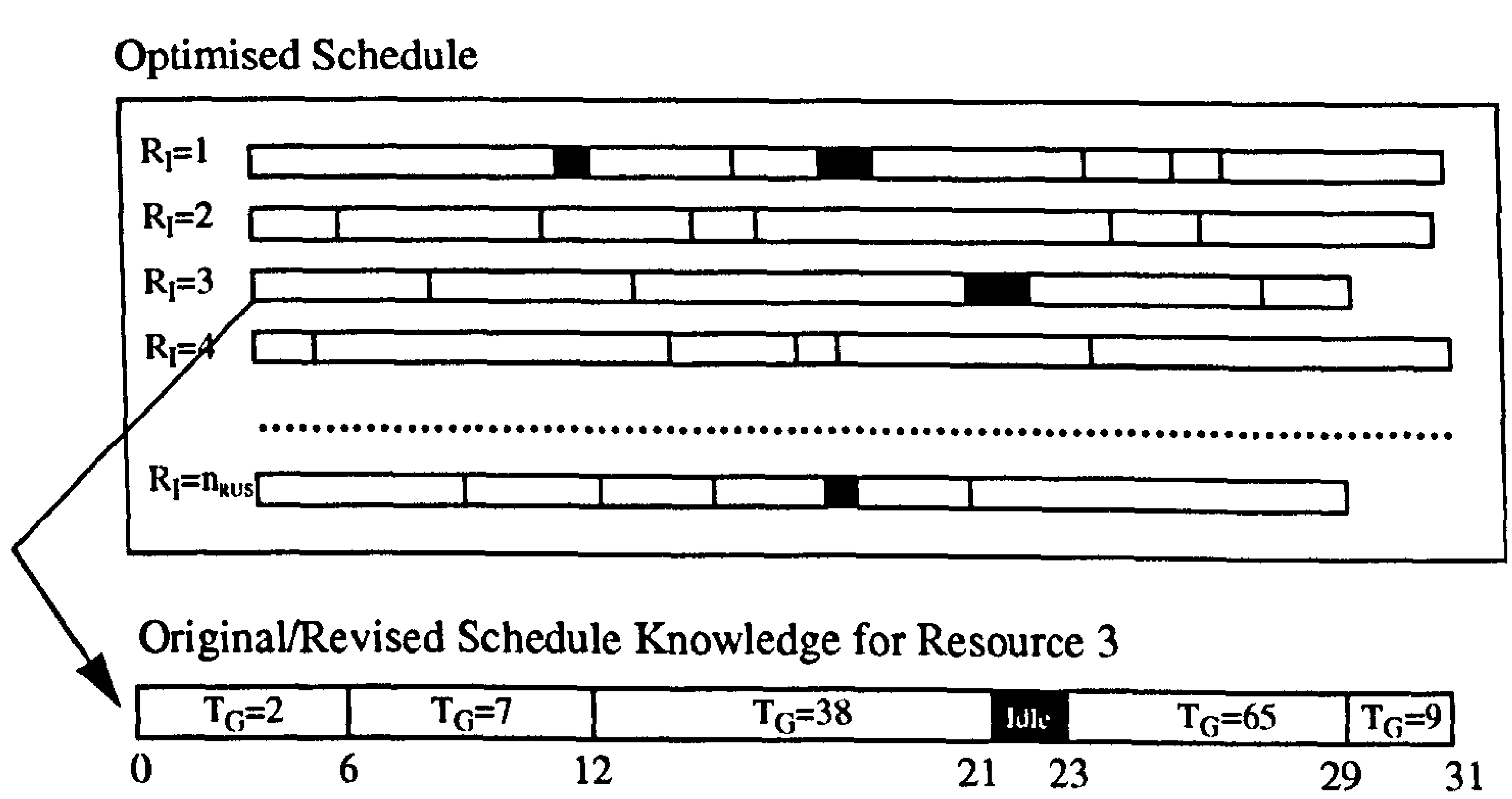

Figure 8.9 Extracting Schedule Knowledge from an Optimised Schedule

For example, resource R_I=3 has five tasks allocated for completion. The first task to be completed is that with T_G=2. The task is scheduled to commence at time T_S=0 and be completed at time T_F=6 with an estimated duration of T_{ED}=6 units of time. Similarly, the four remaining tasks to be completed are allocated T_S, T_F, and T_{ED}. In addition, resource R_I=3 has a period of idle time of 2 units between the third and fourth task scheduled to be completed.

Knowledge for inclusion in the original/revised schedule model is also obtained from the task model. For each scheduled task, using T_G, the task model is accessed to locate identification and dependency knowledge. Identification knowledge obtained for each scheduled task comprises T_I and T_L. Time knowledge obtained is T_{DD}. Dependency knowledge for each scheduled task is also obtained from the task model, i.e. $T_{[T_{In}]}$, $T_{[T_{Out}]}$, T_N, goal index of the tasks dependent on held within $T_{[T_I]}$, and local task identification index of the tasks dependent on held within $T_{[T_L]}$.

New progress knowledge is also assigned to each scheduled task within an original/revised schedule model, i.e. estimated completion measure, T_{EC}. Given a task's T_{ED}, the relationship with T_{EC} is specified by the designer. As an example, Figure 8.10 illustrates the relationship between the estimated duration and estimated completion measure.

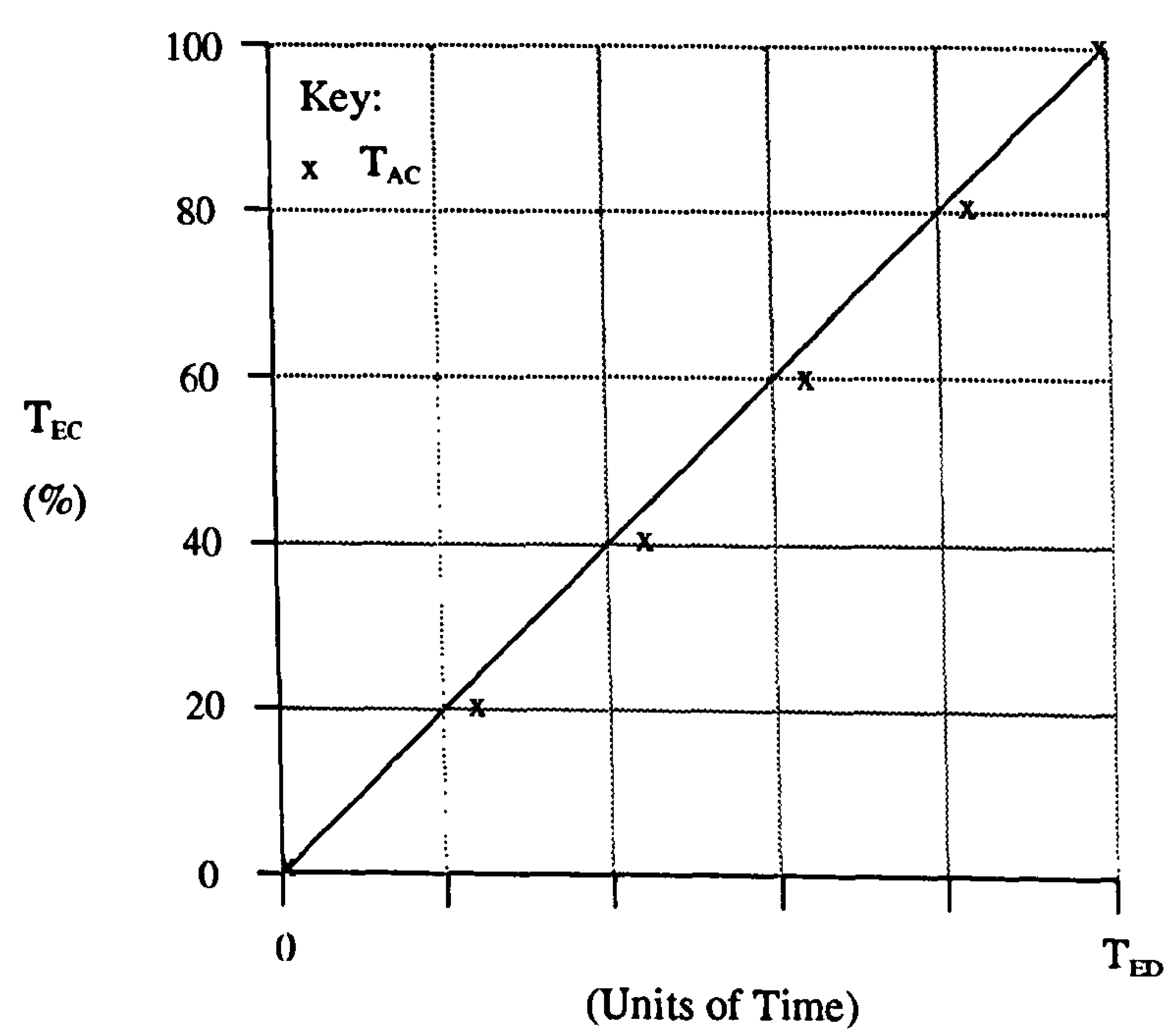

Figure 8.10 T_{EC} versus T_{ED}

The relationship between T_{EC} and T_{ED} is shown as linear, however, the designer may apply any relationship between them, such as a step or ramp. At appropriate junctures during the undertaking of a task, T_{AC} is established. Values of T_{AC} are monitored against T_{EC}, as shown in Figure 8.10, and can be used to determine deviations in a resource's monitored efficiency as described in *Interactions 23* and *24 (page 105)*.

<u>Check Dependencies, Direct and Undertake/Complete Tasks</u> *(Interactions 13, 14, 15 and 16)*

The process of checking dependencies, undertaking and completing tasks is illustrated in Figure 8.11.

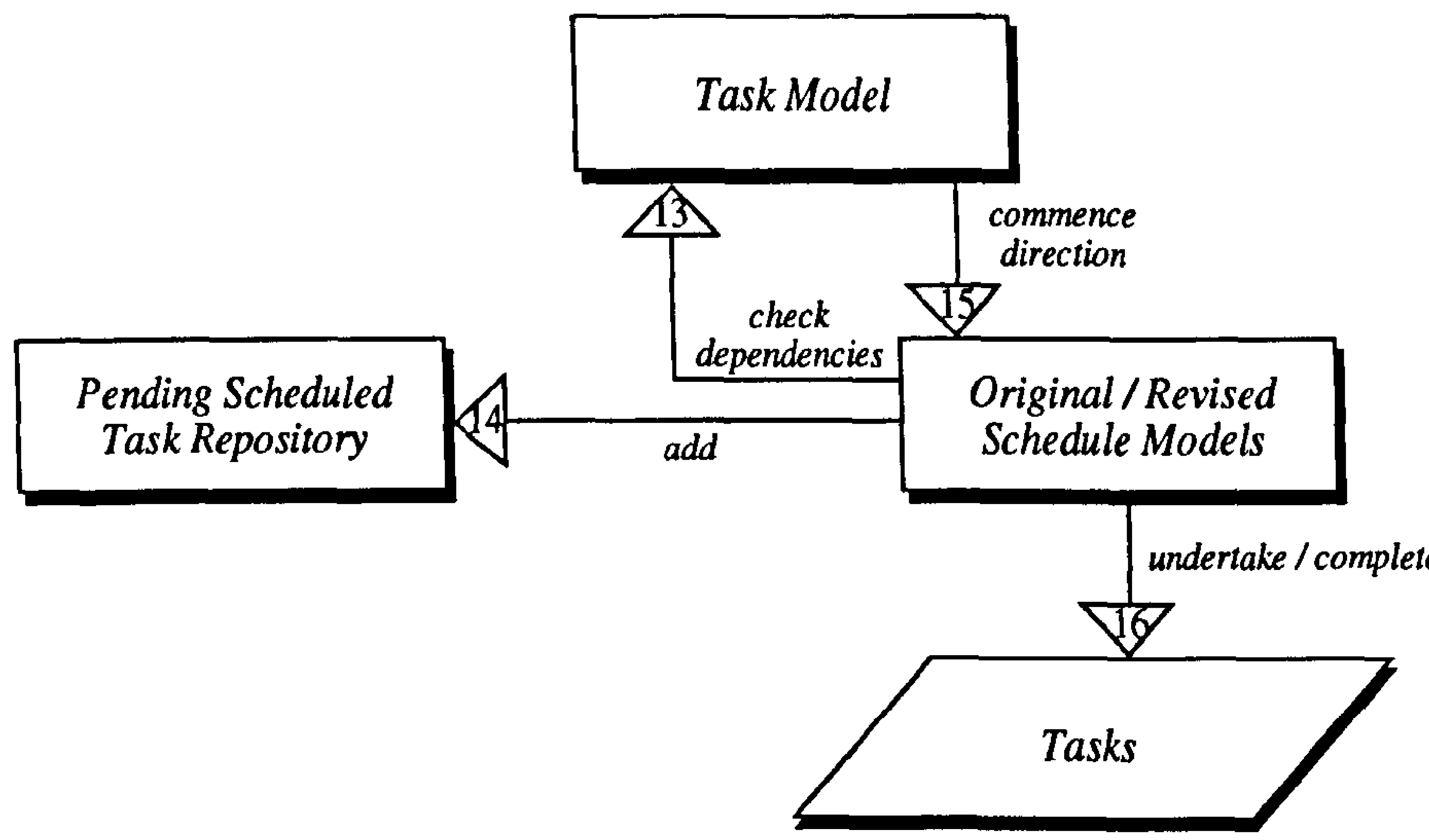

Figure 8.11 Checking Dependencies, Directing and Undertaking/Completing Tasks

Given a particular task to undertake utilising resource R_I in accordance with its associated original/revised schedule model, a check must be made regarding the status of any tasks which it is dependent on *(Interaction 13)*. That is, if a task can only be undertaken on the completion of other tasks then a check needs to be made to determine whether or not they have been completed. However, if a task is not dependent on any other tasks, then no check needs to be made and, thus, *Interactions 13, 14* and *15* can be omitted.

The method of performing a dependency check involves the associated original/revised schedule model and task model as illustrated in Figure 8.12.

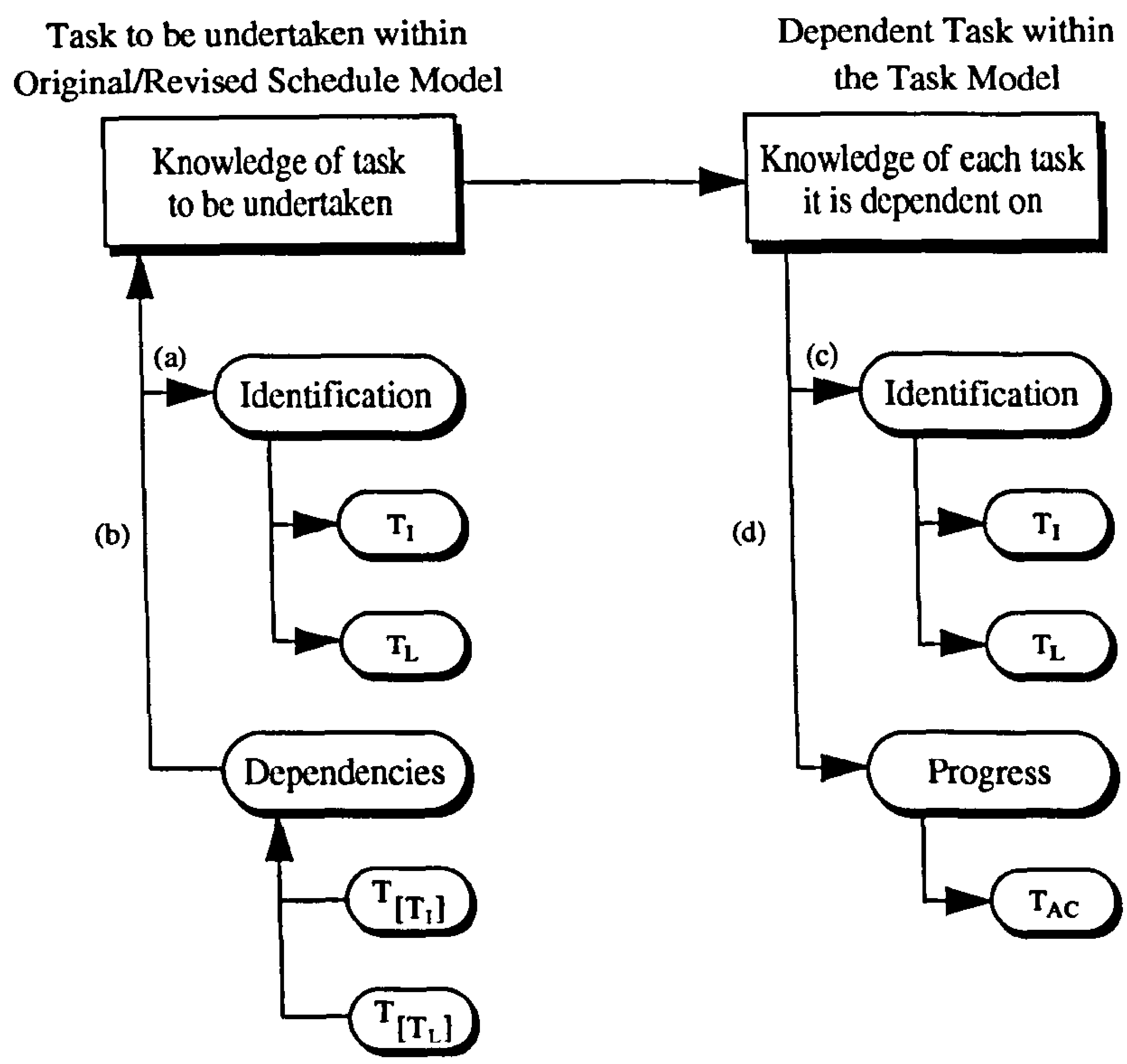

Figure 8.12 Task Dependency Checking

Step (a): In accordance with an original/revised schedule model, a task to be completed can be identified using T_I and T_L.

Step (b): Using T_I and T_L referred to in Step (a), knowledge of all tasks it is dependent on can be obtained from the original/revised schedule model, i.e. $T_{[T_I]}$ and $T_{[T_L]}$.

Step (c): With knowledge of dependent tasks from the original/revised schedule model, the task model can be accessed to locate corresponding knowledge of these tasks. Specifically, $T_{[T_I]}$ and $T_{[T_L]}$ of the task to be undertaken is compared against T_I and T_L of each task within the task model. Knowledge of the dependent tasks is located within the task model once the identification knowledge corresponds with that from the original/revised schedule model, i.e. corresponding elements of $T_{[T_I]}$ and $T_{[T_L]}$ from the original/revised schedule model are equivalent to T_I and T_L in the task model respectively.

Step (d): Given that all dependent tasks have been identified in the task model, T_{AC} is obtained. If T_{AC} of dependent tasks held within the task model indicates that they have been completed, then the task under consideration within the original/revised schedule model can commence *(Interactions 15 and 16)*.

The four-step method of dependency checking describes the scenario in which a task can commence since all the tasks it is dependent on have been completed. An objective of the optimisation algorithm is to order tasks to ensure this scenario by assigning their start and end times such that if the optimised schedule were strictly adhered to then all tasks would commence and be completed on time. Thus, this strict adherence would result in tasks never becoming pending due to tasks they are dependent on always being completed. However, this cannot be guaranteed due to unforeseen variability in the design development process, and thus the completion times of some tasks, and the domino effect of delaying the start time of subsequent tasks. In this event, knowledge of the task is added to the pending scheduled task repository as shown in Table 8.4 *(Interaction 14)*.

Task Identification		**Tasks Dependent on**		
$T_{I,1}$	$T_{L,1}$	$T_{ON,1}$	$[T_{I,1,j}]$	$[T_{L,1,j}]$
$T_{I,2}$	$T_{L,2}$	$T_{ON,2}$	$[T_{I,2,j}]$	$[T_{L,2,j}]$
.....	.....	.....	.....	.....
$T_{I,\,n_{PST}}$	$T_{L,\,n_{PST}}$	$T_{ON,\,n_{PST}}$	$[T_{I,\,n_{PST},\,j}]$	$[T_{L,\,n_{PST},\,j}]$

Table 8.4 Pending Scheduled Task Repository

With regard to Table 8.4, for each of the n_{PST} pending scheduled tasks, for example the ith task, the repository contains: $T_{I,i}$, $T_{L,i}$, $T_{ON,i}$, $T_{I,i,j}$, and $T_{L,i,j}$, where $j = \{1,2,...,T_{ON,i}\}$.

Specifically, $T_{I,i,j}$ is the goal identification index of the jth task that the ith pending task is dependent on, and $T_{L,i,j}$ is the local task identification index of the jth task that the ith pending task is dependent on, where $j = \{1,2,...,T_{ON,i}\}$.

$T_{ON,i}$ represents the number of outstanding tasks the ith pending scheduled task is dependent on rather than the number of tasks it is dependent on, $T_{N,i}$, since some of those dependent tasks may have already been completed.

Only on the completion of all outstanding dependent tasks, i.e. $T_{ON} = 0$, can a pending scheduled task commence. The process of removing outstanding dependent tasks and commencing the direction of pending scheduled tasks is described by *Interactions 21* and *22* *(page 104)*.

<u>Request, Provide and Supply Task Information</u> ***(Interactions 17, 18 and 19)***

Prior to a task being undertaken, information may need to be made available. The information required is specified by a task's $T_{[T_{In}]}$. All information needed at the outset of a task is stored in the task information repository. Thus, if a task requires information to be available before it can be undertaken, then this can be obtained from the task information repository. The relevant task information can always be obtained from the repository since tasks can only be undertaken once any tasks they are dependent on have been completed, as described in *Interaction 13, 14* and *15 (page 101)*. Once the relevant information is provided the task can commence.

The process of requesting, providing and supplying task information is shown in Figure 8.13.

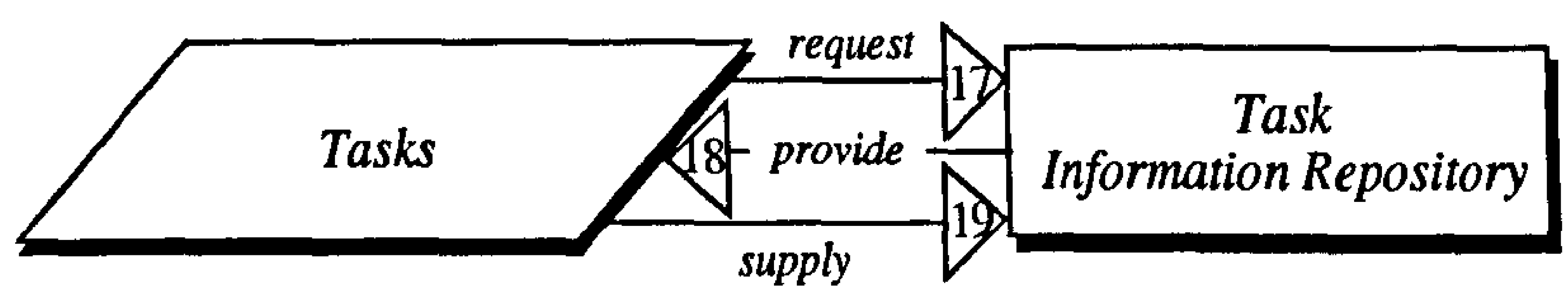

Figure 8.13 Requesting, Providing and Supplying Task Information

On completion of a task, information may be produced, which is specified by $T_{[T_{Out}]}$. Information produced is supplied to the task information repository such that any subsequent use of this information can be made. That is, the information output by one task may be required as input for another task.

<u>Update Task Model</u> ***(Interaction 20)***

Once any task is completed in accordance with its respective original/revised schedule model, the task model must be updated. That is, T_{AC} held within the task model, identified by T_I and T_L, must be set to 100% for pre-emptive tasks or 1 for non pre-emptive tasks. The accurate maintenance of T_{AC} within the task model enables task dependencies to be checked *(Interaction 13, page 101)* and ensures that only outstanding tasks are considered for re-scheduling *(Interaction 9, page 97)*.

<u>Remove Dependencies and Commence Direction of Pending Scheduled Tasks</u> ***(Interactions 21 and 22)***

The process of removing dependencies and commencing the direction of pending tasks is shown in Figure 8.14.

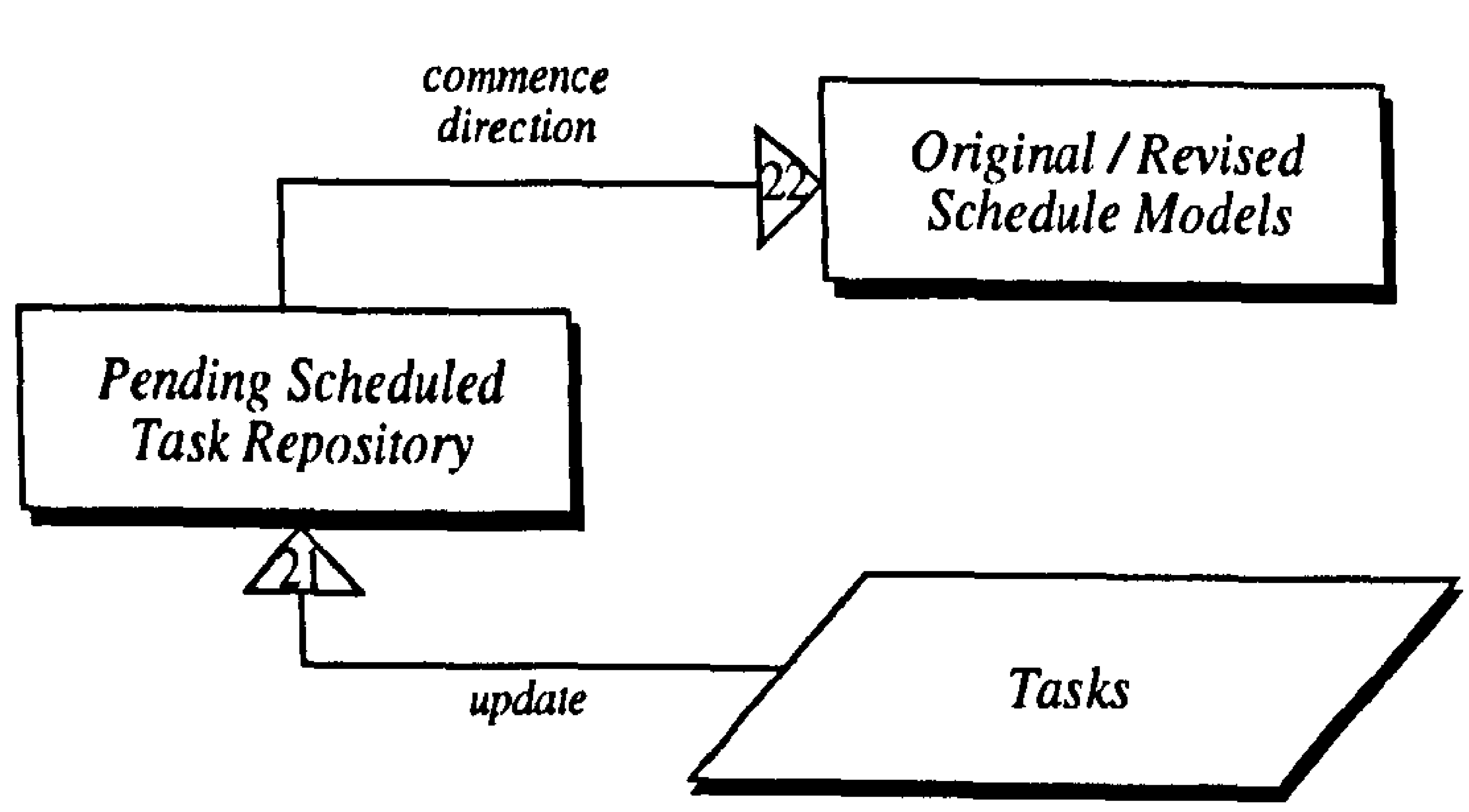

Figure 8.14 Removing Dependencies and Commencing Direction of Pending Tasks

On the completion of a task, in addition to updating the task model *(Interaction 20, page 104)*, the pending scheduled task repository is updated *(Interaction 21)*. That is, if a pending scheduled task is awaiting the completion of this task then knowledge of the dependency, i.e. T_I and T_L, are removed from the repository, and the number of outstanding tasks the pending scheduled task is dependent on, i.e. T_{ON}, is decremented. Furthermore, if as a result of a dependent task being completed $T_{ON} = 0$ then knowledge of the pending scheduled task is removed from the repository and the task is commenced *(Interaction 22)*. Otherwise, if $T_{ON} > 0$ then the task must remain pending.

<u>Monitor Resources and Schedule Models</u> *(Interactions 23 and 24)*

Monitoring facilitates the detection of deviations between R_{FE} and R_{ME} *(Interaction 23)*, which can be calculated using T_{EC} and T_{AC} *(Interaction 24)*. Deviations are considered significant if they exceed monitored efficiency thresholds specified by the designer. Each resource to be utilised is allocated R_{UT} and R_{LT} for each task it can undertake.

As mentioned in *Interaction 5 (page 91)*, R_{FE} can be initially based on T_{DD} and T_{ED}, i.e. $R_{FE}=T_{DD}/T_{ED}$, where T_{ED} is estimated by the designer or retrieved from the task/resource history repository. Monitoring resource performance efficiency ensures, if necessary, the appropriate revision of R_{FE} throughout the design development process.

For pre-emptive tasks, a series of monitored resource efficiencies can be calculated at various time intervals based on the existing R_{FE}, T_{EC} and T_{AC} of the task being completed. That is,

$$R_{ME_t} = R_{FE} \times \frac{T_{AC_t}}{T_{EC_t}}$$

where $t = \{1,2,\ldots,T_{ED}\}$, and T_{EC} and T_{AC} are obtained as described in *(Interaction 12, page 99)*.

As an example, Figure 8.15 illustrates the monitored efficiency of a resource recorded at equal interval time steps over a period to complete a task.

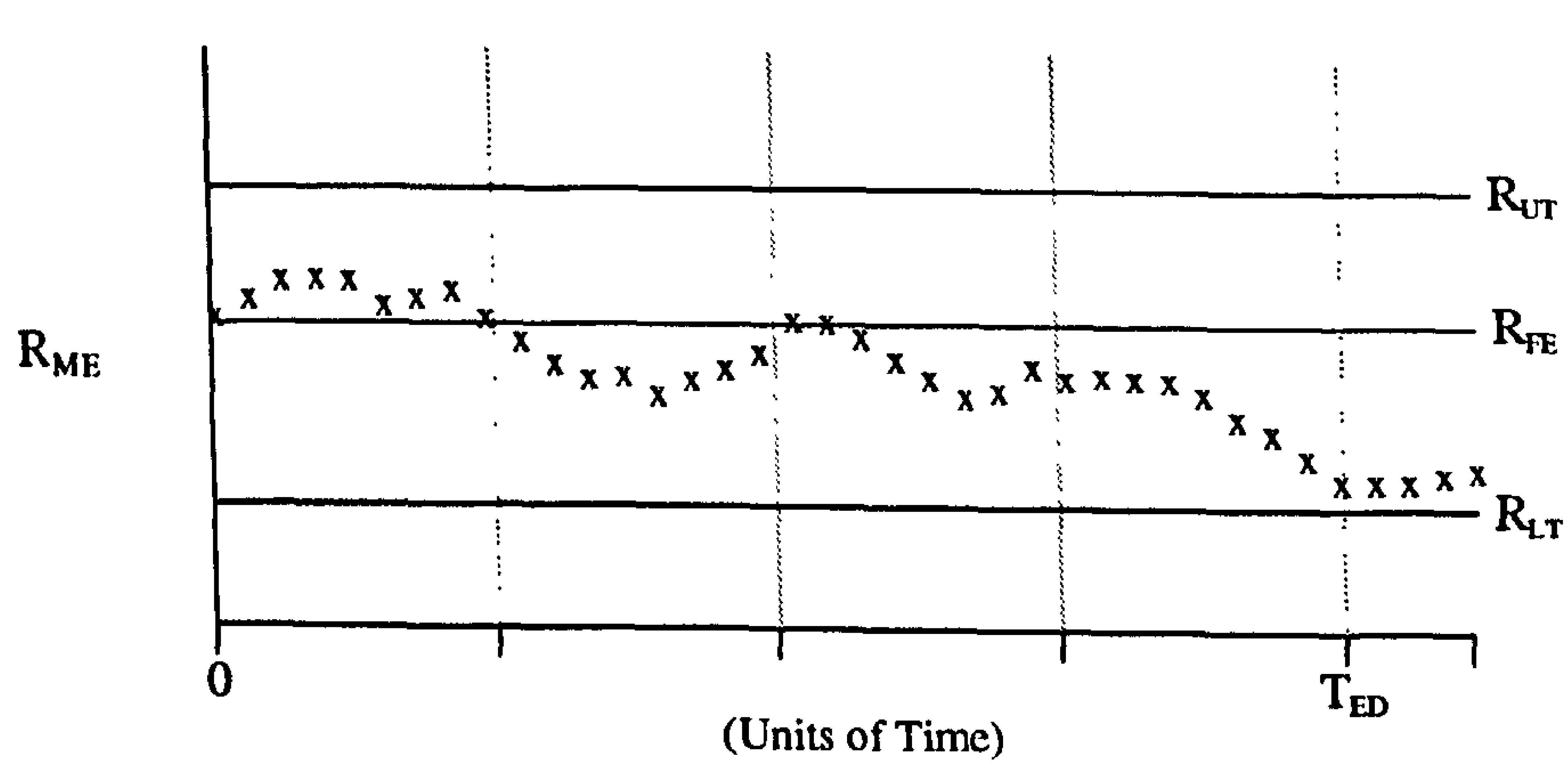

Figure 8.15 Monitoring Resource Efficiency

It is shown that the monitored efficiency fluctuates about the forecasted efficiency throughout the duration of the task, however, neither thresholds are exceeded leading to no requirement to consider re-scheduling. However, due to the monitored efficiency predominantly being lower than the forecasted efficiency, the duration to complete the task would be greater than estimated.

In situations where either monitored efficiency threshold was exceeded then re-scheduling would be considered, which would also lead to a revised forecasted efficiency as described in *Interactions* 25 and 26. That is, if $R_{ME_t} > R_{UT}$ then re-scheduling should be considered since the task will actually be completed in less time than estimated. Conversely, if $R_{ME_t} < R_{LT}$ then re-scheduling should be considered since the task will actually be completed in more time than estimated. Thus, as a result of either scenario, re-scheduling will be considered, as discussed in *Interaction 9 (page 97)*, to determine whether this course of action will result in more appropriate utilisation of resources with the aim of minimising the time to complete all outstanding tasks.

<u>Forecast and Revise Resource Model and Task Model</u> ***(Interactions 25 and 26)***

If at any time t, the R_{ME_t} of a resource exceeds either R_{UT} or R_{LT} for a particular task, a more appropriate value of R_{FE} must be established *(Interaction 25)*. In addition, values of R_{UT} and R_{LT} are revised to reflect the new threshold values for the resource, with respect to the task being undertaken, that when exceeded will cause re-scheduling to be considered again. Knowledge of a revised resource forecasted efficiency is included within the resource model such that in the event of re-scheduling, future resource allocation and utilisation can continue to be optimised with regard to the completion of outstanding tasks.

In order to determine a more appropriate forecasted efficiency for a resource, the designer may use judgement or a suitable forecasting technique. The designer's judgement can be viewed as an ad-hoc means of determining a forecasted efficiency, whereas a forecasting techniques can be thought of as a systematic means based on current and historical knowledge. That is, a suitable forecasting technique with a statistical time series would enable a prediction to be made based on monitored efficiency, which is itself based on actual and estimated task completion measures as described in *Interactions* 23 and 24 *(page 105)*.

While a forecasting technique and time series can only provide a revised forecasted efficiency, the designer may interpret the forecasted efficiency to be correct, and T_{DD} and T_{ED} of a task, identified by T_I and T_L, to have been incorrectly estimated. In this case the task datum duration knowledge within the task model will need to be revised according to the designer's judgement

(Interaction 26). The estimated duration of a task is calculated within the process of determining whether or not it can be included within an interim schedule model as described in *Interaction 27*.

Derive Interim Schedule Models *(Interaction 27)*

Given that the resource model has been revised to reflect the current forecasts of efficiency, and/or the task model has been revised to account for the change in datum duration of a task, along with the original/revised schedule model revised for the estimated duration, a decision is made regarding whether re-scheduling is appropriate.

If it is decided that re-scheduling is inappropriate then the original/revised schedule models continue to be administered. However, if re-scheduling is appropriate, then the composition of interim schedule models need to be derived, as shown in Figure 8.16.

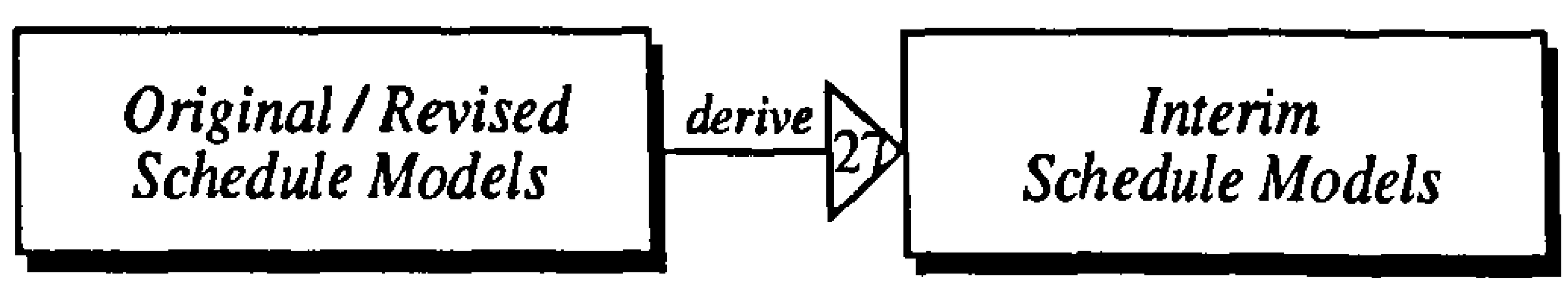

Figure 8.16 Derivation of Interim Schedule Models

The tasks included within the interim schedule models will be completed during the period of re-scheduling. Furthermore, selecting the appropriate tasks to complete during re-scheduling while the remainder are re-scheduled ensures the optimised utilisation of resources during this period. This is achieved by applying the three step procedure described in the explanation regarding determining an estimated time to derive a revised schedule.

The decision whether or not to re-schedule is made based on comparing the estimated time to (i) complete the current schedule, and (ii) derive and, subsequently, (iii) complete a revised schedule.

Estimated Time to Complete the Current Schedule

An estimate of the time taken to complete the current schedule, $\hat{T}_{CCS}$, is obtained by establishing the greatest estimated time to complete the existing original/revised schedule models. That is, for each resource, the datum duration of each outstanding task, within the original/revised schedule model, is divided by the recent forecasted efficiency. That is,

$$T_{ED,(R_i = i)} = \sum_{j=1}^{n_{OTCSM}} \frac{T_{DD}}{R_{FE}} \qquad i = \{1, 2, \ldots, n_R\}$$

where n_{OTCSM} is the number of outstanding tasks within the respective current schedule model, and n_R is the number of resources to be utilised.

The resource exhibiting the greatest estimated time to complete the outstanding tasks within its original/revised schedule model is defined as the estimated time to complete the current schedule. That is,

$$\hat{T}_{CCS} = \max\{T_{ED,(R_i = i)}\} \qquad i = \{1, 2, \ldots, n_R\}$$

Estimated Time to Derive a Revised Schedule

Prior to determining the estimated time to derive a revised schedule, $\hat{T}_{DRS}$, the optimum number of outstanding tasks to be re-scheduled must be calculated, n_{OTRS}. This is achieved by applying a three-step iterative procedure, which also establishes the tasks that can be included within an interim schedule model and, thus, completed while the optimum number of outstanding tasks are re-scheduled. Through optimising re-scheduling / task completion, resource idleness is minimised leading to the least delay between completing interim schedule models and commencing revised schedule models.

Step 1 - Based on the number of outstanding tasks at the point in time when re-scheduling is suggested for consideration, an estimate is made for the time to re-schedule. Known characteristics of the optimisation algorithm employed for scheduling may be used for this purpose. In addition to the number of outstanding tasks, knowledge of task durations and dependencies, and the number of resources available, and their forecasted efficiencies, will influence the duration of re-scheduling.

Step 2 - Using the associated original/revised schedule model for each resource, the number of outstanding tasks is determined that could be completed during the time to re-schedule, estimated in Step 1. Specifically, the identity and number of tasks that can be completed since (i) they are not dependent on any outstanding tasks, and (ii) the sum of their estimated duration is less than the estimated time to re-schedule. For each resource, based on their recent forecasted efficiency, the cumulative estimated duration to complete these tasks is calculated.

Step 3 - The cumulative number of outstanding tasks that could be completed by all resources determined in Step 2 is deducted from the total number of outstanding tasks originally considered for re-scheduling in Step 1.

If the cumulative number of outstanding tasks that could be completed during the estimated time to re-schedule is greater than zero, then Step 1 is repeated such that a time estimate can be obtained to re-schedule the number of tasks calculated in Step 3. The repetition of Step 1 is necessitated since a proportion of the tasks considered to be re-scheduled will be completed during this period. Thus, the time to re-schedule will, in fact, be less than that calculated since not all of the tasks originally considered will be re-scheduled. Step 2 and 3 are then also repeated. Otherwise, the estimated time to re-schedule the number of outstanding tasks originally considered in Step 1 is defined as that to derive a revised schedule. A drawback of not being able to concurrently undertake and complete tasks and re-schedule is that all resources remain idle during this period.

The procedure described is re-iterated until the sum of the number of tasks to be re-scheduled (Step 1) and the number of tasks able to be completed during re-scheduling (Step 3) is equal to the original number of outstanding tasks to be re-scheduled (first iteration of Step 1). That is, the appropriate division of outstanding tasks to be (i) re-scheduled, and (ii) completed during re-scheduling, has been achieved. Consequently, the idleness of resources is minimised between successive schedule models. On satisfying this condition, the estimated time to re-schedule the number of tasks is defined as the time to derive a revised schedule.

Estimated Time to Complete a Revised Schedule

Unlike determining an estimate of the time taken to complete the current schedule, an estimated completion time for a revised schedule, $\hat{T}_{CRS}$, must be obtained without using a schedule. This is achieved by determining the critical path of the outstanding tasks to be re-scheduled while considering the number of resources available and their forecasted efficiencies.

A three-step iterative procedure is used to determine the critical path and, thus, an estimate of the time to complete a revised schedule.

Step 1 - Based on the dependencies between the outstanding tasks to be re-scheduled, arrange tasks within groups such that the groups must be completed sequentially, however, tasks within groups may be completed in parallel.

Step 2 - Within the first, or next, group of tasks, order tasks in descending order with regard to datum duration.

Step 3 - Assign the first task within the first group to the resource with the greatest forecasted efficiency. Subsequently, assign the next task to the resource, which will result in the minimum estimated time to complete the assigned tasks. Continue assigning tasks to resources in this manner until all tasks have been assigned.

Steps 2 and 3 are repeated until all groups identified in Step 1 have been assigned to the appropriate resources. Thus, the estimated time to complete a revised schedule is defined as that of the resource with the greatest duration to complete the assigned tasks.

Decision to Re-Schedule

The decision is made to re-schedule if the estimated time to complete the current schedule is greater than the estimated time to derive and, subsequently, complete a revised schedule, i.e. re-scheduling is performed if:

$$\hat{T}_{CCS} > \hat{T}_{DRS} + \hat{T}_{CRS}$$

Otherwise, re-scheduling is inappropriate.

If the decision is made to re-schedule, then the tasks identified in the last iteration of Step 2 of the procedure to estimate the derivation of a revised schedule are included within the interim schedule model of the respective resources. That is, those tasks that can be completed concurrently with re-scheduling. As tasks are included in an interim schedule model, certain knowledge is mapped directly from the corresponding original/revised schedule model. Specifically, T_I, T_L, $T_{[T_{In}]}$ and $T_{[T_{Out}]}$. T_S and T_F are re-assigned according to T_{ED}, and that of preceding tasks already included in the interim schedule model.

Modify Task Model *(Interaction 28)*

Once the interim schedule models have been derived, not only can the overlapped tasks be undertaken, but also knowledge within the task model can be modified in preparation for re-scheduling.

Modifications to the task model involve changing T_{AC} of those tasks that will be completed in accordance with the interim schedule models during re-scheduling. That is, T_{AC} of these tasks held within the task model is modified to indicate that they cannot be considered for re-scheduling since they will in fact be completed during this period.

Other modifications to the task model involve changing the global identification numbers of outstanding (i) tasks, and (ii) dependent tasks.

The outstanding task with the lowest value of T_G is set to zero or one, depending on the designer's preference. The task with the next lowest value of T_G is set to one greater than that for the previous task, and so on. If T_G of an outstanding task is changed, then if the task is depended on by other tasks then their corresponding $T_{[T_G]}$ is also changed. This ensures that task dependency knowledge is maintained for all outstanding tasks within the task model. In addition, dependency knowledge is removed from the task model for any tasks that have been completed according to the original/revised schedule model or will be completed according to the interim schedule model, as indicated by T_{AC}, and are depended on by any outstanding tasks. Consequently, T_N is also altered to reflect how many of them remain outstanding.

As a result of this modification, the new task knowledge contained within the task model along with the resource knowledge held in the resource model can be used with a suitable optimisation algorithm to determine an optimised schedule as described in *Interaction 9 (page 97)*.

<u>Undertake and Complete Overlapped Tasks</u> ***(Interaction 29)***

While re-scheduling occurs, the interim schedule models are enacted such that the overlapped tasks can be undertaken and completed as shown in Figure 8.17.

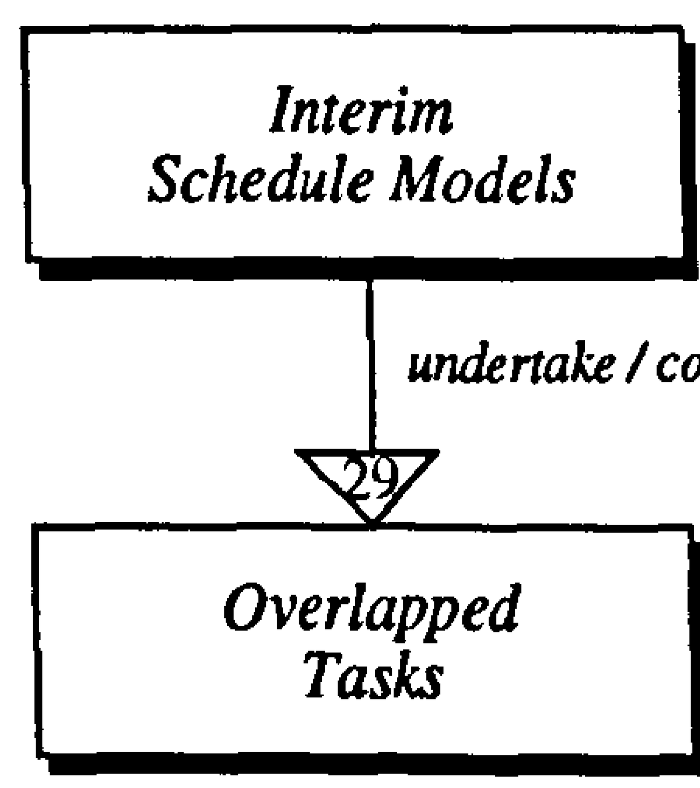

Figure 8.17 Undertaking and Completing Overlapped Tasks

Due to the fact that interim schedule models only comprise outstanding tasks with all, if any, tasks which they are dependent on being completed, there is no requirement for *Interactions 13, 14* and *15 (page 101)*.

<u>Request, Provide and Supply Task Information</u> ***(Interactions 30, 31 and 32)***

As described for tasks being completed in accordance with their associated original/revised schedule model, information may be requested *(Interaction 30)* and provided *(Interaction 31)* prior to overlapped tasks being completed during a period of re-scheduling, and on completion supplied *(Interaction 32)* to the task information repository. These interactions are as described in *Interactions 17, 18* and *19 (page 103)*.

<u>Summary of Operation</u> ***(Interactions 9 to 32)***

The operation stage of the real-time operational design co-ordination part of the methodology, involving *Interactions 9* to *32*, is illustrated in Figure 8.18.

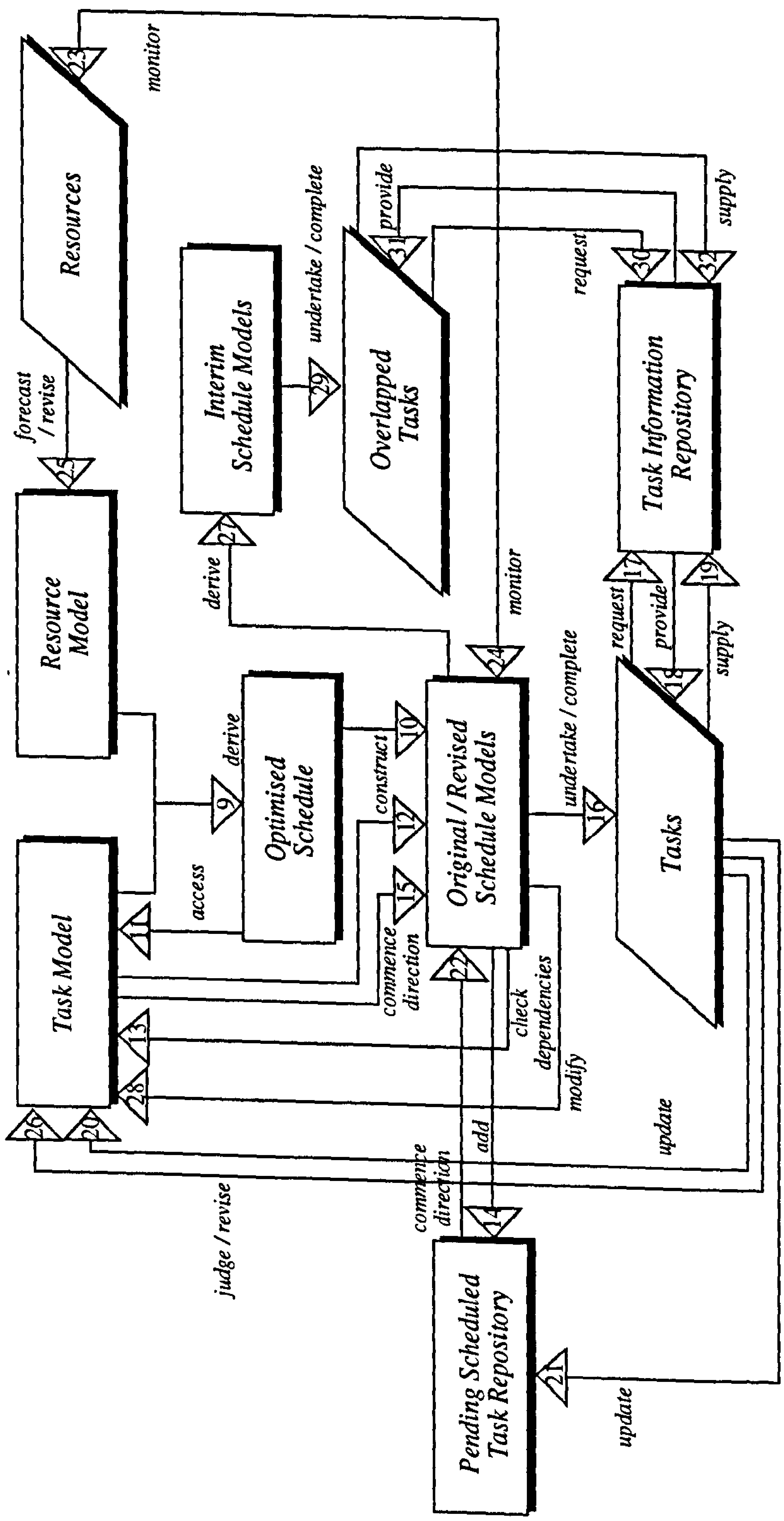

Figure 8.18 Real-Time Operational Design Co-ordination - Operation

Table 8.5 summarises the involvement of modelled knowledge in the interactions shown in Figure 8.18.

Interaction	Knowledge Modelled	
	Task / Scheduled Task	Resource
9	$T_{AC}, T_G, T_{DD}, T_N, T_{[T_G]}, T_S, T_P, T_{ED}$	$R_A, R_I, R_{[R_{FE}]}$
10	T_G, T_S, T_P, T_{ED}	R_I
11	T_G	n/a
12	$T_I, T_L, T_G, T_{DD}, T_N, T_{[T_I]}, T_{[T_L]}, T_{AC}, T_{EC}, T_{[T_{In}]}, T_{[T_{Out}]}$	n/a
13	$T_I, T_L, T_{AC}, T_{[T_I]}, T_{[T_L]}$	R_I
14	T_I, T_L	n/a
15	T_I, T_L, T_{AC}	R_I
16	T_I, T_L	R_I
17	$T_I, T_L, T_{[T_{In}]}$	R_I
18	$T_I, T_L, T_{[T_{In}]}$	R_I
19	$T_I, T_L, T_{[T_{Out}]}$	R_I
20	T_I, T_L, T_{AC}	R_I
21	T_I, T_L	R_I
22	T_I, T_L	R_I
23	n/a	$R_I, R_{FE}, R_{ME}, R_{UT}, R_{LT}$
24	T_{AC}, T_{EC}	R_I
25	n/a	$R_I, R_{FE}, R_{\{ME_i\}}, R_{UT}, R_{LT}$
26	T_I, T_L, T_{DD}, T_{ED}	n/a
27	$T_I, T_L, T_S, T_P, T_{ED}, T_{DD}, T_{[T_{In}]}, T_{[T_{Out}]}$	$R_I, R_{[R_{FE}]}$
28	$T_G, T_{AC}, T_N, T_{[T_G]}$	n/a
29	T_I, T_L	R_I
30	$T_I, T_L, T_{[T_{In}]}$	R_I
31	$T_I, T_L, T_{[T_{In}]}$	R_I
32	$T_I, T_L, T_{[T_{Out}]}$	R_I

Table 8.5 Summary of Involvement of Modelled Knowledge

8.2 Prospective Operational Design Co-ordination

Prospective operational design co-ordination enables deficiencies in the resources used within the derived optimised schedule to be identified and, consequently, the proposal and assessment of a variety of designer specified improvements to the resources. Deficiencies are identified as those where the lack of resource efficiency contributes to increasing the time taken and/or associated cost to complete the scheduled tasks. Designer specified improvements are measured improvements to the resources that would enable reductions in estimated time and/ or cost of enacting the schedule.

The prospective operational design co-ordination aspect of the methodology, involves *Interactions 33* to *37*.

<u>Identify Deficiencies in the Optimised Schedule and Propose Support in the form of Simulated Resource Models</u> *(Interaction 33)*

Within real-time operational design co-ordination, each optimised schedule derived is enacted to facilitate the timely and appropriate completion of tasks within the design development process. In parallel to the actual completion of tasks, deficiencies within the optimised schedule need to be identified and support proposed in order to overcome them. Figure 8.19 illustrates that as a result of identifying deficiencies in the optimised schedule a set of simulated resource models is proposed.

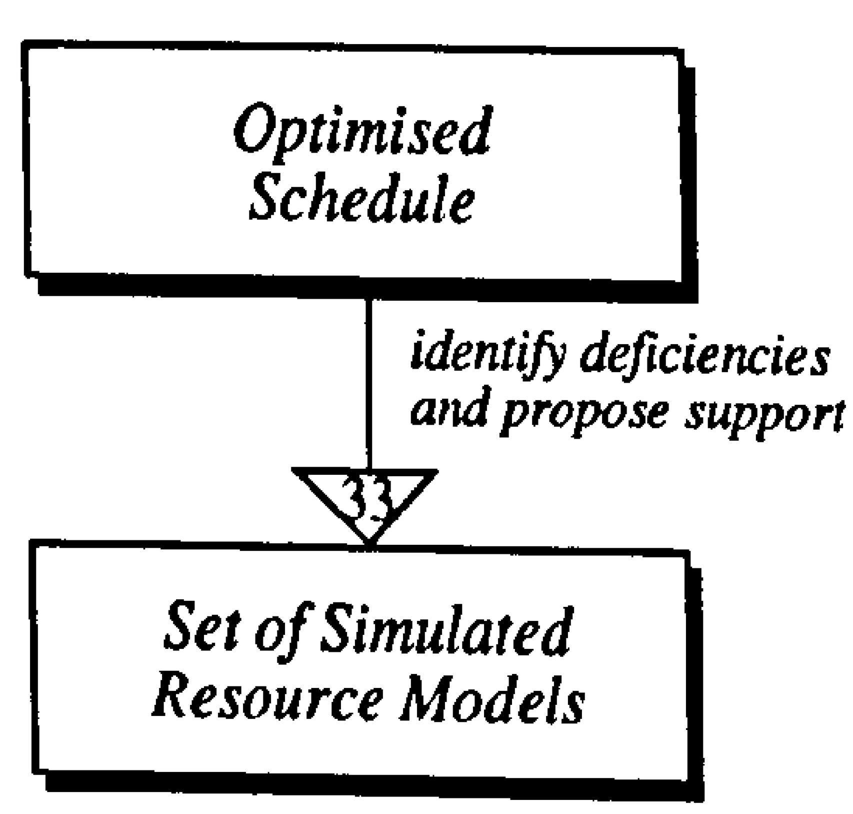

Figure 8.19 Identifying Deficiencies and Proposing Support

That is, measured changes can be suggested to improve the resources leading to reductions in the time and cost of completing scheduled tasks.

Figure 8.20 depicts an optimised schedule example, which is based on 20 tasks to be completed utilising 6 resources.

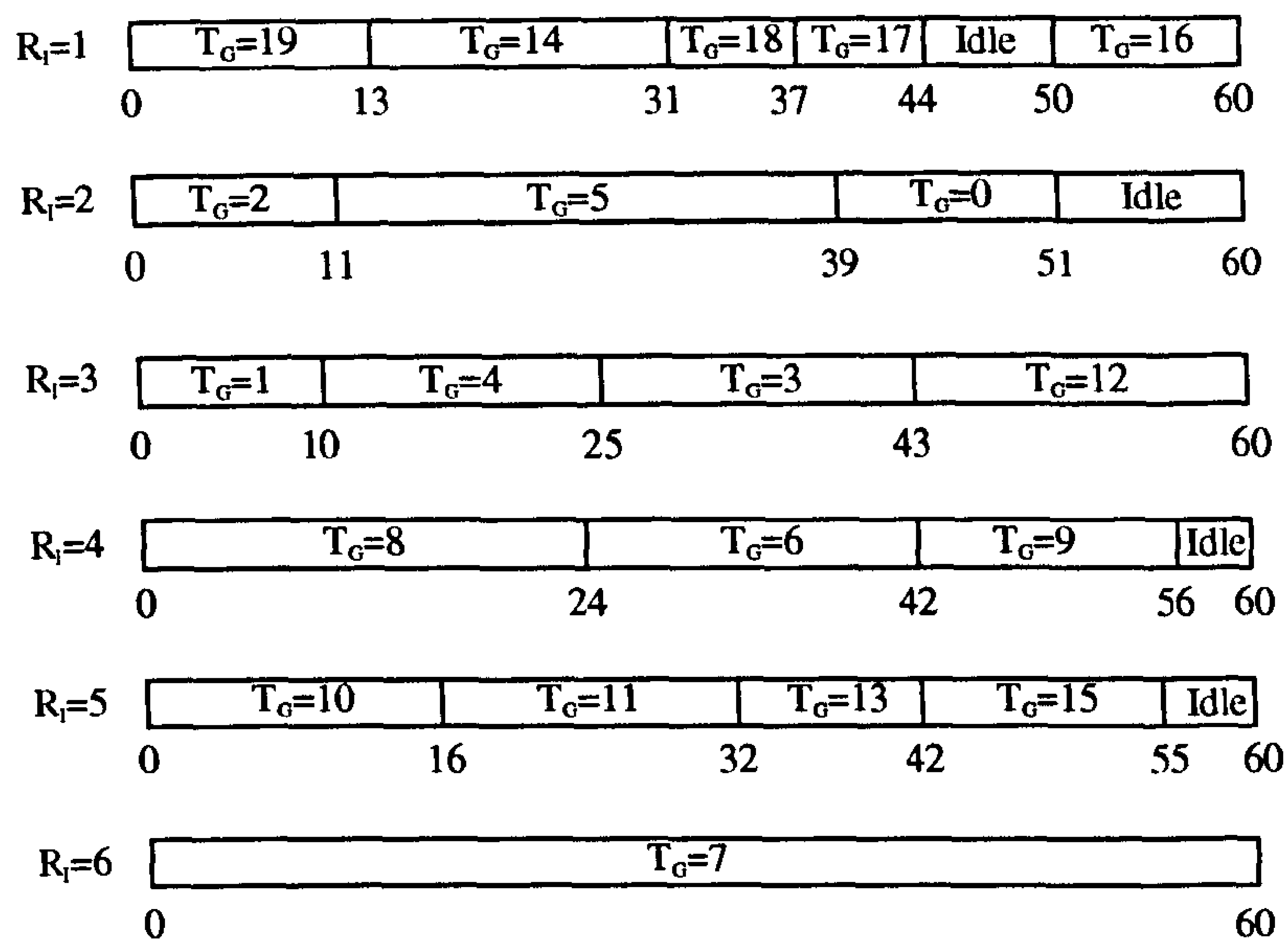

Figure 8.20 An Optimised Schedule Example

With regard to the optimised schedule, the tasks would be allocated to the resources based on the optimisation algorithm used, and the task and resource knowledge represented in Table 8.6 and 8.7 respectively.

T_G	T_I	T_L	T_{DD}	T_{ED}	T_G	T_I	T_L	T_{DD}	T_{ED}
0	0	0	11	12	10	2	0	11	16
1	0	1	8	10	11	2	1	11	16
2	0	2	10	11	12	2	2	5	17
3	0	3	14	18	13	2	3	7	10
4	0	4	12	15	14	2	4	7	18
5	1	0	11	28	15	2	5	9	13
6	1	1	9	18	16	3	0	9	10
7	1	2	12	60	17	3	1	6	7
8	1	3	12	24	18	3	2	5	6
9	1	4	7	14	19	3	3	12	13

Table 8.6 Task Knowledge

For the purpose of this example, values of T_{ED} have been rounded to the nearest integer.

	T_I=0	T_I=1	T_I=2	T_I=3
R_I=1	0	0.1	0.4	0.9
R_I=2	0.9	0.4	0	0
R_I=3	0.8	0	0.3	0.2
R_I=4	0	0.5	0	0
R_I=5	0.3	0	0.7	0
R_I=6	0.2	0.2	0	0.6

Table 8.7 Resource Forecasted Efficiencies

In Table 8.7, R_{FE} of each resource is stated with respect to each goal T_I, which is associated with particular tasks. Shaded cells highlight the non-zero values of R_{FE}.

Deficiencies in terms of the resources allocated in the optimised schedule are identified by:

- dividing the datum duration of each task by the forecasted efficiency of the resource to which it has been assigned that corresponds to the associated goal,
- sum the resulting estimated durations of tasks associated with the same goal, and,
- obtain a ratio for each goal by dividing the sum of estimated durations of its associated tasks by the cumulative efficiency of the resources allocated to these tasks.

Ratios with the greatest value indicate where there is the greatest requirement for improvements within the resources with respect to the tasks to be completed. Table 8.8 represents the results of these calculations for the sum of estimated durations and sum of forecasted efficiencies used within the optimised schedule shown in Figure 8.20.

		T_I=0	T_I=1	T_I=2	T_I=3
(a)	ΣR_{FE}	2.2	1.2	1.4	1.7
(b)	ΣT_{ED}	66	144	90	36
	ΣR_{FE}	1.7	1.1	1.4	0.9
	$\Sigma T_{ED}/\Sigma R_{FE}$	39	131	64	40

Table 8.8 Identifying Deficiencies within Resources in the Optimised Schedule

In Table 8.8(a), the cumulative forecasted efficiencies of resources able to complete associated tasks with each goal are shown.

In Table 8.8(b), it can be seen that resources able to complete tasks associated with goal $T_I=1$ are significantly inadequate with respect to the others, i.e. $\Sigma T_{ED}/\Sigma R_{FE}$ = 131, despite having 92% (1.1/1.2) deployment. This contrasts with the resources used to complete tasks associated with goal $T_I=0$, where $\Sigma T_{ED}/\Sigma R_{FE}$ = 39, with only 77% (1.7/2.2) deployment. Thus, it is concluded that support would be proposed in improving the resource efficiencies able to complete tasks associated with goal $T_I=1$, i.e. $T_G=5$ through to $T_G=9$.

Improvements, i.e. reducing the necessary $\Sigma T_{ED}/\Sigma R_{FE}$ ratio, can be achieved by either recruiting new resources or developing existing resources. Recruitment focuses on introducing new resources with the appropriate forecasted efficiency. Development is aimed at improving the forecasted efficiency of existing resources by, say, training. Each individual improvement to the resources, i.e. increase in cumulative forecasted efficiency, is represented within a unique simulated resource model that can be assessed after being used to create an optimised schedule.

<u>Construct a Simulated Task Model</u> *(Interaction 34)*

The simulated task model replicates the actual task model. That is, the simulated task model is a representation of those tasks that were considered for re-scheduling in the design development process. The reason for constructing a simulated task model is that the actual task model is used and constantly updated during the real-time operational design co-ordination of the design development process. That is, constructing a simulated task model enables the prospective operational design co-ordination component to be non-intrusive to the real-time co-ordinated progression of the design development process.

<u>Derive Off-Line Optimised Schedules</u> *(Interaction 35)*

Similar to *Interaction 9 (page 97)*, knowledge contained within the simulated task model and each of the simulated resource models, and a suitable optimisation algorithm are used in order to derive off-line optimised schedules, as shown in Figure 8.21.

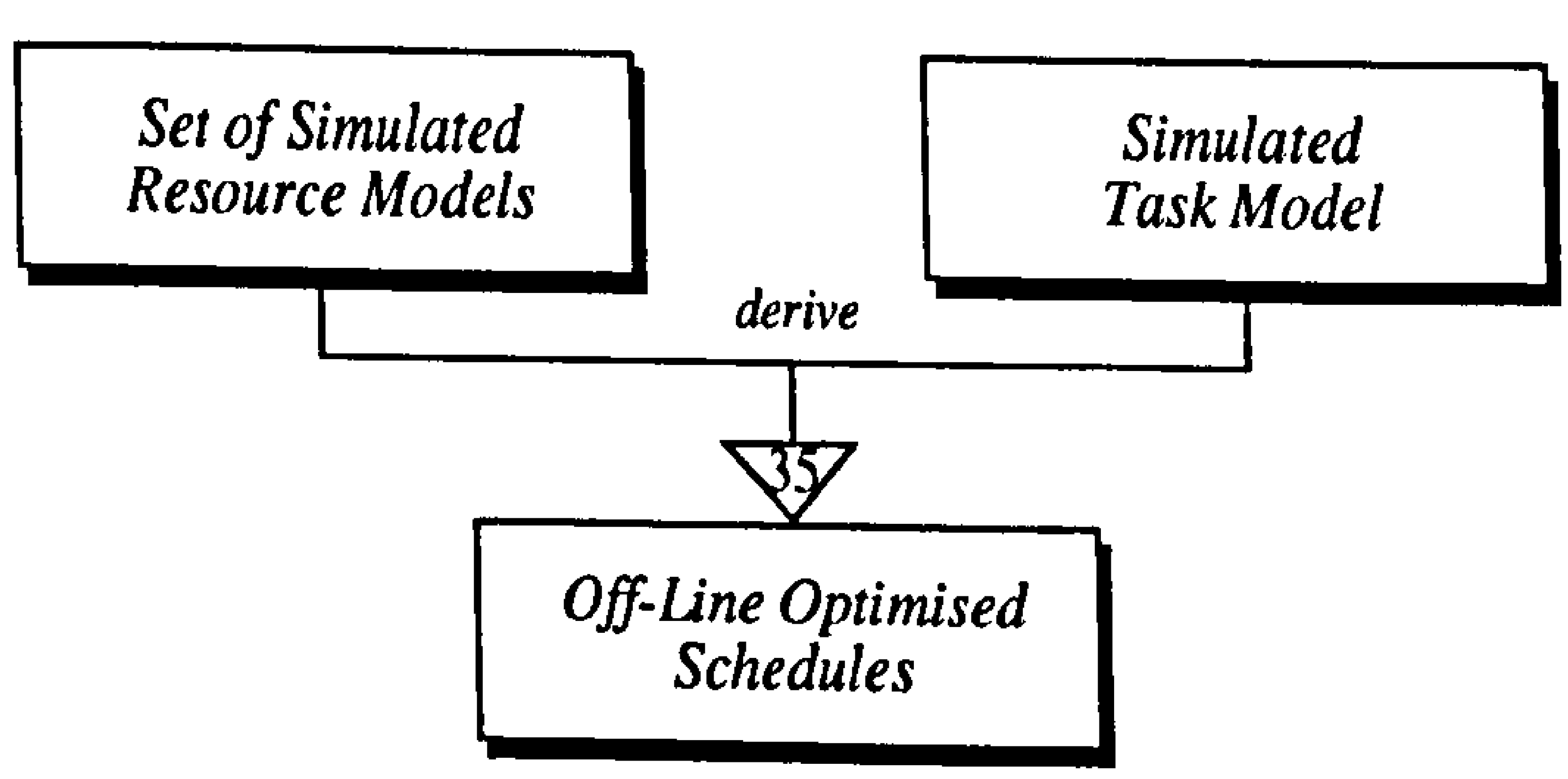

Figure 8.21 Derivation of Off-Line Optimised Schedules

The optimised schedules are termed *off-line* since they are not enacted but rather used to assess the associated time and cost if they were enacted.

<u>Assess Proposed Support and Record in Schedule Evaluation Repository</u> ***(Interaction 36)***

Once off-line optimised schedules have been derived they are assessed in terms of time and cost to complete.

The estimated time, T, to complete the scheduled tasks can be obtained from the optimised schedule. For example, the time to complete the optimised schedule illustrated in Figure 8.20 *(page 115)* is 60 units of time, i.e. T = 60.

The cost, C, to complete the scheduled tasks is established using knowledge of the resources to be utilised in accordance with the optimised schedule. That is, for the schedule of tasks utilising a particular resource, the cost is calculated as the product of the cost of utilising the resource per unit time, R_C, and the cumulative time the resource is estimated to be utilised, ΣT_{ED}:

$$C_{R_I} = R_C \times \Sigma T_{ED}$$

Thus, the cost, C, to complete all of the scheduled tasks is:

$$C = \sum_{i=1}^{n_R} C_{R_{I,i}}$$

where n_R is the number of resource allocated to be utilised within the optimised schedule.

For example, considering the six resources allocated to be utilised according to the optimised schedule illustrated in Figure 8.20, the cost of utilising each resource per unit time could be as shown in Table 8.9.

R_I	R_C	ΣT_{ED}	C_{R_I}
1	12	54	648
2	11	51	561
3	11	60	660
4	4	56	224
5	9	55	495
6	9	60	540
			C = 3128

Table 8.9 Cost Assessment of Resource Utilisation in the Optimised Schedule

A record of the time and cost of the schedule, corresponding to each simulated resource model, is stored within the schedule evaluation repository. An example trade-off between estimated time and cost to complete a schedule is shown in Figure 8.22, where $R^{(n)}$ represents the time and cost of the nth derived off-line optimised schedule based on the nth simulated resource model.

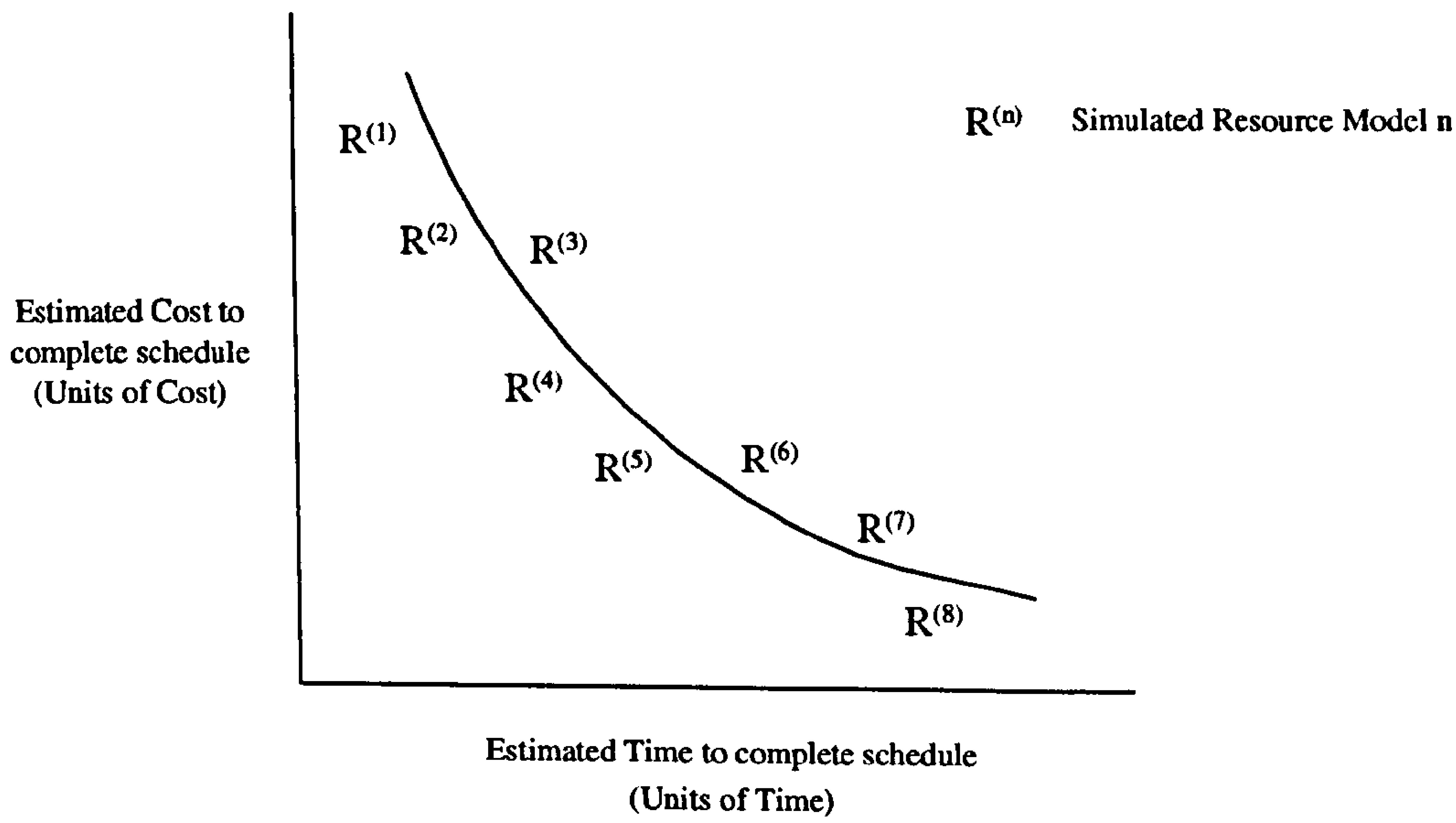

Figure 8.22 Example Trade-off between Estimated Time and Cost to Complete a Schedule

<u>Identify the Existence of any Deficiencies in the Optimised Schedule Resulting from the Proposed Support, and, if appropriate, Propose Support in the form of Further Simulated Resource Models then repeat Interactions 35, 36 and 37</u> *(Interaction 37)*

As discussed in Interaction 33, any existing deficiencies are identified in the resources used to derive the off-line optimised schedules (*Interaction 35*) and assessed (*Interaction 36*). Based on whether any deficiencies still exist, as described in *Interaction 33*, a decision is made regarding whether or not the resources need to be improved further and, if so, how to best improve them. *Interactions 35, 36* and *37* are repeated for each further set of simulated resource models proposed until no deficiencies are deemed to exist.

<u>Summary of Prospective Operational Design Co-ordination</u> *(Interactions 33 to 37)*

The prospective operational design co-ordination part of the methodology is illustrated in Figure 8.23.

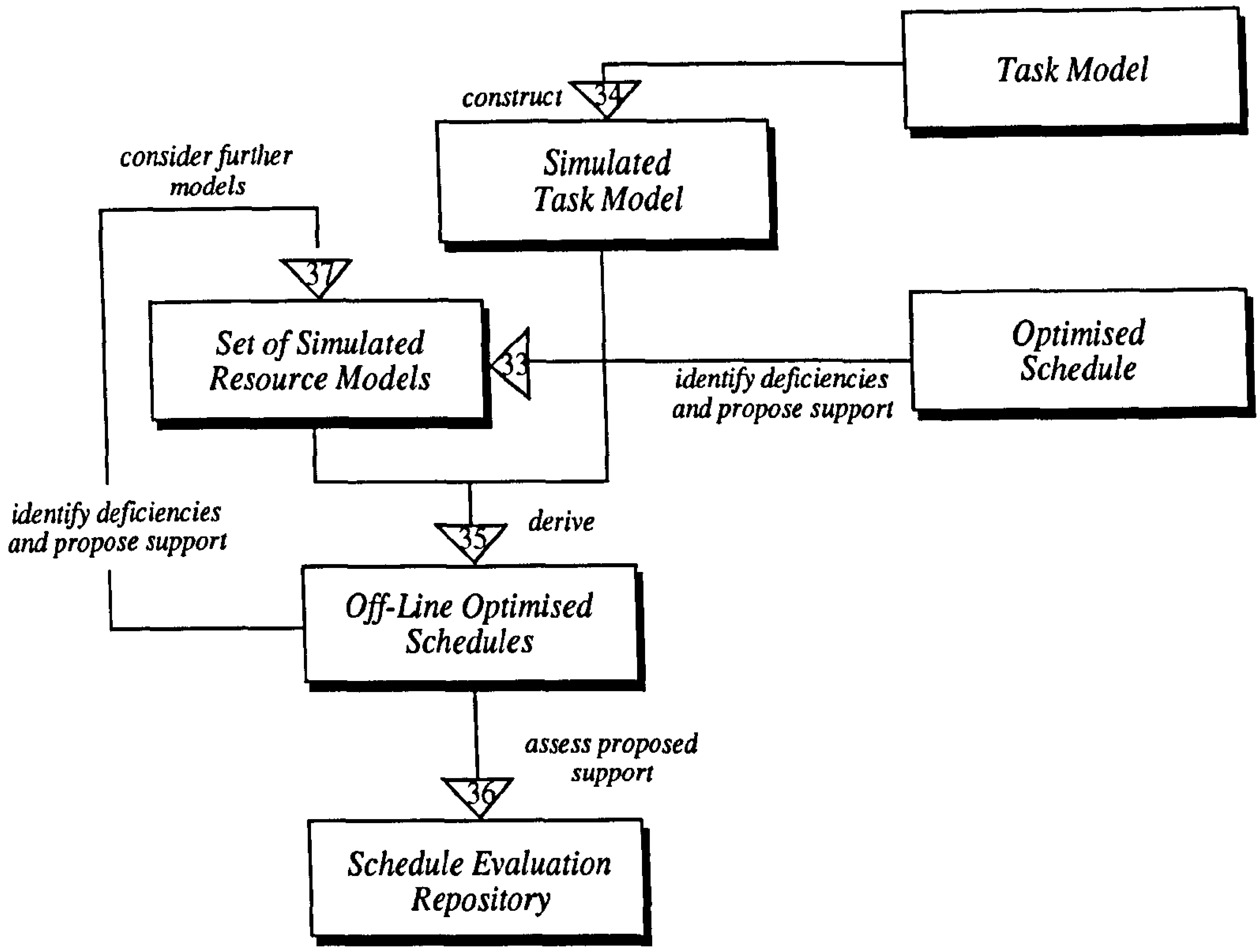

Figure 8.23 Prospective Operational Design Co-ordination

Table 8.10 summarises the involvement of modelled knowledge in the interactions shown in Figure 8.23.

Interaction	Knowledge Modelled	
	Task / Scheduled Task	Resource
33	T_I, T_L, T_G, T_{DD}, T_{ED}	R_I, $R_{[R_{FE}]}$
34	T_I, T_L, T_G, T_{DD}, T_N, $T_{[T_G]}$	n/a
35	T_G, T_{DD}, T_N, $T_{[T_G]}$	R_I, $R_{[R_{FE}]}$
36	n/a	R_C
37	T_I, T_L, T_G, T_{DD}, T_{ED}	R_I, $R_{[R_{FE}]}$

Table 8.10 Summary of Involvement of Modelled Knowledge

8.3 Summary of the Methodology

The real-time and prospective parts of the operational design co-ordination methodology have been presented in Sections 8.1 and 8.2 respectively. This section presents a summary of the methodology encompassing the two parts. The overall methodology encapsulating Figures 8.6, 8.18 and 8.23 is presented in Figure 8.24.

Initially, knowledge regarding tasks is provided by the designer (*Interaction 1, page 91*) and/ or retrieved from the resource/task history repository (*Interaction 2, page 91*). Similarly, knowledge concerning resources is represented in a resource model as supplied by the designer (*Interaction 3, page 91*) and/or retrieved from the resource/task history repository (*Interaction 4, page 91*). Knowledge derived from tasks defined by the designer (*Interaction 5, page 91*) is also represented within the resource model. In addition, knowledge of designer defined tasks is used to derive a task dependency matrix (*Interaction 6, page 94*), which are both then used to construct a task model (*Interactions 7 and 8, page 95*).

Knowledge of tasks and resources, along with a suitable optimisation algorithm, are used to derive an optimised schedule (*Interaction 9, page 97*). Original/revised schedule models are then constructed from knowledge held in the optimised schedule (*Interaction 10, page 99*) and task model (*Interactions 11 and 12, page 99*). According to the original/revised schedule models, design tasks are then undertaken and completed. Prior to a task being undertaken, a check needs to be made to establish if there are any tasks which it is dependent on, and, if so, whether they have been completed. In order ascertain whether these task are completed, the relevant knowledge within the task model is checked (*Interaction 13, page 101*). If any of the tasks dependent on are outstanding, knowledge of the task to be undertaken and the tasks it is dependent on are added the pending scheduled task repository (*Interaction 14, page 101*). Once it is verified that all dependent tasks have been completed, the direction of a task can commence (*Interaction 15, page 101*). If a task is independent then *Interactions 14* and *15* are omitted. The process of undertaking and completing a task can then commence (*Interaction 16, page 101*). This involves the relevant task information being requested (*Interaction 17, page 103*) and provided (*Interaction 18, page 103*) from the task information repository. On completion of a task, any resulting information is supplied to the task information repository (*Interaction 19, page 103*). As tasks are completed, the task model is updated accordingly (*Interaction 20, page 104*). In addition, the pending scheduled task repository is updated if the task completed appears in the dependency list of any pending scheduled tasks (*Interaction 21, page 104*). Thus, the direction of any tasks waiting for the completion of the task just completed can commence (*Interaction 22, page 104*). During the course of tasks being completed, resources (*Interaction 23, page 105*) and schedule models (*Interaction 24, page 105*) are monitored such that the source of any departures from the forecasted resource efficiency can be identified in a timely manner. Given that such a departure occurs, in preparation for re-scheduling, a new forecast of resource efficiency is determined, as well as revised upper and lower monitored efficiency thresholds, are established and the resource model is revised (*Interaction 25, page 106*). In addition, datum durations of tasks may be re-assessed leading to a new judgement being made and the task model being revised accordingly (*Interaction 26, page 106*). If re-scheduling is appropriate, using estimates of the time to re-schedule, an optimum number of tasks are identified that can be completed during re-scheduling. Knowledge of these tasks is derived from the relevant original/revised schedule models and held in the corresponding interim schedule models (*Interaction 27, page 107*). With knowledge of the tasks that will be overlapped with re-scheduling, the task model is modified accordingly (*Interaction 28, page 110*). As previously, knowledge of tasks and resources, along with a suitable optimisation algorithm, is used to re-schedule and, thus, derive an optimised schedule (*Interaction 9, page 97*). As re-scheduling commences, overlapped tasks are undertaken and completed (*Interaction 29, page 111*). As previously, the process of completing a task involves the necessary information being requested (*Interaction 30, page 111*) and provided (*Interaction 31, page 111*) from the task information repository. In addition, any resulting information from the completion of a task is supplied to the task information repository (*Interaction 32, page 111*). On derivation of the new optimised schedule, the process of constructing original/revised schedule models is repeated, and so on.

Once scheduling or re-scheduling is completed, any deficiencies in the schedule are identified and appropriate support is proposed and represented in a set of simulated resource models (*Interaction 33, page 114*). Identification of deficiencies in the schedule is based on judgement as to what additional resource support may reduce the time and/or cost of completing the scheduled tasks. Simulated task models are constructed based on task knowledge used to derive the optimised schedule in the actual design development process (*Interaction 34, page 117*). Using knowledge of tasks and resources, along with a suitable optimisation algorithm, optimised schedules are derived for each respective simulated resource model (*Interaction 35, page 117*). The resulting simulated optimised schedules are assessed in terms of time and cost with respect to the proposed support and recorded in a schedule evaluation repository (*Interaction 36, page 118*). Any remaining deficiencies are identified in the simulated resource models used in assisting the derivation of the optimised schedules and, if appropriate, other support is proposed (*Interaction 37, page 119*). *Interactions 35, 36* and *37* are repeated until all simulated resource models have been considered and the required improvements to the resources have been identified.

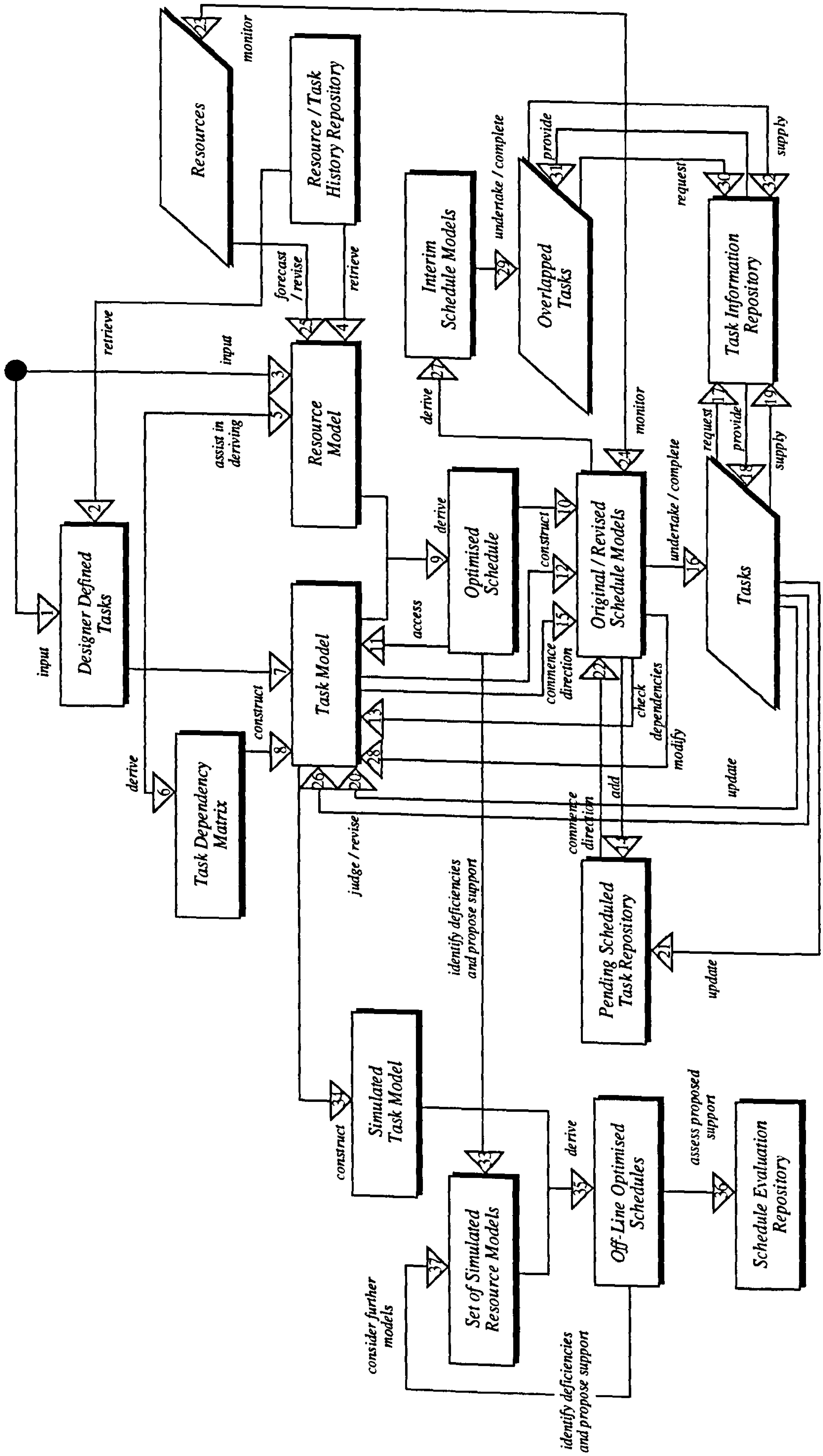

Figure 8.24 Operational Design Co-ordination Methodology

8.4 Summary

This chapter has presented the operational design co-ordination methodology component of the approach. The methodology consists of two parts, namely real-time and prospective operational design co-ordination.

In Section 8.1 and 8.2, real-time and prospective operational design co-ordination were presented respectively. A summary of the operational design co-ordination methodology was presented in Section 8.3.

9 The Design Co-ordination System

The aim of this chapter is to present a prototype computer-based system, called the Design Co-ordination System (DCS). The DCS is a realisation of the real-time operational design co-ordination part of the methodology presented in Chapter 8, supported by the knowledge modelling formalism component of the approach presented in Chapter 7. In order to evaluate the real-time operational design co-ordination part of the methodology, the DCS is applied to a practical case study from engineering industry, which is presented in Chapter 10.

In Section 9.1, an overview of the DCS is presented. The components of the system are discussed in Sections 9.2 to 9.8. Finally, Section 9.9 summarises the DCS and the chapter.

9.1 An Overview of the Design Co-ordination System

The DCS is an agent-oriented system aimed at the real-time operational design co-ordination of a computational design analysis. The DCS comprises three components, i.e. an agent framework, modelled knowledge and user knowledge. An overview of the DCS is shown in Figure 9.1.

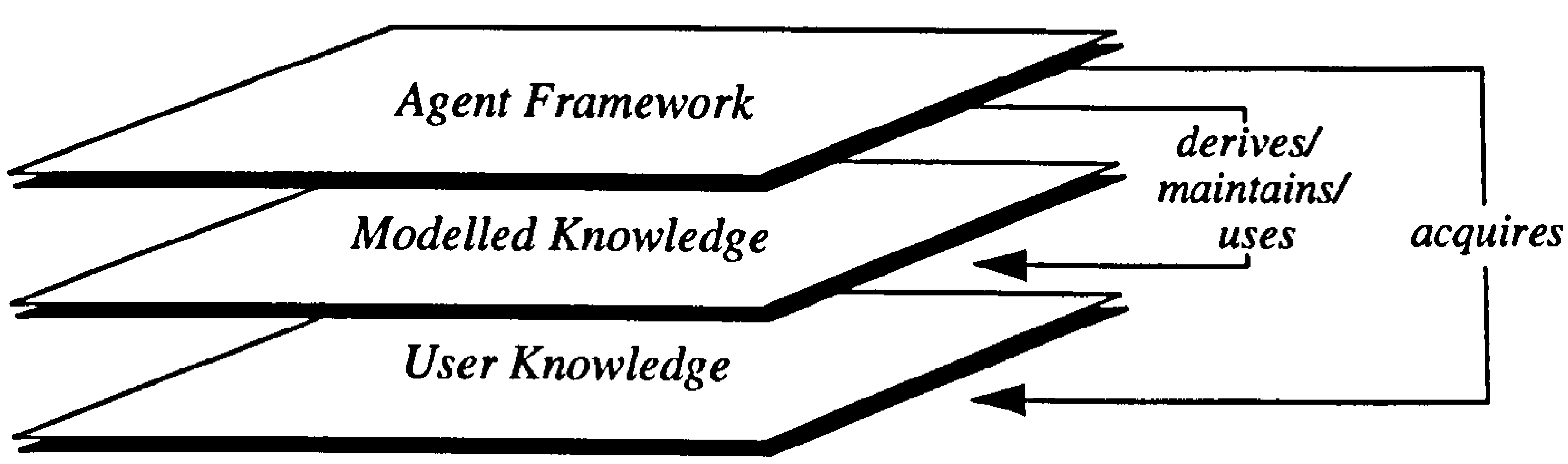

Figure 9.1 An Overview of the Design Co-ordination System

The justification for adopting the agent paradigm within the DCS is discussed later in this section. The agent framework acquires knowledge provided by the user in order to derive modelled knowledge. The agent framework then maintains and uses modelled knowledge through the application of real-time operational design co-ordination. That is, the real-time operational design co-ordination part of the methodology is embedded within the agent framework of the DCS.

The three components of the DCS consist of a number of types of modules:

Agent Framework

- Activity Director
- Co-ordination Manager

- Information Manager
- Resource Manager
- Resource Monitor
- Scheduler
- Task Manager

Modelled Knowledge

- Analysis Tool Dependency Matrix
- Pending Scheduled Task Repository
- Resource Model
- Schedule Models (Original/Revised and Interim)
- Task Model

User Knowledge

- Analysis Tool Knowledge
- Resource Knowledge
- Task Information Repository
- Task Knowledge

Figure 9.2 shows the various modules of the DCS and the interactions between them.

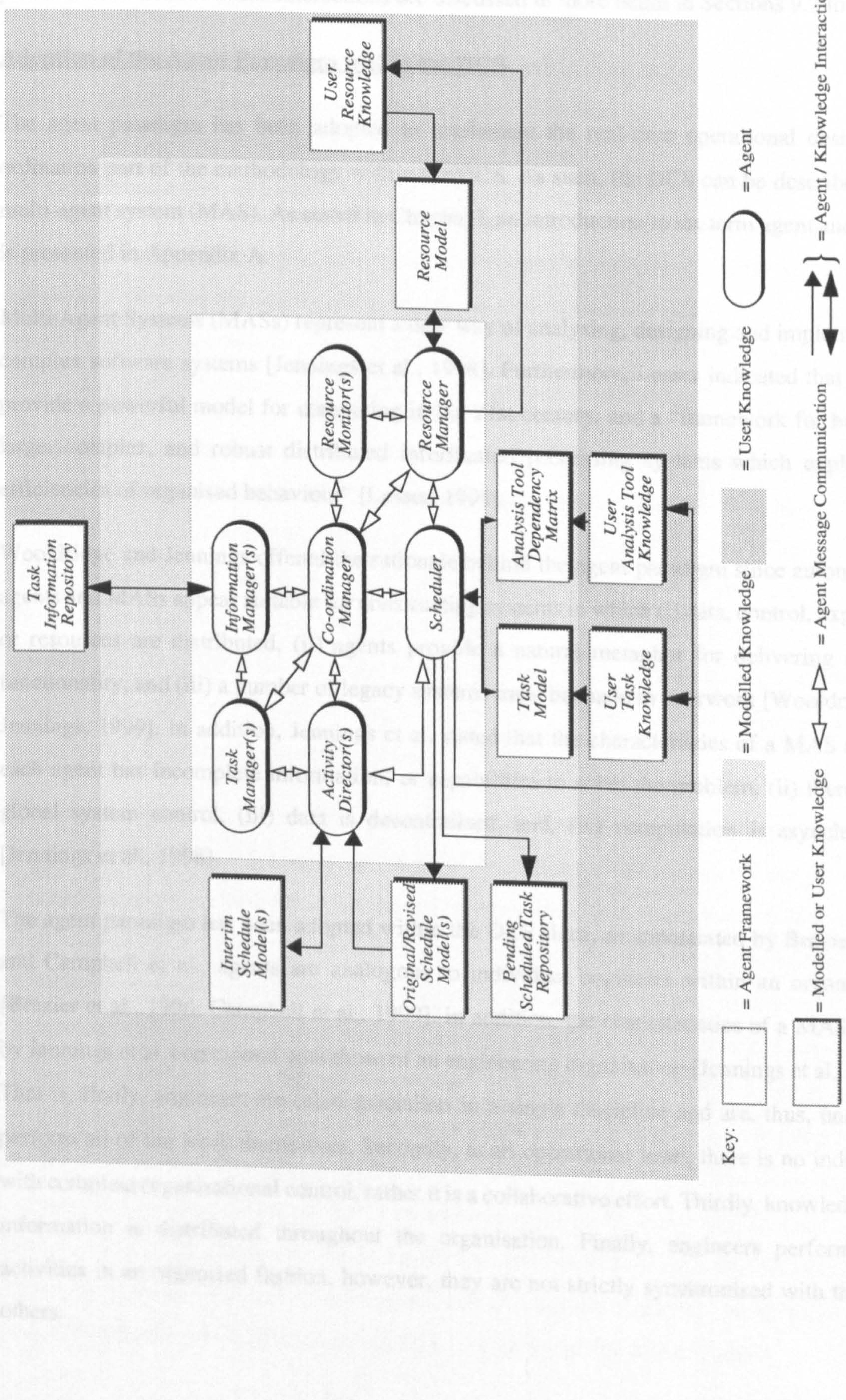

Figure 9.2 Design Co-ordination System Architecture

In Figure 9.2, a distinction is made with interactions between (i) agents, and (ii) agents and knowledge modules, since the nature of these exchanges are different. That is, interactions between agents involves message passing. Interactions between agents and knowledge modules entails agents extracting knowledge from the modules in order to enable them to perform some action. These interactions are discussed in more detail in Sections 9.2 to 9.8.

Adoption of the Agent Paradigm within the DCS

The agent paradigm has been adopted to implement the real-time operational design co-ordination part of the methodology within the DCS. As such, the DCS can be described as a multi-agent system (MAS). As stated in Chapter 3, an introduction to the term agent and MAS is presented in Appendix A.

Multi Agent Systems (MASs) represent a new way of analysing, designing and implementing complex software systems [Jennings et al., 1998]. Furthermore, Lesser indicated that MASs provide a powerful model for computing in the 21st century, and a "framework for building large, complex, and robust distributed information processing systems which exploit the efficiencies of organised behaviour" [Lesser, 1999].

Wooldridge and Jennings offered the rationale behind the agent paradigm since autonomous agents and MASs appear suitable for constructing systems in which (i) data, control, expertise, or resources are distributed, (ii) agents provide a natural metaphor for delivering system functionality, and (iii) a number of legacy systems must be made to interwork [Wooldridge & Jennings, 1999]. In addition, Jennings et al. stated that the characteristics of a MAS are: (i) each agent has incomplete information, or capabilities to solve the problem, (ii) there is no global system control, (iii) data is decentralised, and, (iv) computation is asynchronous [Jennings et al., 1998].

The agent paradigm has been adopted within the DCS since, as appreciated by Brazier et al. and Campbell et al., agents are analogous to individual engineers within an organisation [Brazier et al., 1996; Campbell et al., 1999]. In addition, the characteristics of a MAS stated by Jennings et al. correspond with those of an engineering organisation [Jennings et al., 1998]. That is, firstly, engineers are often specialists in a single discipline and are, thus, unable to perform all of the work themselves. Secondly, at an operational level, there is no individual with complete organisational control, rather it is a collaborative effort. Thirdly, knowledge and information is distributed throughout the organisation. Finally, engineers perform their activities in an organised fashion, however, they are not strictly synchronised with those of others.

An Overview of the Agent Framework within the DCS

Within the DCS, a collection of agents act as members of a multi-functional team operating in a co-ordinated fashion in order to satisfy the objective of ensuring that the specified inter-related design tasks are completed in a structured manner with respect to time, and the allocation and utilisation of the available machines, hereafter referred to as *resources*, within the computer network environment. This involves agents taking the opportunity to complete tasks concurrently when and where appropriate. However, the emphasis is placed on operational design co-ordination by ensuring that agent actions are conducted appropriately with respect to the time and order that they are performed.

In order to avoid any ambiguity in the remainder of this chapter, it is appropriate to define the relationship between the two types of resources used within the DCS, namely agents and machines. Thus, an agent is a software entity, which executes on a machine, in order to perform some activity. A further discussion of resources is presented in Section 9.5.

Seven different agent types are employed within the DCS, namely Co-ordination Manager (CM), Information Manager (IM), Task Manager (TM), Resource Manager (RMan), Scheduler (S), Resource Monitor (RMon) and Activity Director (AD). Each of the agent types fulfils a particular role and is capable of performing various activities. The behaviour of all agents is complimentary in that they assist each other in order to satisfy the overall design objective, i.e. completing the computational design analysis in a co-ordinated and improved manner. Thus, consistent with Lesser, the collection of agents can be described as a co-operative or benevolent agent society [Lesser, 1999].

Within any application of the DCS, the number of agents of type Co-ordination Manager, Resource Manager and Scheduler is fixed at one, whereas the number of agents of type Information Manager, Task Manager, Resource Monitor and Activity Director is dependent on the number of analysis tools to be used in the computational design analysis and/or the number of available resources in the computer network environment. An analysis tool is an individual software module that is executed, which uses input to produce corresponding output. Each execution of an analysis tool uses different input information, and is defined as a task within the context of the DCS. As stated previously, a resource is a machine in the computer network environment on which analysis tools can be executed. The number of Information Managers is equivalent to the number of different analysis tools to be used. The number of Task Managers is equal to the product of the number of analysis tools and the number of resources since a Task Manager exists for each tool on each resource. Each resource being utilised in the computer network environment is allocated a Resource Monitor and an Activity Director.

The agent configuration within the DCS is shown in Figure 9.3. In addition, the aspects of operational design co-ordination of each type of agent and communication links are shown.

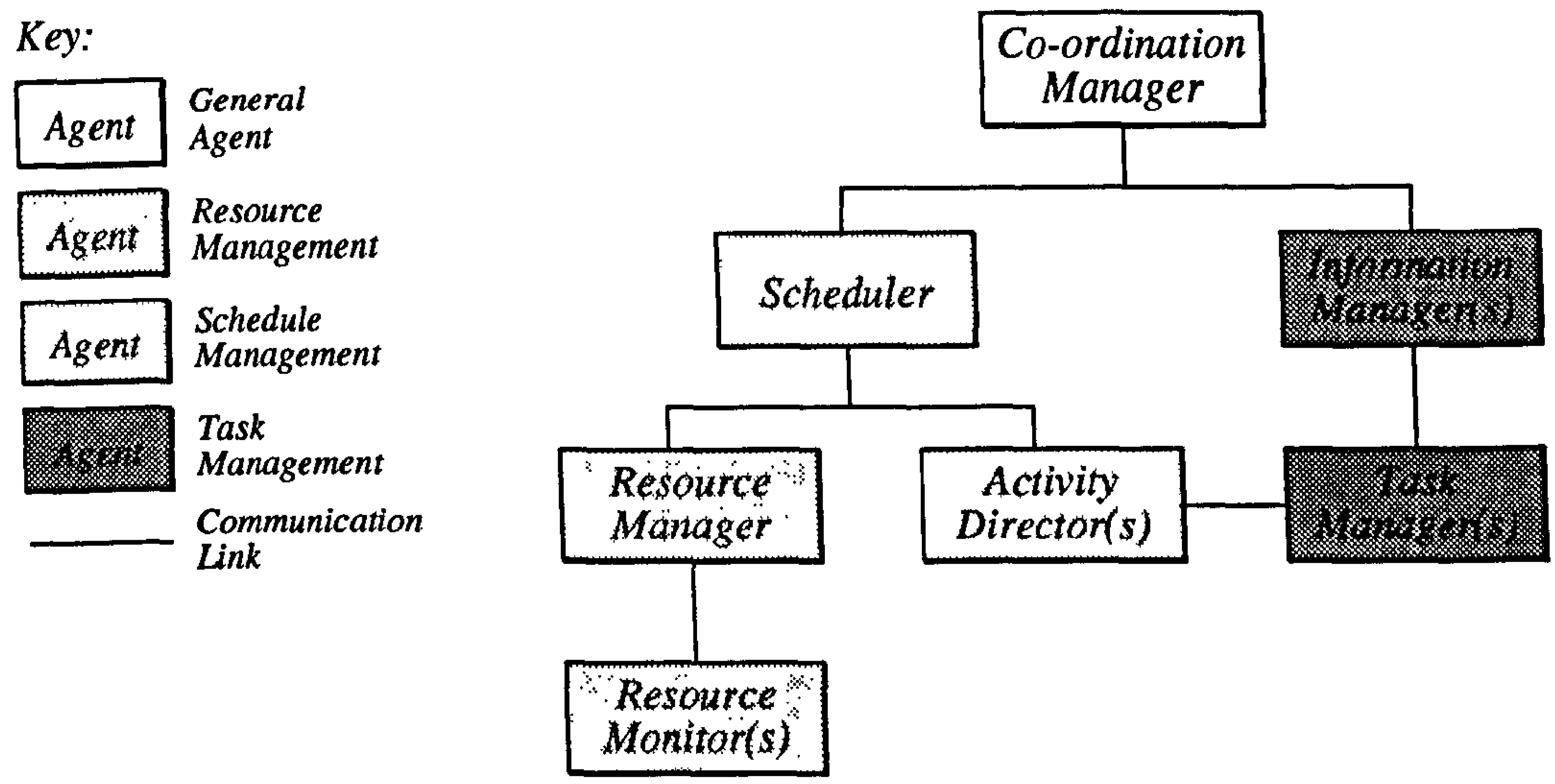

Figure 9.3 Configuration of DCS Agents

Agent communication is facilitated by message passing, which is asynchronous. The action taken by an agent on receiving a message is dependent on the type of message and its content. Three types of messages are used in the communication protocol, namely *notify*, *request*, and *respond*. Messages of type *notify* do not require any reply, however, they do require some action to be taken by the receiving agent. Messages of type *request* must be replied to with a message of type *respond* and may require the receiving agent to perform some activity. Messages of type *respond* also require some action to be taken by the receiving agent. Actions taken by an agent also depend on the content of a message. The content may cause the receiving agent to retrieve or modify knowledge it holds or has access to.

In Sections 9.2 to 9.8, each aspect of the real-time operational design co-ordination part of the methodology is incorporated within the DCS and discussed in terms of the agent framework. In addition, reference is made to the user and modelled knowledge modules of the DCS where appropriate.

9.2 Co-ordination Manager

The role of the Co-ordination Manager is to facilitate communication links between related agents, i.e. agents that need to interact in order to achieve a common goal, at the outset of the operation of the DCS.

During the initial operation of the DCS, the Co-ordination Manager is central to all agent communication in that it acts as a registrar providing an introduction service to enable related agents to ascertain knowledge of each other such that they can communicate directly. In order for an agent to register, it is required to send an introductory message to the Co-ordination Manager. Knowledge contained within this initial communication relates to attributes of the agent, which is dependent on agent type. Table 9.1 summarises the attributes of each agent type, where a tick indicates that the agent has the corresponding attribute and a cross signifies the agent does not have the corresponding attribute.

	Attribute		
Agent Type	**Address**	**Analysis Tool**	**Resource**
Activity Director	✓	×	✓
Co-ordination Manager	✓	×	×
Information Manager	✓	✓	×
Resource Manager	✓	×	×
Resource Monitor	✓	×	✓
Scheduler	✓	×	×
Task Manager	✓	✓	✓

Table 9.1 Attributes of Agent Types

Once the attributes of an agent have been recorded, the Co-ordination Manager acknowledges the registration of the agent. Subsequently, in the event of any agent requiring knowledge regarding another particular agent, this can be obtained from the Co-ordination Manager. Agents wishing to acquire knowledge regarding other agents are those that are related by (i) contributing to the accomplishment of some common goal such as ensuring the optimised utilisation of the resources, or (ii) an attribute such as an analysis tool and/or a resource. This knowledge enables the relevant agents to communicate directly, rather than via the Co-ordination Manager, such that they can work co-operatively to perform their activities, complete their tasks, and achieve their goals. This feature of direct communication between related agents (i) permits efficient message passing, (ii) removes the problem of communication bottlenecks, and, (iii) promotes co-ordination. Message passing is considered to be efficient since communication between agents only occurs when necessary. The Co-ordination Manager facilitates the decentralisation of communication amongst agents, thus avoiding message bottlenecks. Co-ordination is thought of as being promoted since direct communication enables related agents, i.e. by an attribute or through participating in accomplishing a common goal, to work co-operatively in a co-ordinated manner within a collaborative team to meet the overall objective.

The relationships between agent types are indicated in Table 9.2, where a tick indicates that the respective agent types are related and a cross signifies that they are not related. These relationships reflect the agent message communication links illustrated in Figure 9.2. The upper and lower triangle of the matrix are used to indicate that communication is bi-directional between the respective agents.

Agent Type	AD	CM	IM	RMan	RMon	S	TM
AD		✓	✗	✗	✗	✓	✓
CM	✓		✓	✓	✓	✓	✓
IM	✗	✓		✗	✗	✗	✓
RMan	✗	✓	✗		✓	✓	✗
RMon	✗	✓	✗	✓		✗	✗
S	✓	✓	✗	✓	✗		✗
TM	✓	✓	✓	✗	✗	✗	

Table 9.2 Agent Relationships

For example, each Task Manager requests knowledge, i.e. the address, from the Co-ordination Manager regarding their related Information Manager by analysis tool, and Activity Director by resource. If the Information Manager has registered, the Co-ordination Manager provides the Task Manager with the knowledge requested. In the situation where the Information Manager has not yet registered, the Co-ordination Manager indicates this fact to the Task Manager. Subsequently, once the Information Manager does register, the Co-ordination Manager passes the required knowledge to the Task Manager enabling direct communication between them. In the same manner, the Task Manager ascertains knowledge regarding its related Activity Director.

9.3 Information Manager

The main responsibility of an Information Manager is the pre and post management of task information concerned with the completion of tasks, i.e. execution of its associated analysis tool with given input. Specifically, an Information Manager provides task information when and where appropriate for use by Task Managers.

Throughout the computational design analysis, requests are received by an Information Manager from related Task Managers prior to their associated analysis tool being executed. That is, specific task input information is requested for a particular execution of the analysis tool. Figure 9.4 illustrates the management of information between an Information Manager and its related Task Manager(s).

It is noted that the key shown in Figure 9.4 applies to all figures in the remainder of this chapter, unless shown otherwise.

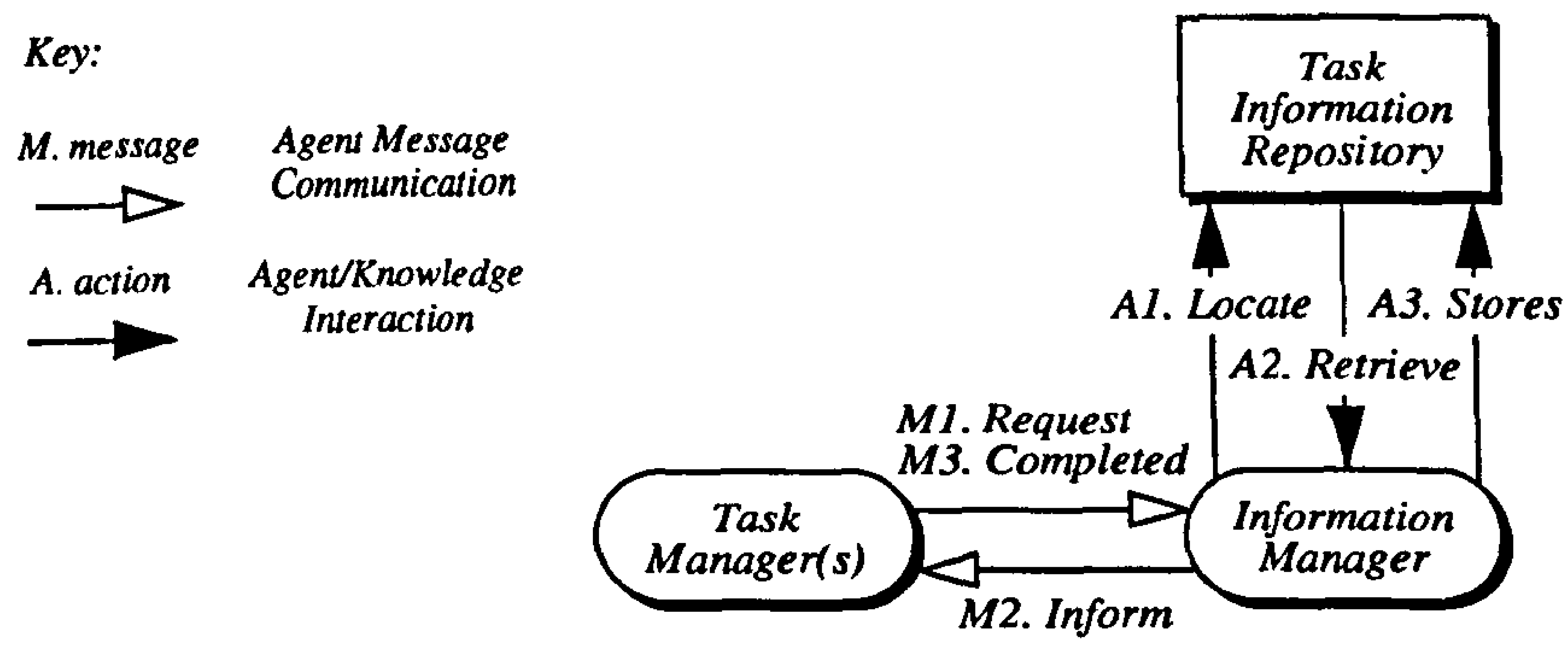

Figure 9.4 Information Management

On receipt of a request (*Message M1*), the Information Manager ensures that the required task input information is made available to the Task Manager. This involves the Information Manager locating (*Action A1*) and retrieving (*Action A2*) the required task input information from the task information repository. The Information Manager then supplies the relevant information and informs the associated Task Manager (*Message M2*). This enables the Task Manager to execute the analysis tool using the requested information, i.e. the task to be undertaken. If required, an Information Manager also provides additional information needed for the execution of the Task Manager's associated analysis tool. On being informed by a Task Manager that a task has been completed (*Message M3*), the related Information Manager stores the task output information in the task information repository (*Action A3*), which is accessible by all Information Managers. This procedure is performed after every analysis tool execution such that, if required, future use can be made of the newly created task output information.

9.4 Task Manager

The principal duty of a Task Manager is the execution of its associated analysis tool utilising its associated resource.

An instruction to a Task Manager indicating that the enactment of a specific task should commence is provided by its related Activity Director. These two types of agent are related since they are associated with a common resource. On receiving an instruction to commence the completion of a specific task, a Task Manager requests the corresponding task input information from its related Information Manager, as discussed with regard to Figure 9.4. Task Managers are able to request a specific input from their related Information Managers so as to accommodate the *random* order of scheduled tasks within the original/revised or interim schedule model of its related Activity Director. On receipt of this task input information, the Task Manager executes its associated analysis tool utilising its associated resource. On completion of the task, in addition to informing its related Information Manager, the Task Manager informs the Activity Director such that it can proceed in instructing the next appropriate Task Manager to commence the enactment of its designated task. Task Managers act as soon as instructed to commence the completion of a particular task by an Activity Director such that the original/revised or interim schedule model is adhered to as closely as possible leading to its timely completion. Task Managers continue to execute their associated analysis tools with specified task inputs until the Activity Director finishes administering its associated original/revised or interim schedule model.

9.5 Resource Manager

The primary role of the Resource Manager is to maintain accurate knowledge within the resource model. The upkeep of the resource model provides the basis for the optimised allocation and utilisation of the resources throughout the computational design analysis.

Within the DCS, machines, on which analysis tools are executed in order to complete tasks, are defined as resources. Agents involved in the completion of tasks, i.e. Task Managers, are also categorised as resources. However, due to the efficiency of Task Managers being directly related to that of the machine on which they are employed and that they are only capable of performing one type of task, i.e. the execution of their associated analysis tool, the only knowledge contained within the resource model is that related to machines. Thus, the term resource is used to describe the machines used in the operation of the DCS.

For each available resource within the computer network environment, the resource model contains knowledge of identification, status and performance, which is provided by the user at the outset of the operation of the DCS. As shown in Figure 9.5, the responsibility of constructing and maintaining the resource model lies with the Resource Manager.

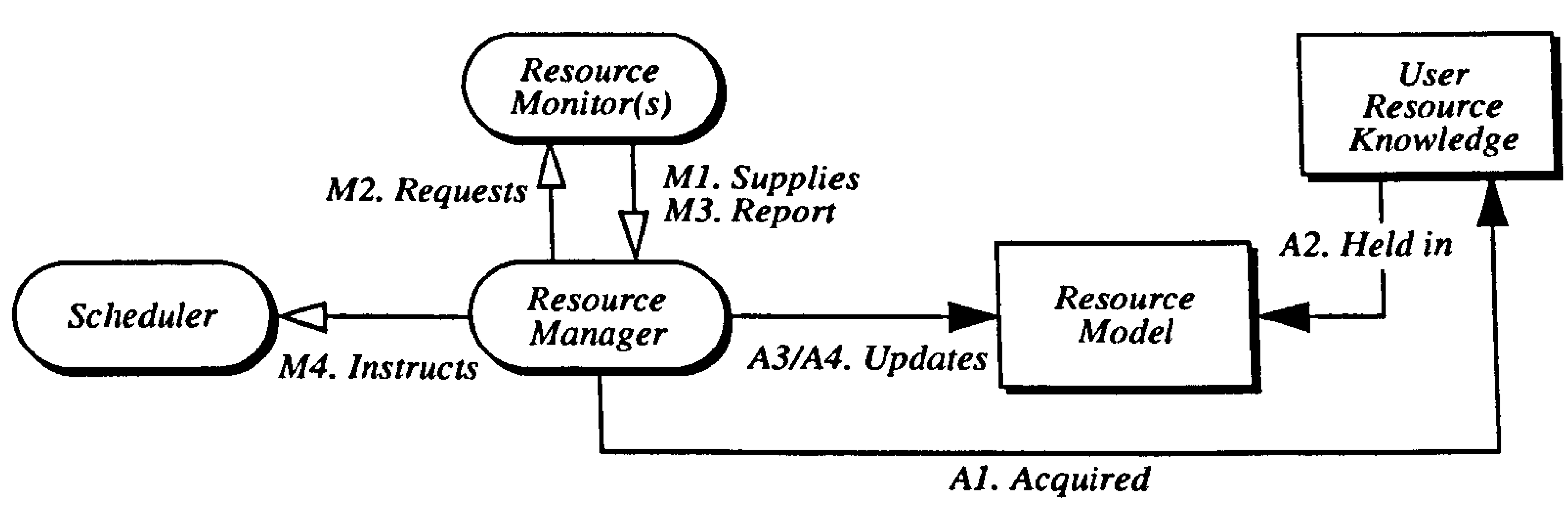

Figure 9.5 Constructing and Maintaining the Resource Model

The Resource Manager acquires user supplied knowledge *(Action A1)* and holds it in the resource model *(Action A2)*. Knowledge of resource performance forecasted and monitored efficiency is acquired by Resource Monitors during the operation of the DCS, i.e. throughout the computational design analysis. Monitored efficiency changes dynamically, thus, reflecting the variability of the resource usage within the computer network environment. In the event of any threshold violation, monitored efficiency knowledge is used to derive forecasted efficiency knowledge, which is supplied to the Resource Manager from the relevant Resource Monitor when necessary *(Message M1)*. In addition, upper and lower efficiency thresholds are re-set. Initially, the user defines and provides knowledge of the thresholds, which may be particular to the individual resources. However, the Resource Manager re-sets the thresholds during the operation of the DCS. A discrepancy in threshold for different resources may exist due to differences in their performance specification. Following notification of a change in the forecasted efficiency of a resource that exceeds a defined threshold, after re-setting the appropriate upper and lower thresholds, the Resource Manager updates the resource model *(Action A3)*. The Resource Manager then requests *(Message M2)* that all other Resource Monitors determine and report *(Message M3)* an up-to-date forecast of the efficiency of their associated resource. This allows the Resource Manager to completely update the resource model *(Action A4)*. The Resource Manager then instructs *(Message M4)* the Scheduler to consider deriving a new schedule using knowledge from the resource model. Due to the resource model being up-to-date, any schedule produced will reflect the most recent efficiency forecast of the resources within the computer network environment. Subsequent action taken by the Scheduler is discussed in Section 9.6.

9.6 Scheduler

The primary objective of the Scheduler is to ensure the optimised scheduling of a number of tasks on the available resources, such that task dependencies are preserved, and the overall time to complete them is minimised. A multi objective genetic algorithm (MOGA) [Todd, 1997] is used by the Scheduler to achieve this objective.

In summary, the Scheduler is responsible for:

- constructing an analysis tool dependency matrix,
- constructing a task model,
- preparation for scheduling / re-scheduling,
- deriving and selecting an optimised schedule,
- constructing original / revised schedule models,
- checking task dependencies / updating task model, and,
- re-scheduling decision-making / constructing interim schedule models.

Constructing an Analysis Tool Dependency Matrix

Once communication links have been formed with all related agents, the Scheduler uses knowledge provided by the user regarding each analysis tool to be used in the computational design analysis *(Action A1)* in order to construct an analysis tool dependency matrix *(Action A2)*, as shown in Figure 9.6.

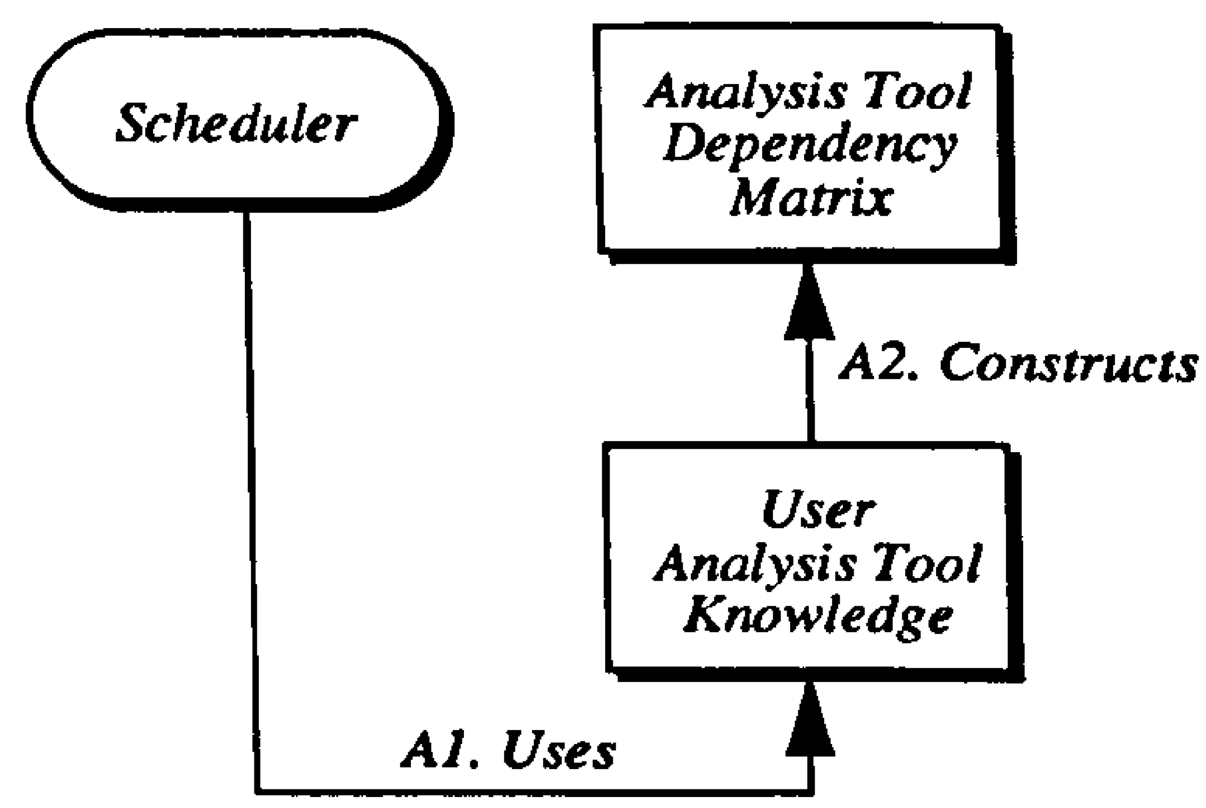

Figure 9.6 Constructing an Analysis Tool Dependency Matrix

The analysis tool dependency matrix contains knowledge of dependencies and datum execution durations. Dependencies are established using knowledge of the input and output requirements for each analysis tool. As an example, in accordance with their input and output requirements, Figure 9.7 represents the flow of information between eight analysis tools within a computational design analysis.

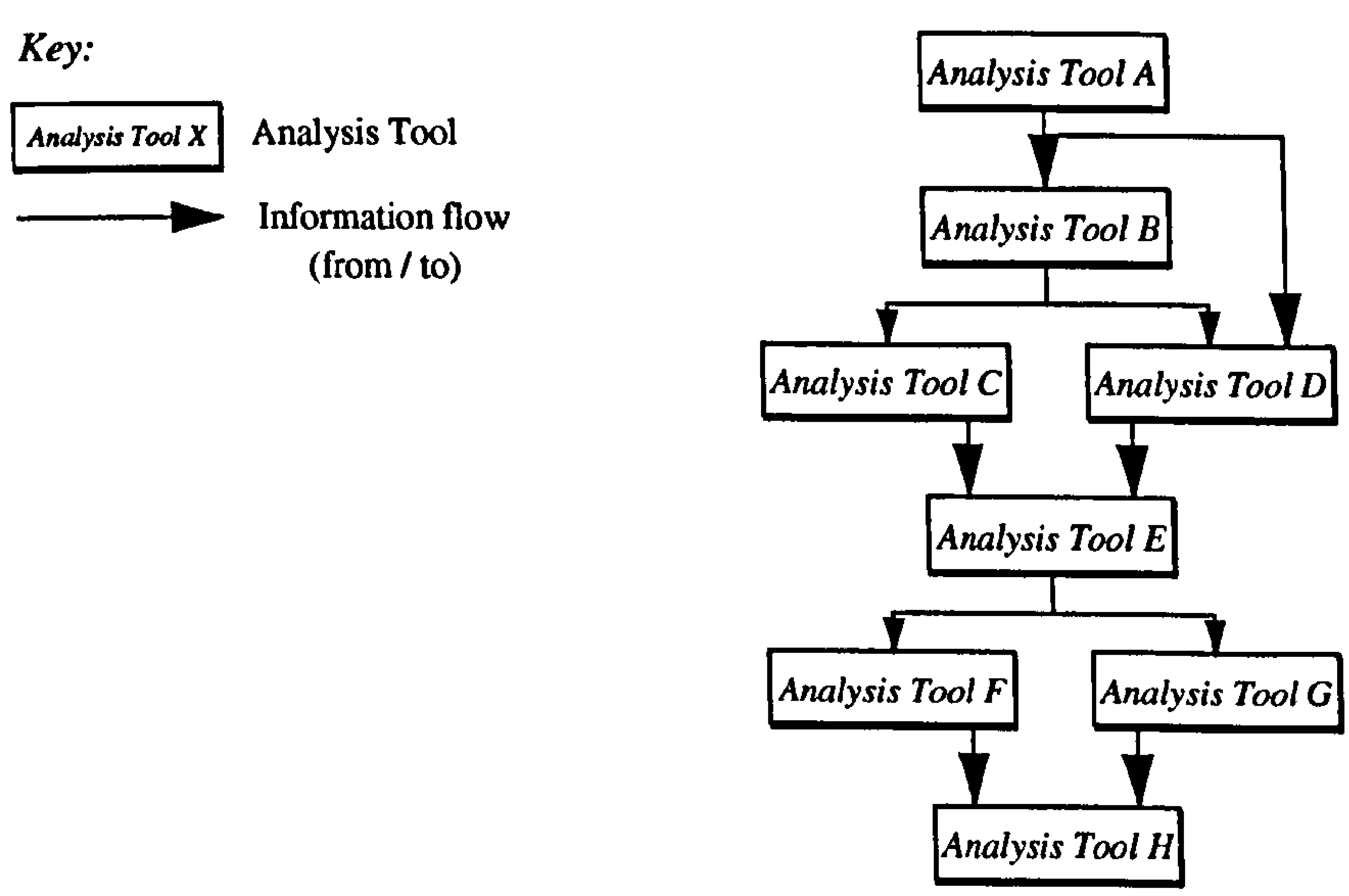

Figure 9.7 Information Flow between Analysis Tools

Datum analysis tool durations are obtained from the user when supplying information regarding each analysis tool. As shown in Table 9.3, and based on Figure 9.7, analysis tool dependencies are represented in the off-diagonal elements by zero for non-dependency or one for dependency. In addition, as discussed by Eppinger et al., datum analysis tool execution durations, using consistent units of time, are represented in the diagonal elements of the matrix

[Eppinger et al., 1994].

Analysis Tool	A	B	C	D	E	F	G	H
A	19	0	0	0	0	0	0	0
B	1	7	0	0	0	0	0	0
C	0	1	14	0	0	0	0	0
D	1	1	0	5	0	0	0	0
E	0	0	1	1	3	0	0	0
F	0	0	0	0	1	63	0	0
G	0	0	0	0	1	0	13	0
H	0	0	0	0	0	1	1	10

Table 9.3 Analysis Tool Dependency Matrix

Constructing a Task Model

The Scheduler is also responsible for ensuring that the task model is constructed and, using information provided by the Activity Directors, maintained throughout the lifetime of the computational design analysis. As shown in Figure 9.8, the Scheduler uses task knowledge provided by the user *(Action A3(a))* and contained within the analysis tool dependency matrix *(Action A3(b))* in order to construct a task model *(Actions A4(a) and A4(b))*.

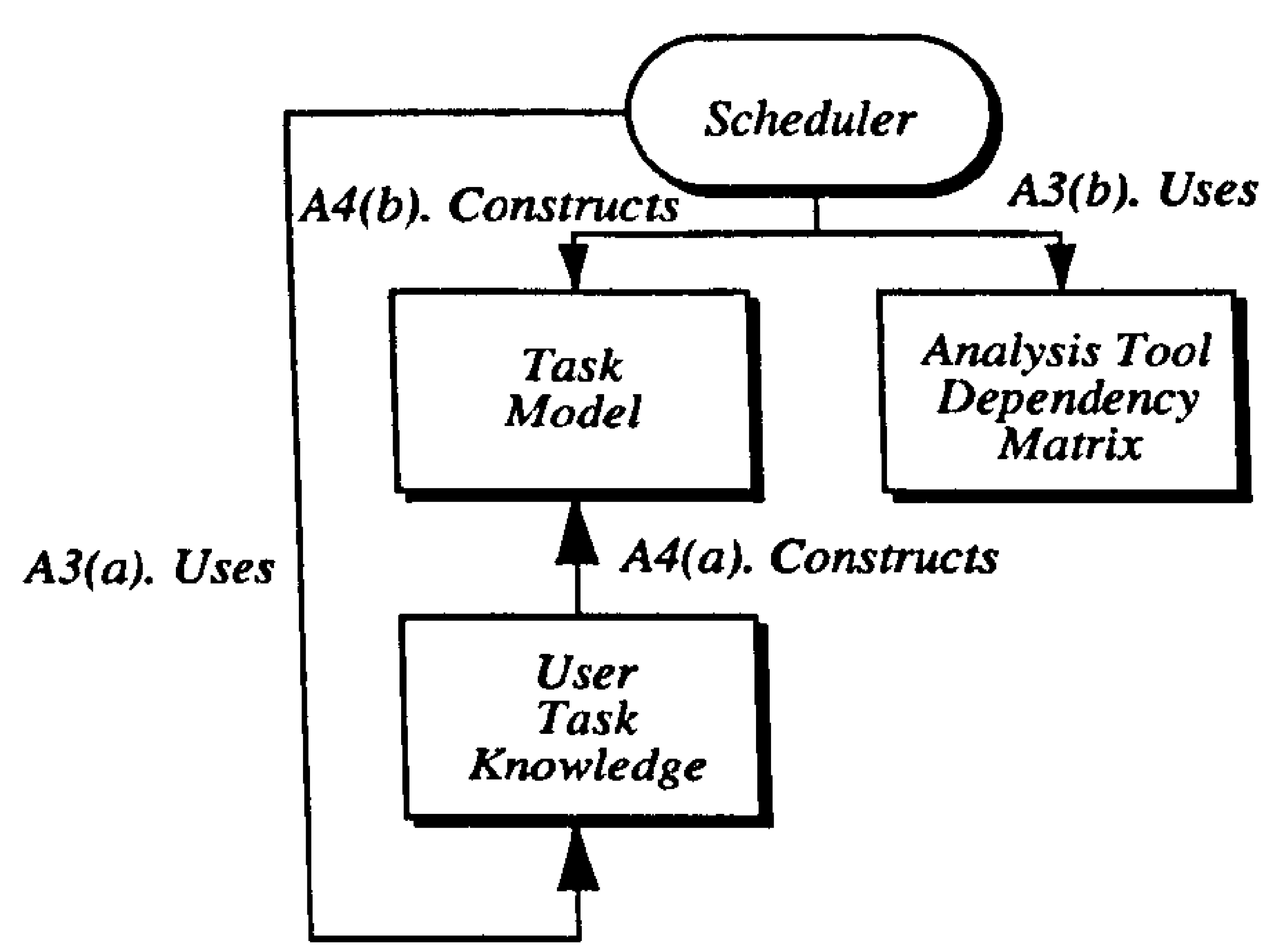

Figure 9.8 Constructing a Task Model

Based on the off-diagonal elements of the analysis tool dependency matrix, the Scheduler is able to establish knowledge of relationships between tasks for inclusion within the task model. Thus, the task model can represent knowledge of task dependencies.

Preparation for Scheduling / Re-scheduling

Preparatory work performed by the Scheduler for the purpose of scheduling/re-scheduling involves accessing up-to-date knowledge of task and resources from the task model and resource model respectively.

Scheduling is performed once the task model and resource model have been constructed prior to any tasks being undertaken.

As shown in Figure 9.9, notification of the potential need to re-schedule occurs when the Resource Manager instructs the Scheduler to consider deriving a new schedule *(Message M1)*.

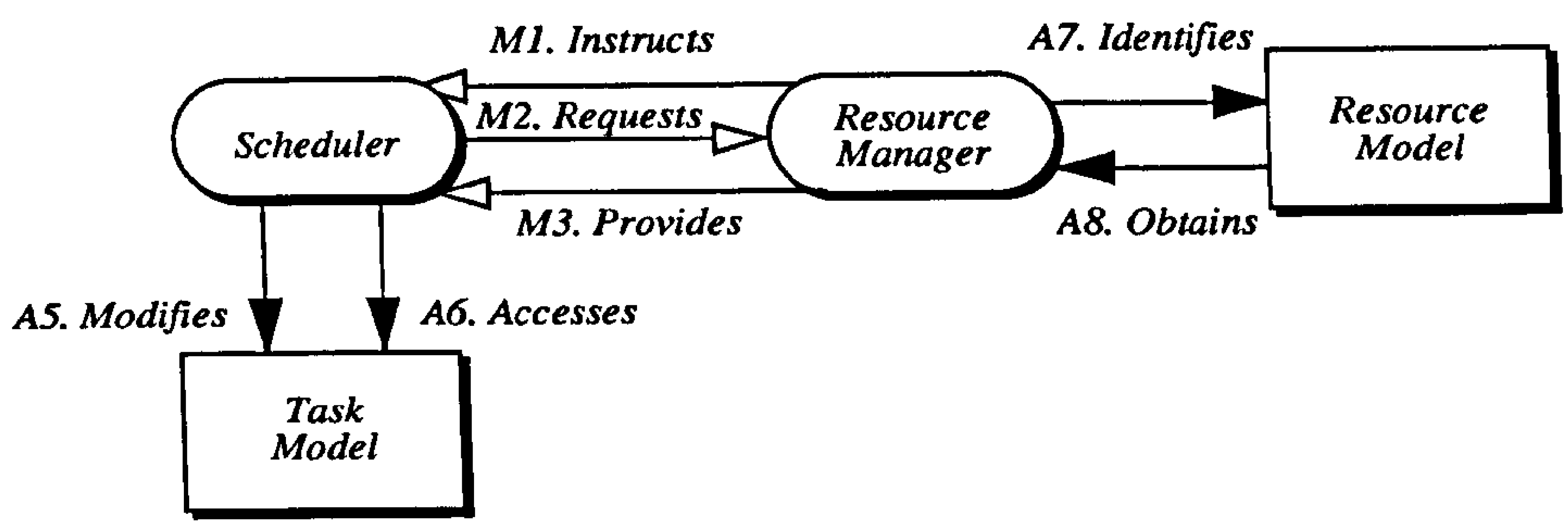

Figure 9.9 Preparation for Scheduling

The decision-making process of the Scheduler regarding whether or not to re-schedule is discussed later in this section.

If the Scheduler decides to re-schedule, initially the task model is modified with respect to the tasks to be completed during re-scheduling *(Action A5)*, i.e. (i) progress knowledge of tasks (T_{AC}) is updated, (ii) global task identification indices are re-numbered, and (iii) the number of dependencies and global task identification indices of those tasks that a task is dependent on are checked and changed if necessary. As a result of these modifications, the knowledge held within the task model is appropriate for use with the MOGA. The use of accurate task knowledge, in addition to accurate resource knowledge and the MOGA, results in an appropriate optimised schedule being produced. Specifically, the Scheduler prepares the knowledge required for scheduling / re-scheduling, i.e. the application of the MOGA, by accessing knowledge held in the recently modified task model *(Action A6)* and identifying and obtaining the relevant knowledge from the resource model *(Actions A7 and A8)* via the Resource Manager *(Messages M2 and M3)*.

With regard to the task model, tasks are considered for scheduling based on knowledge of their progress, i.e. T_{AC}. Due to the nature of the tasks to be completed through the operation of the DCS, i.e. executions of analysis tools given input information, once they are started they must be completed. That is, tasks are described as non pre-emptive since they cannot be interrupted. Thus, a T_{AC} equivalent to zero represents a task that has not been completed whereas a T_{AC} of unity indicates that a task has been completed. Only tasks with a T_{AC} of zero are selected for scheduling, i.e. those that have not been completed. Knowledge extracted from the task model comprises: (i) the number of tasks to be scheduled, (ii) the total number of tasks that the tasks to be scheduled are dependent on, (iii) the global task numbers of the tasks to be scheduled, (iv) the datum durations of the tasks to be scheduled, (v) the number of tasks that each scheduled task is dependent on, and (vi) the global task numbers of the tasks that each task is dependent on. Knowledge extracted from the resource model entails: (i) the number of resources available for use in the computational design analysis and (ii) the forecasted efficiency of each of those resources.

Deriving and Selecting an Optimised Schedule

At the outset of the computational design analysis or when instructed by the Resource Manager, if appropriate, the Scheduler executes the MOGA and produces a Pareto optimal set [Pareto, 1896] of schedules. A Pareto optimal set comprises Pareto optimal solutions, in which no increase can be achieved in any of the criteria without resulting in a simultaneous decrease in at least one of the remaining criteria.

Within the MOGA, three objective functions have been defined:

- minimise time,
- minimise number of resources used, and,
- minimise utilisation of the resources used.

If the user of the DCS decides to prescribe different criteria then the appropriate objective functions must be used within the MOGA.

Once scheduling/re-scheduling is performed, the Scheduler uses multi criteria decision making (MCDM) to select the most appropriate schedule from the Pareto optimal set. The criteria used co-incides with the objective of completing the computational design analysis in the least time using the least number of resources while consuming the least utilisation of those resources. The first criterion applied to the Pareto optimal set is that of minimising the time estimate to complete all scheduled tasks. Thus, the schedule with the least time estimate to complete the tasks scheduled is selected. In the event that more than one schedule within the Pareto optimal set satisfies this first criterion, a second criterion is applied such that the schedule with the least number of resources used to achieve the completion of the tasks scheduled is chosen. Again, in the event that more than one schedule satisfies the first and second criterion, a third, and final, criterion is used. That is, the schedule exhibiting the least cumulative percentage utilisation of the resources employed is selected. If there are a number of schedules within the

Pareto optimal set that satisfy all three criteria then a schedule is arbitrarily chosen since all of these schedules are expected to be equally as "good".

Constructing Original/Revised Schedule Models

After scheduling or re-scheduling has been completed, as shown in Figure 9.10, the Scheduler uses the derived optimised schedule to construct an original/revised schedule model for each resource allocated for use *(Action A9)*. The Scheduler then notifies and provides the corresponding original/revised schedule model to each associated Activity Director *(Message M4)*. Each original/revised schedule model comprises knowledge of the tasks and the order in which they are to be undertaken on each Activity Director's associated resource.

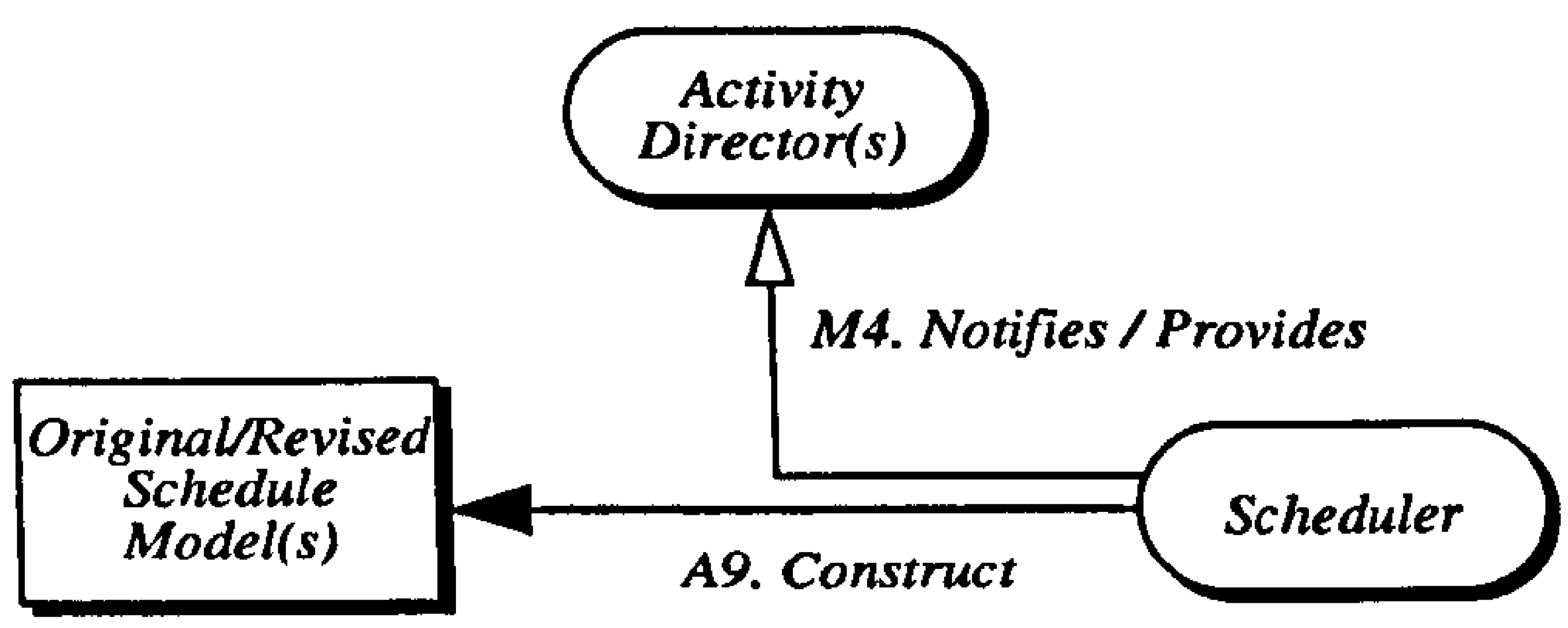

Figure 9.10 Constructing and Providing Original/Revised Schedule Models

Checking Task Dependencies / Updating Task Model

With regard to Figure 9.11, if on the implementation of an original/revised schedule model, a task is dependent on other tasks, then the Activity Director confers with the Scheduler in order to establish if those tasks have been completed *(Message M5)*.

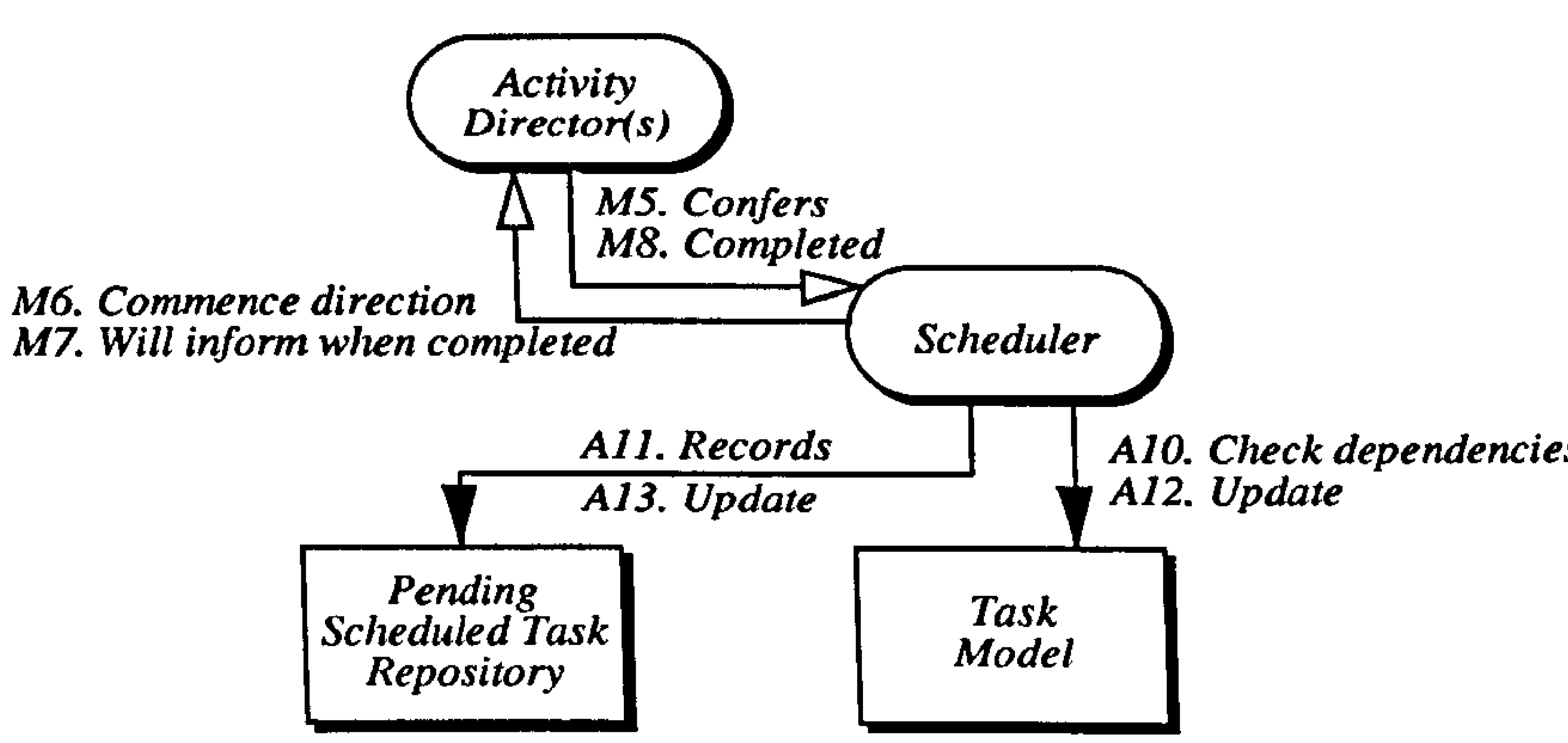

Figure 9.11 Checking Task Dependencies

The Scheduler ascertains this knowledge by checking the progress of the tasks dependent on within the task model *(Action A10)*. If all the tasks dependent on have been completed, the Scheduler informs the querying Activity Director that it may commence task direction *(Message M6)*. Otherwise, the Scheduler records knowledge of the task and those it is dependent on within the pending scheduled task repository *(Action A11)* and advises the

Activity Director that it will be informed once the tasks dependent on are all completed *(Message M7)*.

During the enactment of each original/revised schedule model, Activity Directors inform the Scheduler each time a task is completed *(Message M8)*. This enables the Scheduler to update the task model accordingly *(Action A12)*. Specifically, progress knowledge of tasks, i.e. T_{AC}, is updated indicating that they have been completed, such that in the event of re-scheduling only those uncompleted tasks are considered. In addition, the pending scheduled task repository is updated *(Action A13)* such that if the completed task appears, i.e. is delaying the scheduled start of other tasks, then it can be removed from the dependency list of pending scheduled tasks. Thus, other tasks waiting for the completion of the task may commence if there are no other outstanding tasks they are dependent on.

<u>Re-scheduling Decision-Making / Constructing Interim Schedule Models</u>

At the time instructed by the Resource Manager to consider re-scheduling, the Scheduler, with the assistance of the Activity Directors, is responsible for deciding whether or not re-scheduling is the most appropriate course of action. That is, the Scheduler must assess whether it would be more economical time-wise to continue with the current schedule or, alternatively, re-schedule a proportion of the outstanding tasks and complete the revised schedule. During the period of re-scheduling the remainder of outstanding tasks, i.e. those outstanding tasks not re-scheduled, would be able to be completed in accordance with the interim schedule models.

Prior to making a decision regarding re-scheduling, the Scheduler requests that all Activity Directors suspend their original/revised schedule models. This ensures that knowledge of tasks considered by the Scheduler is not subject to change during the decision-making process.

In order to make the decision whether or not to re-schedule, the Scheduler must determine estimated times to:

- *complete the current schedule* based on estimates provided by each Activity Director regarding the time to complete their existing original/revised schedule model,
- *derive a revised schedule* based on (i) empirically derived knowledge of the execution time of the MOGA, and (ii) knowledge held within the original/revised schedule model of each Activity Director, and,
- *complete a revised schedule* by simulating the grouping and assignment of tasks to the resources associated with the Activity Directors.

Providing it would be more economical time-wise to produce and complete a revised schedule, as opposed to adhering to the current schedule, the Scheduler makes the decision to re-schedule.

Interim schedule models are derived as a by-product of determining an estimated time to derive a revised schedule. Using the original/revised schedule models, the Scheduler establishes which tasks can be undertaken by considering (i) outstanding task dependency relationships, and (ii) the estimated cumulative time to complete these tasks remaining within the bounds of the time estimate for re-scheduling, while taking into consideration the new knowledge available regarding the forecasted efficiency of its associated resource.

Further, by determining the appropriate outstanding tasks to re-schedule and, thus, an estimated time to re-schedule, such that the remaining outstanding tasks could be undertaken and completed, the Scheduler aims to make the completion of re-scheduling near co-incident with the completion of the interim schedule models. That is, minimise the transition delay between the current and revised schedules.

In addition, simultaneously re-scheduling and undertaking tasks, using the interim schedule models, enables the agents involved in this aspect of the computational design analysis to remain as active as possible during this time period. However, concurrent re-scheduling/ undertaking tasks does not necessarily eradicate agent idleness since the tasks to be completed, according to the corresponding interim schedule model for a resource, may not precisely co-incide with the end of re-scheduling.

9.7 Resource Monitor

A Resource Monitor is responsible for sensing, forecasting and reporting resource efficiency. That is, a Resource Monitor is responsible for ensuring that throughout the operation of the DCS, the efficiency of its associated resource is observed such that, if any significant changes occur, a forecast can be made and communicated to the Resource Manager. Consequently, if appropriate, corrective action may be taken to resume the optimised allocation and utilisation of resources.

A Resource Monitor continuously monitors, records and analyses the utilisation of its associated resource in order to identify any significant changes in its actual efficiency. In particular, a Resource Monitor establishes what proportion of the current utilisation of its associated resource, expressed as a percentage, is attributed to:

- user processes, R_{user},
- system processes, R_{system}, and,

- idle, R_{idle}.

Furthermore, R_{user} may be divided into two components, i.e. user processes associated with (i) DCS operation comprising analysis tool executions, R_{DCS}, and (ii) non-DCS operation consisting of other user processes, R_{other}.

Thus, the total resource utilisation at any point in time will equal 100%, i.e.

$$R_{user} + R_{system} + R_{idle} = 100$$

where

$$R_{DCS} + R_{other} = R_{user}$$

Each Resource Monitor records resource utilisation at equal time intervals.

Monitored efficiency values at time t, R_{ME_t}, are derived using the resource coefficient, R_{CF}, with an appropriate number of the most recent measures of resource utilisation in accordance with the relationship:

$$R_{ME_t} = R_{CF} \times \left[R_{idle_t} + R_{DCS_t} + \frac{R_{other_t}}{n_{ps}}(1 + R_{system_t}) \right]$$

where n_{ps} is the number of processes being executed on the resource. This relationship has been developed from that derived by Wolski et al. in relation to sensing the availability of machines within a network [Wolski et al., 1997]. The developed relationship (i) caters for the replacement of a DCS user process as well as the addition of other processes, (ii) further divides the resource utilisation attributed to users into that associated with the operation of the DCS and that not. Assumptions regarding this relationship are that the replacement process will be entitled to all of the existing DCS and idle utilisation availability, and a fair share of other user utilisation availability.

The resource coefficient is a relative measure of the speed of a resource and is used to determine the monitored efficiency of a resource such that the variation in speed of resources can also be taken into account. If a Resource Monitor observes the utilisation of its associated resource causing its monitored efficiency to deviate beyond a specified threshold during the computational design analysis, a forecast of future efficiency must be determined. Since the monitored efficiency is calculated using the resource coefficient, then the forecasted efficiencies determined for all resources are directly comparable, which is required for purposes of scheduling and re-scheduling.

Within the DCS, forecasts of resource efficiency are determined using statistical regression analysis, which can be used for prediction [Montgomery & Johnson, 1976; Draper & Smith, 1998]. Regression can be viewed as the examination and use of associations among variables, which can be used for prediction purposes [Graybill & Iyer, 1994]. Specifically, regression, using orthogonal polynomials, is used in order to obtain a prediction of future efficiency of resources used within the DCS. Orthogonal polynomials are used to fit a polynomial model of any order in one variable.

As an example of how orthogonal polynomials are used to determine an efficiency forecast, consider the utilisation of a resource with a resource coefficient, R_{CF}, of 1.0 over twelve time steps, n, of equal interval, as presented in Table 9.4.

Time Step (n)	Resource Utilisation ($x10^{-2}$)				Resource Monitored Efficiency ($x10^{-2}$)
	R_{user}		R_{system}	R_{idle}	R_{ME}
	R_{DCS}	R_{other}			
1	0.05	0.01	0.01	0.93	0.985
2	0.04	0.01	0.02	0.93	0.975
3	0.05	0.02	0.03	0.90	0.960
4	0.05	0.04	0.03	0.88	0.951
5	0.11	0.05	0.03	0.81	0.946
6	0.07	0.06	0.03	0.84	0.941
7	0.04	0.08	0.02	0.86	0.941
8	0.03	0.08	0.02	0.87	0.941
9	0.04	0.09	0.01	0.86	0.946
10	0.05	0.06	0.02	0.87	0.951
11	0.04	0.07	0.01	0.88	0.955
12	0.03	0.06	0.01	0.90	0.960

Table 9.4 Example Resource Utilisation and Monitored Efficiency

The information presented in Table 9.4, which is based on one DCS process and one other user process, is illustrated in Figure 9.12.

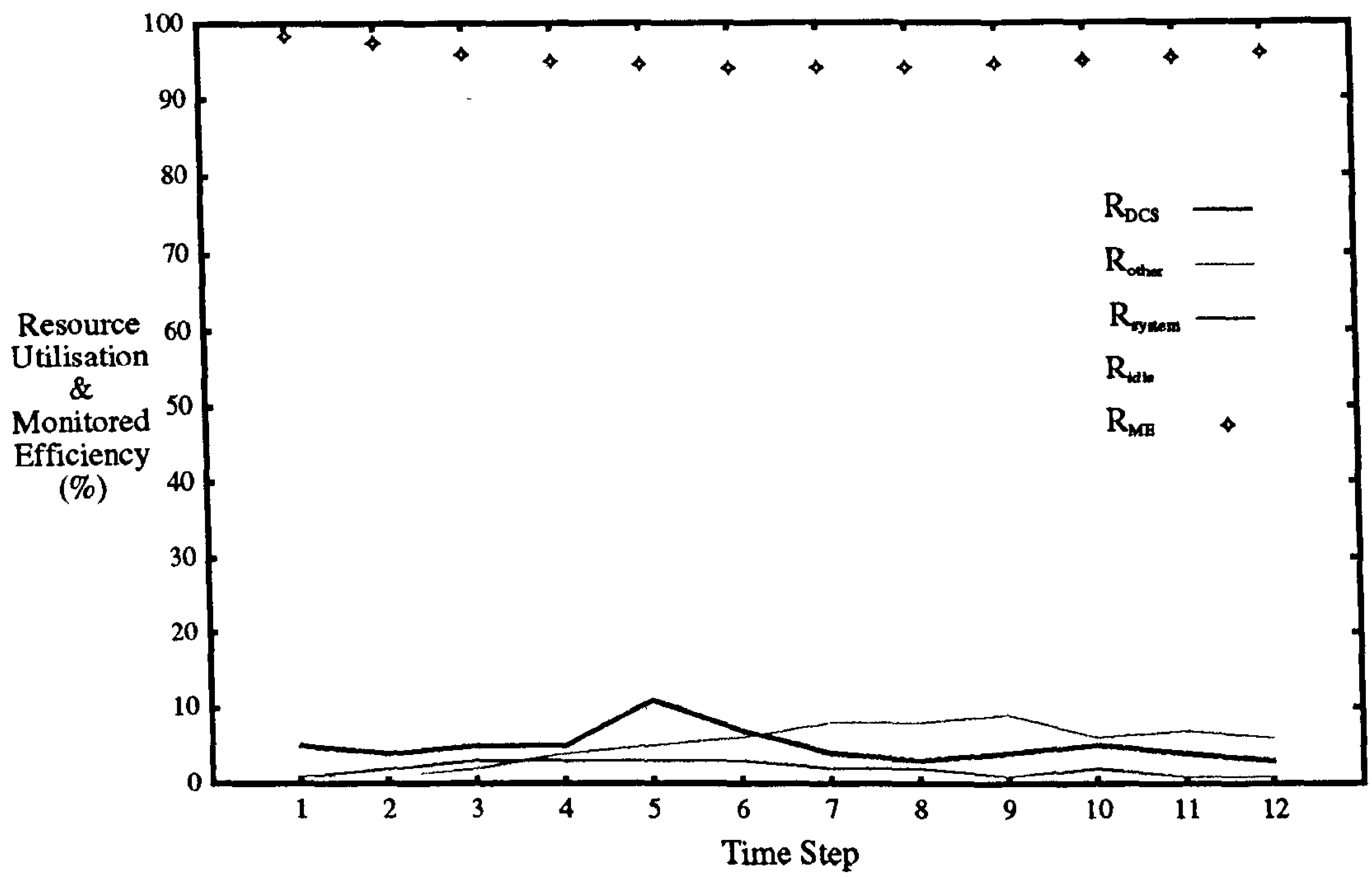

Figure 9.12 Example Resource Utilisation and Monitored Efficiency

Given the monitored efficiency for the resource under consideration over a number of time steps, a regression analysis can be performed using orthogonal polynomials. This procedure can be divided into three steps:

- calculate orthogonal polynomial table data,
- perform an analysis of variance using orthogonal polynomial table data, and,
- derive the regression equation using orthogonal polynomials.

Step 1

The calculation of orthogonal polynomial table data, using the values of monitored efficiency established in Table 9.4, is presented in Table 9.5. Orthogonal polynomial table data can be found in statistical literature [Draper & Smith, 1998].

In Table 9.5, where appropriate, (i) the sum of each variable, or (ii) the sum of the squares of each variable, are shown in the shaded cells indicating those values to be used in Steps 2 and 3.

	(a_n)	(b_n)	(c_n) $(b_n x b_n)$	(d_n)	(e_n) $(b_n x d_n)$	(f_n)	(g_n) $(b_n x f_n)$	(h_n)	(i_n) $(b_n x h_n)$	(j_n)	(k_n) $(b_n x j_n)$	(l_n)	(m_n) $(b_n x l_n)$	(n_n)	(o_n) $(b_n x n_n)$
	x	y	y^2	Ψ_1	$y\Psi_1$	Ψ_2	$y\Psi_2$	Ψ_3	$y\Psi_3$	Ψ_4	$y\Psi_4$	Ψ_5	$y\Psi_5$	Ψ_6	$y\Psi_6$
	1	98.5	9702.25	-11	-1083.5	55	5417.5	-33	-3250.5	33	3250.5	-33	-3250.5	11	1083.5
	2	97.5	9506.25	-9	-877.5	25	2437.5	3	292.5	-27	-2632.5	57	5557.5	-31	-3022.5
	3	96.0	9216.00	-7	-672.0	1	96.0	21	2016.0	-33	-3168.0	21	2016.0	11	1056.0
	4	95.1	9044.01	-5	-475.5	-17	-1616.7	25	2377.5	-13	-1236.3	-29	-2757.9	25	2377.5
	5	94.6	8949.16	-3	-283.8	-29	-2743.4	19	1797.4	12	1135.2	-44	-4162.4	4	378.4
	6	94.1	8854.81	-1	-94.1	-35	-3293.5	7	658.7	28	2634.8	-20	-1882.0	-20	-1882.0
	7	94.1	8854.81	1	94.1	-35	-3293.5	-7	-658.7	28	2634.8	20	1882.0	-20	1882.0
	8	94.1	8854.81	3	282.3	-29	-2728.9	-19	-1787.9	12	1129.2	44	4140.4	4	376.4
	9	94.6	8949.16	5	473.0	-17	-1608.2	-25	-2365.0	-13	-1229.8	29	2743.4	25	2365.0
	10	95.1	9044.01	7	665.7	1	95.1	-21	-1997.1	-33	-3138.3	-21	-1997.1	11	1046.1
	11	95.5	9120.25	9	859.5	25	2387.5	-3	-286.5	-27	-2578.5	-57	-5443.5	-31	-2960.5
	12	96.0	9216.00	11	1056.0	55	5280.0	33	3168.0	33	3168.0	33	3168.0	11	1056.0
Σ	78	1145.2	109311.52		-55.8		429.4		-35.6		-30.9		13.9	4488	-8.1
Σ^2				572		12012		5148		8008		15912			

Table 9.5 Orthogonal Polynomial Table Data

Step 2

Given n data points, the highest order polynomial that can be used to represent the data, if appropriate, is m = n - 1, i.e. there are m degrees of freedom. For the example data under consideration, n = 12 and, as such, there are 11 degrees of freedom. Thus, an eleventh order polynomial is the highest order polynomial able to represent the data.

Table 9.6 represents the analysis of variance (ANOVA) table, which allows the polynomial to be determined that best represents the relationship between time and monitored efficiency.

The significance of each term considered in the ANOVA table can be assessed by comparing the mean square ratio against the F value obtained from the F distribution [Neave, 1978]. It is deduced that there is a significant difference between the variance, i.e. mean sum of squares, of the 1st, 2nd, 3rd and 4th order terms and that of their respective residual. However, the 5th and 6th order terms are insignificant. These two consecutive insignificant terms imply that the monitored efficiency data can best be represented using a 4th order, i.e. quartic, polynomial.

Source	Sum of Squares			Degrees of Freedom		Mean Sum of Squares			Mean Square Ratio		
Total	SS_T	$\Sigma y^2 - (\Sigma y)^2/n$	21.267	m	11						
1st Order	SS_a	$(\Sigma y\Psi_1)^2 / \Sigma\Psi^2_1$	5.443	1	1	MSS_a	(SS_a)	5.443	MSR_1	MSS_a/MSS_b	3.44
Residual	SS_b	$SS_T - SS_a$	15.824	m-1	10	MSS_b	$SS_b/(m-1)$	1.582			
2nd Order	SS_c	$(\Sigma y\Psi_2)^2 / \Sigma\Psi^2_2$	15.350	1	1	MSS_c	SS_c	15.350	MSR_2	MSS_c/MSS_d	>289
Residual	SS_d	$SS_b - SS_c$	0.474	m-2	9	MSS_d	$SS_d/(m-2)$	0.053			
3rd Order	SS_e	$(\Sigma y\Psi_3)^2 / \Sigma\Psi^2_3$	0.246	1	1	MSS_e	SS_e	0.246	MSR_3	MSS_e/MSS_f	8.48
Residual	SS_f	$SS_d - SS_e$	0.228	m-3	8	MSS_f	$SS_f/(m-3)$	0.029			
4th Order	SS_g	$(\Sigma y\Psi_4)^2 / \Sigma\Psi^2_4$	0.119	1	1	MSS_g	SS_g	0.119	MSR_4	MSS_g/MSS_h	7.44
Residual	SS_h	$SS_f - SS_g$	0.109	m-4	7	MSS_h	$SS_h/(m-4)$	0.016			
5th Order	SS_i	$(\Sigma y\Psi_5)^2 / \Sigma\Psi^2_5$	0.012	1	1	MSS_i	SS_i	0.012	MSR_5	MSS_i/MSS_j	<1
Residual	SS_j	$SS_h - SS_i$	0.097	m-5	6	MSS_j	$SS_j/(m-5)$	0.016			
6th Order	SS_k	$(\Sigma y\Psi_6)^2 / \Sigma\Psi^2_6$	0.015	1	1	MSS_k	SS_k	0.015	MSR_6	MSS_k/MSS_l	<1
Residual	SS_l	$SS_j - SS_k$	0.082	m-6	5	MSS_l	$SS_l/(m-6)$	0.016			

Table 9.6 ANOVA Table

Step 3

It has been established that in order to fit the existing data, a 4th order polynomial is required, which has the form:

$$\hat{y} = \hat{\beta}_0\Psi_0(x) + \hat{\beta}_1\Psi_1(x) + \hat{\beta}_2\Psi_2(x) + \hat{\beta}_3\Psi_3(x) + \hat{\beta}_4\Psi_4(x)$$

where:

$$\hat{\beta}_0 = \frac{\Sigma y}{n} \qquad \hat{\beta}_1 = \frac{\Sigma y\Psi_1}{\Sigma\Psi^2_1} \qquad \hat{\beta}_2 = \frac{\Sigma y\Psi_2}{\Sigma\Psi^2_2} \qquad \hat{\beta}_3 = \frac{\Sigma y\Psi_3}{\Sigma\Psi^2_3} \qquad \hat{\beta}_4 = \frac{\Sigma y\Psi_4}{\Sigma\Psi^2_4}$$

and the orthogonal polynomials are:

$$\Psi_0(x) = 1 \qquad \Psi_1(x) = \lambda_1 X \qquad \Psi_2(x) = \lambda_2\left\{X^2 - \left(\frac{n^2-1}{12}\right)\right\}$$

$$\Psi_3(x) = \lambda_3\left\{X^3 - \left(\frac{3n^3-7}{20}\right)X\right\} \qquad \Psi_4(x) = \lambda_4\left\{X^4 - \left(\frac{3n^3-13}{14}\right)X^2 + \frac{3}{560}(n^2-1)(n^2-9)\right\}$$

where $X = (x-\bar{x})/\Delta x$, and $\Delta x = 1$ since the time steps are taken at equal intervals.Within this example, $\bar{x} = (\Sigma x) / n = 6.5$, and, thus X can be replaced with x - 6.5 within the orthogonal polynomials. In addition, from orthogonal polynomial tables [Draper & Smith, 1998], $\lambda_1 = 2$, $\lambda_2 = 3$, $\lambda_3 = 2/3$, and $\lambda_4 = 7/24$.

Using the equations above, the polynomial can be derived as:

$$\hat{y} = 98.8816 - 1.2772x - 0.0545x^2 + 0.0247x^3 - 0.0011x^4$$

Thus,

$$\hat{y}_{13} \approx 96.09$$

That is, the forecasted efficiency for the resource, i.e. at time step n+1, is approximately 0.961.

Since this prediction has the resource's coefficient built in, as for all forecasted efficiencies predicted within the DCS, then it is directly comparable with that of other resources, which is required for the purposes of scheduling / re-scheduling when the resource model is being accessed.

The process involving Resource Monitors supplying the Resource Manager with up-to-date forecasted efficiencies for their associated resource such that the resource model can be maintained in preparation for re-scheduling is discussed in relation to Figure 9.5, which is presented in Section 9.5.

9.8 Activity Director

The main responsibility of an Activity Director is to implement its assigned original/revised model(s) and, if appropriate, interim schedule model(s). Further, an Activity Director is responsible for assisting the Scheduler in deciding whether or not to re-schedule.

Implementation of Original/Revised Schedule Model(s)

On each occasion a new schedule is created by the Scheduler, each relevant Activity Director is allocated an original/revised schedule model, which contains knowledge of all tasks that need to be completed on its associated resource. Subsequently, an Activity Director instructs related Task Managers to execute their associated analysis tools for a particular task in the appropriate order on their common resource.

Prior to instructing the appropriate Task Manager to commence the enactment of a specific task, if that task is dependent on other tasks, the Activity Director confers with the Scheduler regarding the progress of those tasks, as discussed in accordance with Figure 9.11. If there are dependencies that have all been completed then the Scheduler indicates to the Activity Director that the task can commence. However, if the tasks dependent upon have not been completed then the Scheduler informs the Activity Director of this fact and that it will be advised once the tasks are completed. If the task under consideration is not dependent on other tasks, the Activity Director omits this consultation with the Scheduler and directly contacts the relevant Task Manager instructing it to commence the specified task.

As shown in Figure 9.13, a Task Manager can only execute its associated analysis tool if authorised to do so by its related Activity Director *(Message M1)*.

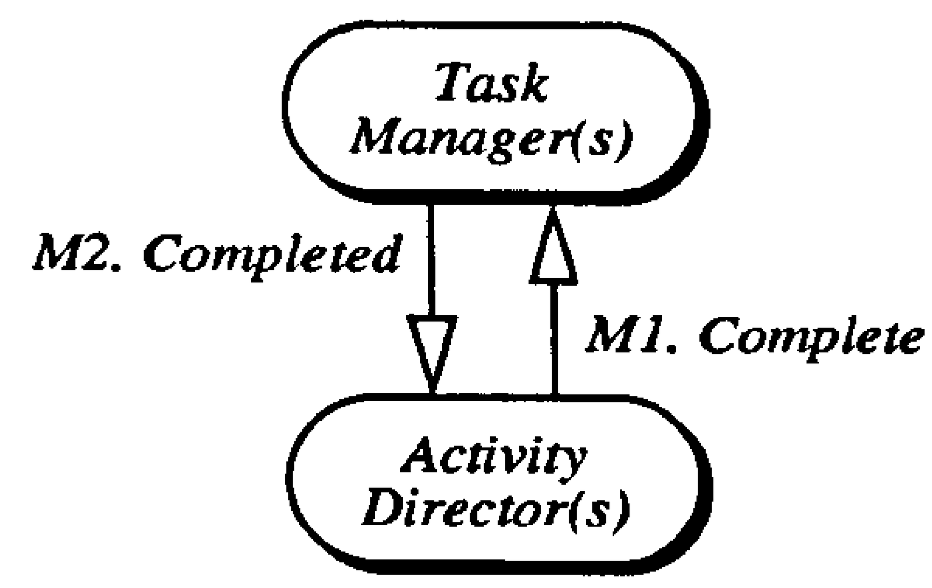

Figure 9.13 Completing a Task

Once the Task Manager receives this authorisation, and is provided with any necessary information from its related Information Manager, it proceeds to execute its associated analysis tool for a given task. On completion of its designated task, the Task Manager informs the Activity Director of this fact *(Message M2)*, which then informs the Scheduler such that it can up date the task model, and if necessary the pending scheduled task repository, to reflect this fact. In accordance with its original/revised schedule model, the Activity Director then proceeds to instruct the next Task Manager to execute its analysis tool for a particular task. This process continues until all of the tasks in the original/revised schedule model have been completed at which point the Activity Director informs the Scheduler.

The implementation of interim schedule models is as discussed for the original/revised schedule models. However, checking task dependencies is not required since all tasks are independent within the interim schedule models. The removal of checking task dependencies is required since during the implementation of the interim schedule models, the Scheduler will be occupied performing re-scheduling.

<u>Assist Re-Scheduling Decision-Making</u>

In order to make the decision whether or not to re-schedule, amongst other time estimates, the Scheduler must determine the estimated time to complete the current schedule based on estimates provided by each Activity Director regarding the time to complete their respective existing original/revised schedule model.

As illustrated in Figure 9.14, initially, the Scheduler informs each Activity Director of the need to consider re-scheduling and supplies them with an up-to-date forecasted efficiency for their respective resource *(Message M3)*.

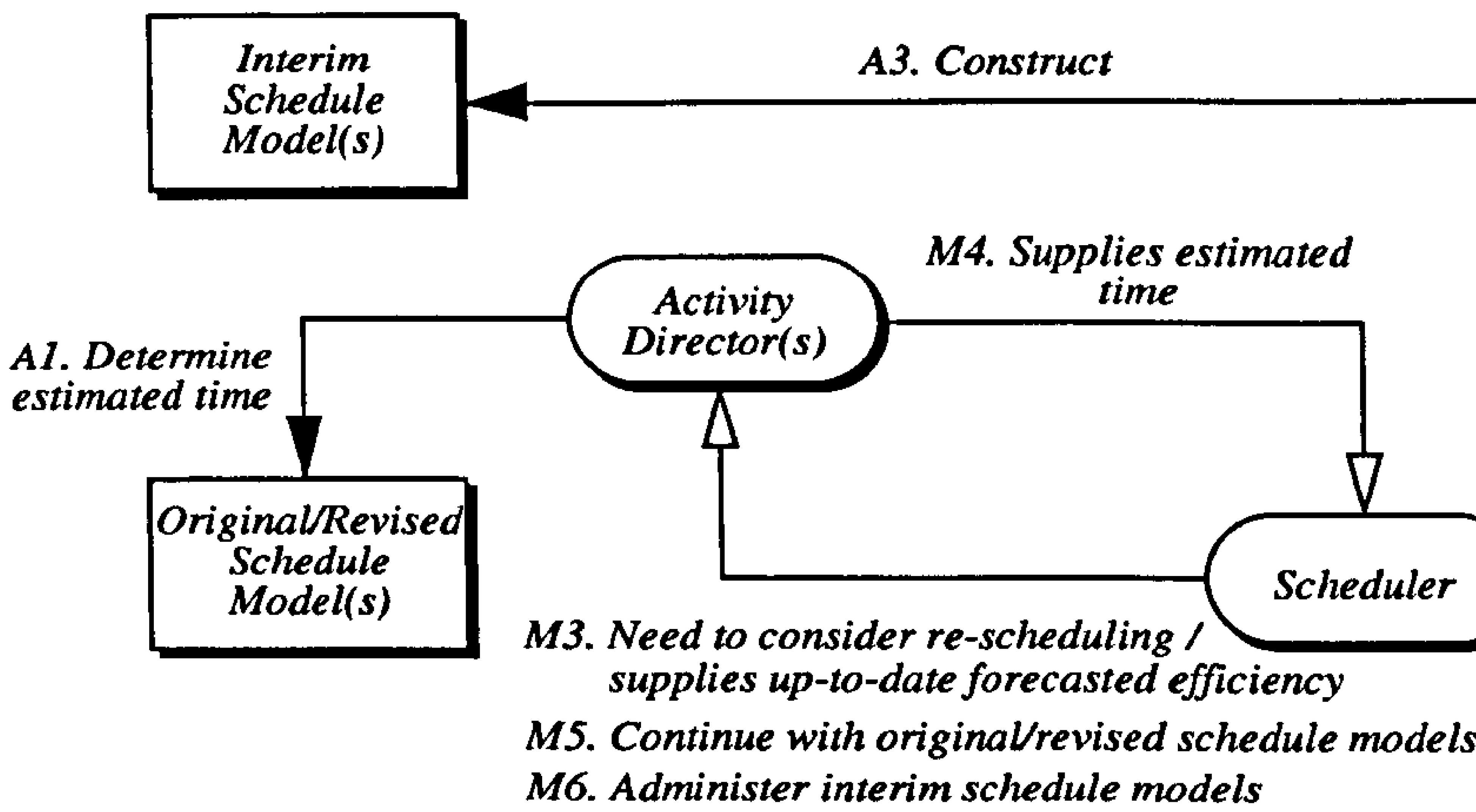

Figure 9.14 Assisting with the Re-Scheduling Decision-Making Process

Each Activity Director applies the up-to-date forecasted efficiency of its associated resource to the cumulative datum duration of its outstanding tasks in order to determine an estimated time to complete its original/revised schedule model *(Action A1)*. The Scheduler is supplied this estimated time from each Activity Director *(Message M4)*. Based on the provided time estimates to complete the current original/revised schedule models, and other time estimates, the Scheduler makes a decision of whether or not to re-schedule. If re-scheduling is not deemed appropriate, the Scheduler informs each Activity Director to continue administering its current original/revised schedule model (*Message M5*). However, if re-scheduling is required, the Scheduler informs each Activity Director that they should administer their respective interim schedule model *(Message M6)*, which were constructed *(Action A3)* as a by-product of determining an estimated time to derive a revised schedule.

9.9 Summary

The collection of agents operating within the DCS has been designed such that a computational design analysis can be conducted in an operationally co-ordinated manner. The design of the DCS enables agents to perform activities involving task management, resource management, information management, dynamic scheduling, schedule management, and task enactment simultaneously, when and where appropriate in a co-ordinated and coherent manner. For example, in the situation where re-scheduling is required, the direction of tasks and their completion, i.e. the execution of analysis tools with given input, continues simultaneously while resources are managed, monitored, and analysed.

Figure 9.15 indicates how agent types operate under normal conditions once the Co-ordination Manager has registered all agents and the necessary introductions between related agents have been made.

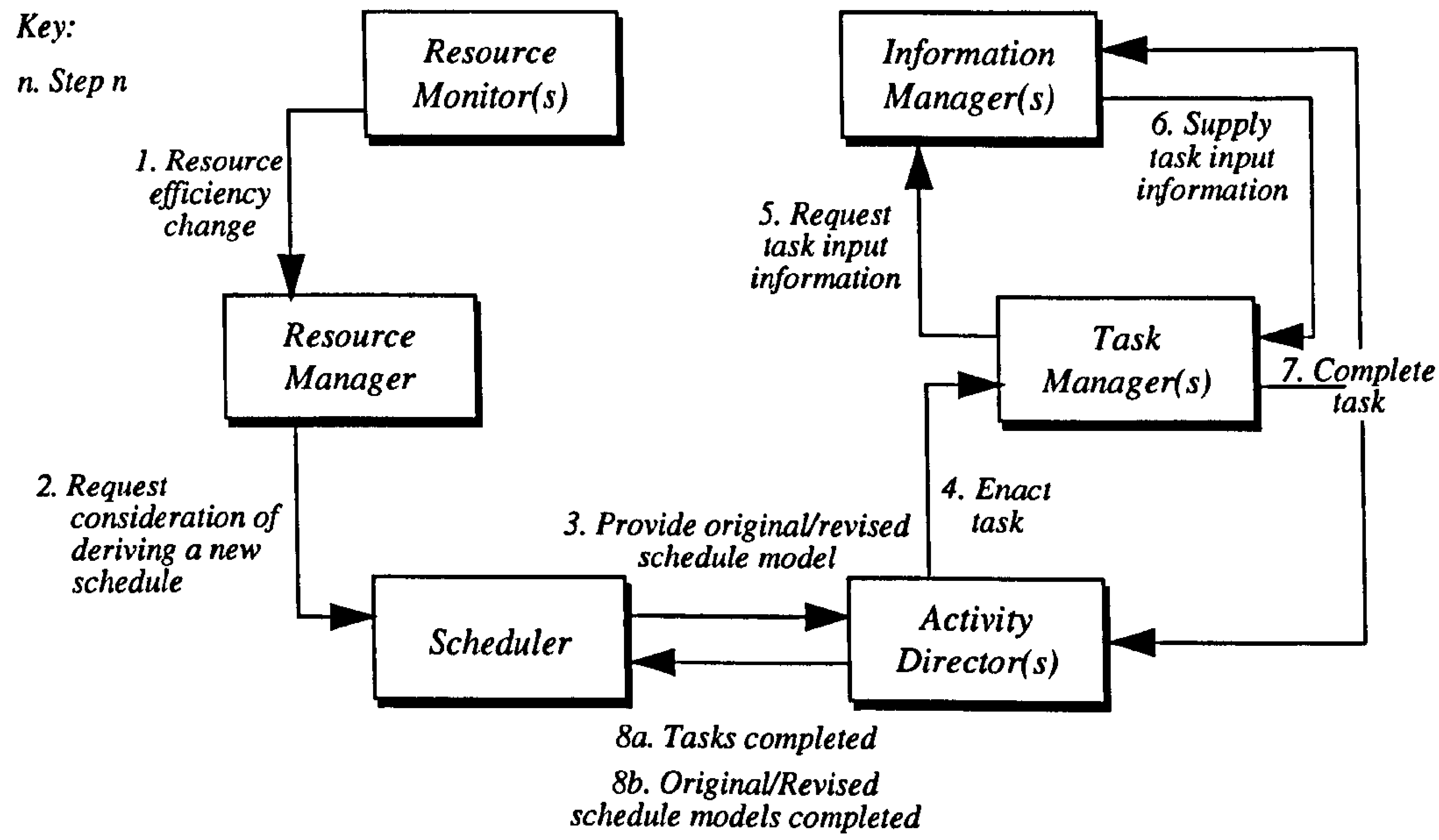

Figure 9.15 Summary of DCS Agent Operations

Step 1: Resource Monitors observe and analyse the monitored efficiency of their associated resource and inform the Resource Manager of any significant change, i.e. forecasts of resource efficiency.

Step 2: The Resource Manager is responsible for ensuring that at all times the resource model is maintained and informing the Scheduler if a new schedule may be required.

Step 3: The Scheduler, on instruction from the Resource Manager and if appropriate, invokes the MOGA to derive a schedule from which the original/revised schedule models are based. These schedule models enable the optimised utilisation to be made of the available resources with respect to the outstanding tasks within the task model.

Step 4: Activity Directors orchestrate Task Managers in accordance with their respective original/revised such that their designated tasks can be completed.

Step 5: Task Managers operate such that prior to executing their tasks, the appropriate task input information is requested from their related Information Manager.

Step 6: Information Managers provide Task Managers with the specified task input information on request.

Step 7: Task Managers complete their tasks and inform their related Activity Director *(See Step 8a)* and Information Manager, which stores the resulting task output information.

Steps 8a and 8b: Activity Directors inform the Scheduler as tasks are completed *(Step 8a)* and when they have completed their original/revised schedule models *(Step 8b)*.

This chapter has presented an agent-oriented, computer-based system. The DCS implements the real-time operational design co-ordination part of the methodology of the approach introduced in Chapter 6 and presented in Chapter 8. The DCS architecture has been presented and the agent framework, with reference to user and modelled knowledge, has been discussed.

The DCS has been developed for the purpose of evaluating the real-time operational design co-ordination part of the methodology. The evaluation of this part of the methodology, using an appropriate industrial case study, is presented in Chapters 10 and 11 respectively.

10 Practical Case Studies

The aim of this chapter is to present the application of the approach to operational design co-ordination using three practical case studies from engineering industry. Collectively, these case studies aim to facilitate the evaluation of the approach, as presented in Chapter 11.

In Section 10.1, an overview of the origin of each case study is presented. Section 10.2 presents the application of the real-time part of the methodology to a turbine blade design process, using the Design Co-ordination System presented in Chapter 9. Sections 10.3 and 10.4 present applications of the prospective part of the methodology to a marine vessel conversion design programme and the design development phase of a rotary drum dryer respectively. Throughout the presentation of each practical case study, the knowledge modelling formalism supports the respective parts of the methodology. Finally, the chapter is summarised in Section 10.5.

10.1 Overview

In order to enable the evaluation of the approach to operational design co-ordination, practical case studies from three different sectors of engineering industry have been applied to the real-time and prospective parts of the methodology.

Real-Time Operational Design Co-ordination

The real-time part of the operational design co-ordination methodology is used to demonstrate that the coherent management of tasks, resources and schedules can result in the turbine blade design process being performed in an improved manner. That is, as a result of the appropriate and timely management, tasks can be undertaken in a co-ordinated manner while resources are continuously utilised in an optimised fashion within a dynamic and unpredictable environment.

Siemens Power Generation Limited provided a practical case study to enable the application of the real-time part of the methodology, through the use of the Design Co-ordination System. Within the company, the Turbine Engineering Department is responsible for the design and development of turbine modules to upgrade/replace existing plant. One aspect of this work is the thermodynamic and mechanical design of turbine blades and bladepaths within prescribed boundaries to give optimum thermodynamic efficiency and mechanical integrity. The case study involves the use of a suite of analysis tools used in the selection of blades and bladepath, and the calculation of the associated stresses and vibration characteristics of the blades to meet the criteria stated.

Prospective Operational Design Co-ordination

The prospective part of the operational design co-ordination methodology is used to provide the designer/manager with the means of assessing the suitability of the composition of the design team at the outset of the design development phase / design programme. Such visibility at the outset will enable proposals to improve the design team to be assessed.

Practical case studies have been provided by Armstrong Technology Associates and domnick hunter limited to enable the application of the prospective part of the methodology.

Armstrong Technology Associates provide a marine design and engineering consultancy service, which can undertake the design, engineering analysis and production definition of all types of ships and floating structures for the offshore industry. The case study provided is concerned with the design programme of the conversion of a Lighter Aboard SHip (LASH) carrier, i.e. barge carrier, to a multi-role offshore support vessel.

domnick hunter limited is an international group of companies involved in the development and provision of filtration, purification and separation products for various industries and applications. The case study provided by the research and development department involves the new product introduction design development phase of a rotary drum dryer.

Two case studies are used to apply the prospective part of the methodology since the design teams are modelled differently in each case. With respect to the Armstrong Technology Associates conversion design programme, single-skilled engineers worked within a multi-disciplinary design team. In contrast, the domnick hunter limited design development phase involved multi-skilled engineers within a multi-disciplinary design team.

10.2 Turbine Blade Design Process

This case study is presented in accordance with the various interactions within the initialisation and operation stages of the real-time part of the methodology presented in Chapter 8 *(Figure 8.6, page 96 and Figure 8.18, page 112)*, and the agents operating within the Design Co-ordination System discussed in Chapter 9 *(Figure 9.2, page 127)*.

The case study provided by Siemens Power Generation Limited involves the use of a suite of analysis tools that the designer uses in the turbine blade design process. The deterministic analysis tools are related as shown in Figure 10.1.

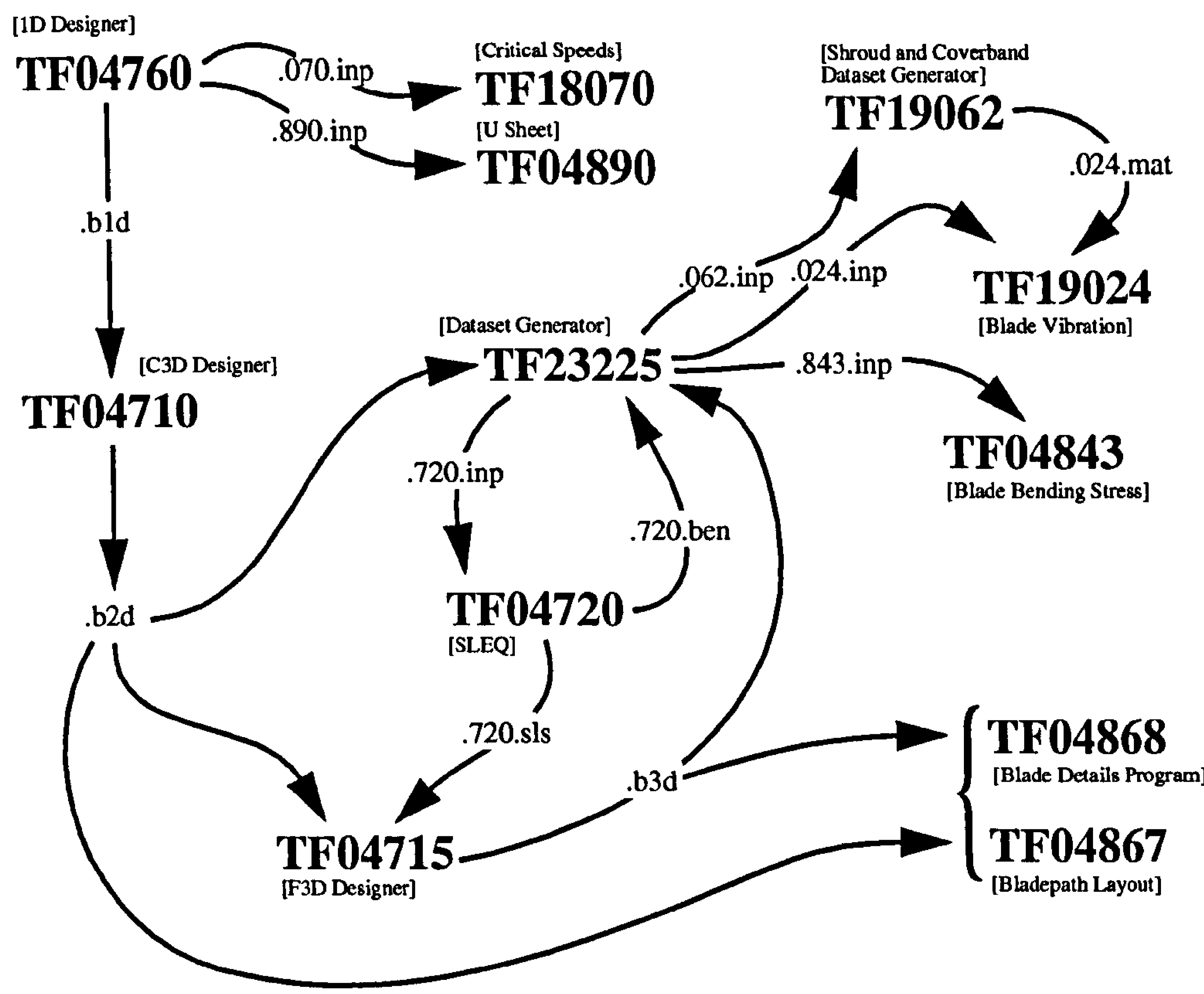

Figure 10.1 Siemens Power Generation Limited: Turbine Blade Design Process

For reasons of confidentiality, descriptions of these analysis tools were not divulged by the company. Thus, throughout this section, analysis tools are referred to by their associated *TF number.*

In Figure 10.1, the turbine blade design process is shown to involve twelve analysis tools. Analysis tools *TF18070*, *TF04890*, *TF04868* and *TF04867* were not provided. Further, analysis tool *TF23225* could be used for three purposes and, as such, it is modelled as three individual analysis tools, i.e. *TF23225_1*, *TF23225_2* and *TF23225_3*. Thus, the case study to be used consists of ten analysis tools.

10.2.1 Initialisation

On instantiation of the DCS, the appropriate agents are created. As in any application of the DCS, a single Co-ordination Manager, Resource Manager and Scheduler are created. In this case study ten analysis tools and four resources are used. Thus, ten Information Managers are created, forty Task Managers, four Resource Monitors and four Activity Directors. Collectively, sixty one agents are created for operation within the DCS.

Initially, the Co-ordination Manager receives messages from all other agents that are registered and acknowledged. On acknowledgement of their registration, agents request knowledge regarding related agents from the Co-ordination Manager. Once this knowledge is supplied, related agents can then communicate directly with one another when required.

Designer Defined Tasks

The designer provides knowledge of the tasks to be completed, i.e. executions of analysis tools. Subsequently, this knowledge is used by the (i) Resource Manager to construct a resource model (See Table 10.2), and (ii) Scheduler to construct an analysis tool dependency matrix (See Table 10.3) and task model (See Table C.1 in Appendix C).

The turbine blade design process involves a number of executions of each of the analysis tools as shown in Table 10.1, where n_{BR} is the number of blade rows under consideration.

T_I	Analysis Tool	Number of Executions
0	TF04760	1
1	TF04710	1
2	TF23225_1	1
3	TF04720	1
4	TF23225_2	n_{BR}
5	TF23225_3	$n_{BR}/2$
6	TF19062	$n_{BR}/2$
7	TF19024	$n_{BR}/2$
8	TF04843	n_{BR}
9	TF04715	1

Table 10.1 Number of Analysis Tool Executions

In this case study, the number of blade rows under consideration is thirty six, i.e. eighteen fixed and eighteen rotating, as specified by the designers at Siemens Power Generation Limited. Thus, the total number of tasks to be undertaken and completed is one hundred and thirty one. In accordance with Table 10.1, five of the analysis tools are only required to be executed once. Two of the analysis tools need to be executed for each blade row. In addition, three of the analysis tools are only required to be executed for each of the rotating blade rows.

For each task, the designer allocates T_I, T_L, T_{DD}, $T_{[T_{In}]}$ and $T_{[T_{Out}]}$. Values of T_I assigned to each analysis tool are shown in Table 10.1. Designer defined task knowledge for the turbine blade design process is included within the task model, which is summarised in Table C.1 of Appendix C.

Resource Model

Based on knowledge provided by the designer and ascertained from the Resource Monitors, the Resource Manager constructs a resource model. For each of the four resources to be used, the resource model consists of knowledge attributes as shown in Table 10.2.

Identification	Status	Performance		
R_I	R_A	R_{FE}	R_{LT}	R_{UT}
1	1	0.989	0.5	1.0
2	1	0.996	0.5	1.0
3	1	0.961	0.5	1.0
4	1	0.916	0.5	1.0

Table 10.2 Resource Model

Values of R_I are arbitrarily assigned 1, 2, 3, and 4. Values of R_A are assigned to unity for each resource since they are all available for use.

The Resource Manager maintains values of forecasted efficiency, R_{FE}, within the resource model with the assistance of the Resource Monitors. As described in Chapter 9, forecasted efficiency is expressed in terms of availability since, within the operating environment of the DCS, it is the measure of the potential efficiency able to be used that determines the expected efficiency of a resource.

Initial values assigned to R_{FE} are calculated by the respective Resource Monitor based on values of R_{ME} observed over the period of time prior to scheduling. The procedure of obtaining R_{FE} based on values of R_{ME} is explained in *monitor resources (page 163)* and *forecast and revise resource model (page 165)* in Section 10.2.2. Within the resource model shown in Table 10.2, a single value is assigned to R_{FE}, R_{LT} and R_{UT} since only one type of task can be undertaken and completed utilising a resource, i.e. the execution of an analysis tool for given input.

Analysis Tool Dependency Matrix

Knowledge provided by the designer regarding the (i) input and output requirements, and (ii) datum durations, of each analysis tool enables the Scheduler to construct an analysis tool dependency matrix. The designer provided knowledge is based on the relationships between the analysis tools in accordance with Figure 10.1, i.e. the input and output files required for each analysis tool. The analysis tool dependency matrix also includes the datum durations of executing each respective analysis tool in the diagonal elements of the matrix, which are obtained from arbitrary executions using a reference resource, i.e. machine, in the local area network. By comparing the input requirements of each analysis tool, $T_{[T_{In}]}$, against the output requirements, $T_{[T_{Out}]}$, of all other analysis tools, the Scheduler is able to determine the dependency relationships between them.

The analysis tool dependency matrix for the turbine blade design process is presented in Table 10.3.

	TF04760	TF04710	TF23225_1	TF04720	TF23225_2	TF23225_3	TF19062	TF19024	TF04843	TF04715
TF04760	97	0	0	0	0	0	0	0	0	0
TF04710	1	6	0	0	0	0	0	0	0	0
TF23225_1	0	1	6	0	0	0	0	0	0	0
TF04720	0	0	1	14	0	0	0	0	0	0
TF23225_2	0	1	0	1	1	0	0	0	0	0
TF23225_3	0	1	0	0	0	2	0	0	0	0
TF19062	0	0	0	0	0	1	1	0	0	0
TF19024	0	0	0	0	0	1	1	1	0	0
TF04843	0	0	0	1	1	0	0	0	1	0
TF04715	0	1	0	1	0	0	0	0	0	11

Table 10.3 Analysis Tool Dependency Matrix

Task Model

In order to construct the task model, the Scheduler uses knowledge of the designer defined tasks and the analysis tool dependency matrix.

As stated earlier, knowledge of designer defined tasks comprises of T_I, T_L, T_{DD}, $T_{[T_{In}]}$ and $T_{[T_{Out}]}$.

Within the task model, tasks are assigned additional knowledge, namely T_G and T_{AC}. In addition, the analysis tool dependency matrix, which was constructed using knowledge of $T_{[T_{In}]}$ and $T_{[T_{Out}]}$ for each analysis tool, is used to determine T_N and $T_{[T_G]}$ for each task. A summary of the task model for the turbine blade design process is shown in Table C.1 of Appendix C.

10.2.2 Operation

Once the initialisation stage of the real-time part of the methodology implemented within the DCS is completed, the operation stage can begin.

Derive an Optimised Original Schedule

Prior to commencing the turbine blade design process, an original schedule must be derived such that tasks can be undertaken in a co-ordinated fashion while resources are utilised in an optimised manner. In order to derive an optimised original schedule, the Scheduler uses a multi objective genetic algorithm (MOGA) [Todd, 1997] allied with knowledge of outstanding tasks and available resources from their respective models.

At the outset of the turbine blade design process, all tasks are outstanding, i.e. $T_{AC} = 0$, and, thus, all need to be scheduled such that they can be undertaken and completed in a co-ordinated manner. The Scheduler prepares the task and resource knowledge required for use with the MOGA. Task knowledge comprises T_G, T_{DD}, T_N, and $T_{[T_G]}$ for each task, which is obtained from the task model. Furthermore, the Scheduler notes the number of tasks to be scheduled, n_{TS}, and the cumulative number of dependencies for those tasks, n_{TD}.

As indicated in the resource model, each of the four resources are available for utilisation since R_A=1 for all of them. With regard to each of the available resources to be utilised, the Scheduler requests that the Resource Manager provide the relevant knowledge, i.e. R_I and R_{FE}. Knowledge of the forecasted efficiency for each resource is readily available since the Resource Manager has recently had this supplied from each respective Resource Monitor as described in Section 10.2.1. The Scheduler also notes the number of resources to be considered for scheduling, n_{RS}.

On execution of the MOGA a Pareto optimal set of schedules is created. The *best* schedule is selected from this set based on three decision-making criteria, i.e. minimise (i) time, (ii) number of resources, and (iii) resource utilisation. The *best* schedule is presented in the form of an original schedule model for resource $R_I = 1$ in Table 10.4. For resources $R_I = 2$, 3 and 4, values of T_G for tasks within original schedule models are presented in Table C.2 of Appendix C.

With regard to the schedule, tasks are allocated to resources taking into consideration the datum duration of the tasks, dependencies between tasks, and the forecasted efficiencies of the resources.

Construct Original Schedule Models

The Scheduler uses the *best* optimised schedule to construct an original schedule model for each resource allocated to be utilised. The responsibility of administering the enactment of each original schedule model lies with the Activity Director of the corresponding resource.

Thus, the Scheduler notifies and provides each Activity Director with their respective original schedule model. In Table 10.4, a number of knowledge attributes are shown regarding the tasks to be undertaken and completed utilising resource R_I=1. Furthermore, tasks are listed in the order that they should be undertaken.

Certain knowledge attributes have not been included within the original schedule models, since they are not used, namely T_S, T_F, T_{ED}, T_{AC}, and T_{EC}. That is, T_S and T_F are implicit in the order the tasks appear in the original schedule model. T_{ED} can be obtained by dividing T_{DD} by R_{FE}. T_{AC} and T_{EC} are not included since tasks are non pre-emptive, i.e. once started they cannot be interrupted.

T_I	T_L	T_G	T_{DD}	$T_{[T_{In}]}$	$T_{[T_{Out}]}$	T_N	$T_{[T_I]}$, $T_{[T_L]}$
1	0	1	6	hp1.b1d	hp1.b2d	1	[0],[0]
2	0	2	6	hp1.b2d	hp1.720.inp	1	[1],[0]
5	7	47	2	hp1.b2d	hp1.016.024.inp, hp1.016.062.inp	1	[1],[0]
5	0	40	2	hp1.b2d	hp1.002.024.inp, hp1.002.062.inp	1	[1],[0]
5	8	48	2	hp1.b2d	hp1.018.024.inp, hp1.018.062.inp	1	[1],[0]
6	12	70	1	hp1.026.062.inp	hp1.026.062.out, hp1.026.024.mat	1	[5],[12]
7	15	91	1	hp1.032.024.inp, hp1.032.024.mat	hp1.032.024.out	2	[5,6], [15,15]
5	10	50	2	hp1.b2d	hp1.022.024.inp, hp1.022.062.inp	1	[1], [0]
5	16	56	2	hp1.b2d	hp1.034.024.inp, hp1.034.062.inp	1	[1],[0]
6	14	72	1	hp1.030.062.inp	hp1.030.062.out, hp1.030.024.mat	1	[5], [14]
4	33	37	1	hp1.b2d, hp1.720.ben	hp1.034.843.inp	2	[1,3], [0,0]
9	0	130	11	hp1.b2d, hp1.720.sls	hp1.b3d	2	[1,3], [0,0]
4	13	17	1	hp1.b2d, hp1.720.ben	hp1.014.843.inp	2	[1,3], [0,0]
4	5	9	1	hp1.b2d, hp1.720.ben	hp1.006.843.inp	2	[1,3], [0,0]
8	20	114	1	hp1.720.ben, hp1.021.843.inp	hp1.021.843.out	2	[3,4], [0,20]
4	0	4	1	hp1.b2d, hp1.720.ben	hp1.001.843.inp	2	[1,3], [0,0]
7	9	85	1	hp1.020.024.inp, hp1.020.024.mat	hp1.020.024.out	2	[5,6], [9,9]
8	18	112	1	hp1.720.ben, hp1.019.843.inp	hp1.019.843.out	2	[3,4], [0,18]
4	3	7	1	hp1.b2d, hp1.720.ben	hp1.004.843.inp	2	[1, 3], [0,0]
8	9	103	1	hp1.720.ben, hp1.010.843.inp	hp1.010.843.out	2	[3,4], [0,9]
8	21	115	1	hp1.720.ben, hp1.022.843.inp	hp1.022.843.out	2	[3,4], [0,21]
4	26	30	1	hp1.b2d, hp1.720.ben	hp1.027.843.inp	2	[1,3], [0,0]
4	32	36	1	hp1.b2d, hp1.720.ben	hp1.033.843.inp	2	[1,3], [0,0]
8	19	113	1	hp1.720.ben, hp1.020.843.inp	hp1.020.843.out	2	[3,4], [0,19]
8	13	107	1	hp1.720.ben, hp1.014.843.inp	hp1.014.843 out	2	[3,4], [0,13]
8	12	106	1	hp1.720.ben, hp1.013.843.inp	hp1.013.843.out	2	[3,4], [0,12]

Table 10.4 Original Schedule Model for Resource R_I = 1

Check Dependencies, Direct and Undertake/Complete Tasks

On being provided their original schedule models, the Activity Director of each resource to be utilised begins administering the designated tasks to be undertaken. In addition to the Activity Directors, this procedure involves the collaborative effort of the Scheduler, related Task Managers and Information Managers. Indeed, Activity Directors, Task Managers and Information Managers associated with each resource work simultaneously in a coherent manner throughout the operation of the DCS.

As indicated in Table 10.4, the task with $T_I = 1$ and $T_L = 0$ is the first task to be undertaken using resource $R_I = 1$, i.e. the only execution of analysis tool *TF04710* as shown in Table 10.2. For brevity, in the remainder of this section, task's T_I and T_L will be abbreviated to $T(T_I, T_L)$, i.e. the task previously stated is denoted as T(1,0).

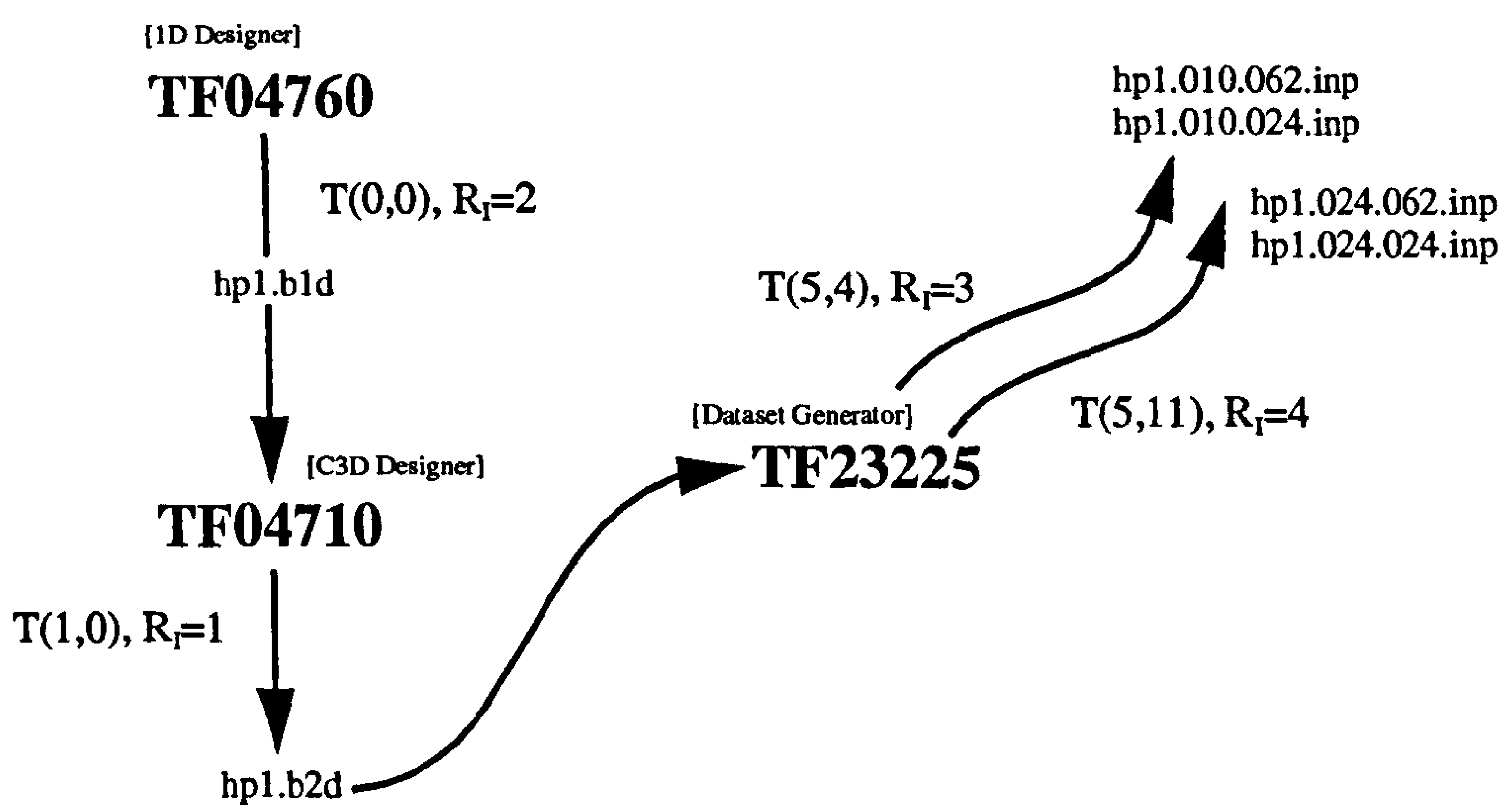

Figure 10.2 Initial Tasks to be Undertaken

On inspecting its associated original schedule model, the Activity Director recognises that this task is dependent on the completion of T(0,0), i.e. the single execution of analysis tool *TF04760* as shown in Figure 10.2. This dependency exists since *TF04710* requires the output file produced on executing *TF04760*, i.e. *hp1.b1d*. Thus, the Activity Director confers with the Scheduler in order to establish if the task dependent on has been completed. The Scheduler checks the task model to determine T_{AC} of the dependent T(0,0). Since the execution of *TF04760* has not been completed, i.e. $T_{AC} = 0$, *TF04710* cannot commence. As such, the Scheduler records within the pending scheduled task repository that T(1,0) is awaiting the completion of T(0,0). Similarly, as shown in Figure 10.2, the first task to be undertaken using resource $R_I = 3$, i.e. T(5,4), and $R_I = 4$, i.e. T(5,11), cannot be executed since they require information that will only be made available on the completion of T(1,0), i.e. *hp1.b2d*.

At the outset of the turbine blade design process, only T(0,0) on resource $R_I = 2$ is able to commence since it has no dependencies. That is, *hp1.760.inp* is provided by the designer prior to the start of the turbine blade design process.

The pending scheduled task repository at the point described is shown in Table 10.5.

i	T_I	T_L	T_{ON}	$[T_{I,i,j}]$	$[T_{L,i,j}]$
1	1	0	1	0	0
2	5	4	1	1	0
3	5	11	1	1	0

Table 10.5 Pending Scheduled Task Repository

where $i = \{1, 2, ..., n_{PST}\}$ and $j = \{1, 2, ..., T_{ON,i}\}$.

When intending to undertake any task, one of three possible situations exist:

- the task can start since it is not dependent on any other tasks,
- the task can start since all tasks it is dependent on have been completed, or,
- the task cannot start since at least one of the tasks it is dependent on has not been completed.

Tasks are only recorded within the scheduled task repository in the third situation since they cannot start.

Once the Activity Director associated with resource R_I=2 has conferred with the Scheduler and is informed that T(0,0) may be undertaken, it instructs the related Task Manager associated with the analysis tool to complete the task, i.e. execute *TF04760.*

Request, Provide and Supply Task Information

Prior to undertaking the task, i.e. executing analysis tool *TF04760*, the relevant Task Manager requests that its related Information Manager provide necessary information according to $T_{[T_{In}]}$, i.e. input file *hp1.760.inp*. In response, the Information Manager retrieves the input file from the task information repository. On notification that the requested information has been provided, the Task Manager commences with the execution of its associated analysis tool.

Once *TF04760* has been executed, the Task Manager informs its related Information Manager such that the output files produced in accordance with $T_{[T_{Out}]}$, i.e. *hp1.760.out* and *hp1.b1d*, can be stored in the task information repository. Thus, these files are readily available in the event of either of them being required as input for the execution of other analysis tools, specifically, at this time in the process, the pending scheduled T(1,0).

Update Task Model

On completion of T(0,0), the Task Manager informs its related Activity Director, which then informs the Scheduler of this fact. The Scheduler updates the task model to reflect the completion of the task by setting $T_{AC}=1$. Updating the task model in this manner ensures that in the event of the need to re-schedule, only outstanding tasks will be considered, i.e. tasks with $T_{AC}=0$.

Remove Dependencies and Commence Direction of Pending Scheduled Tasks

In addition to updating the task model, the Scheduler updates the pending scheduled task repository such that any tasks solely awaiting the completion of the recently completed task may be undertaken. Specifically, since T(0,0) has been completed, the Scheduler removes this dependency from the pending scheduled task repository and decrements T_{ON} where appropriate. Consequently, since T_{ON} becomes nil for T(1,0) then it can be undertaken. The commencement of this task is instigated by the Scheduler who informs the appropriate Activity Director.

Monitor Resources

At regular time intervals throughout the operation of the DCS, each Resource Monitor observes the actual monitored efficiency of their associated resource such that any significant deviation exceeding the specified thresholds, i.e. R_{UT} or R_{LT}, can be identified.

Throughout the turbine blade design process, Resource Monitors observe the various constituents of usage of their associated resource at 5 second intervals. Based on these observations, each Resource Monitor determines the monitored efficiency at corresponding time intervals of its associated resource using the equation:

$$R_{ME_t} = R_{CF} \times \left[R_{idle_t} + R_{DCS_t} + \frac{R_{other_t}}{n_{ps}}(1 + R_{system_t}) \right]$$

where each parameter is as defined in Section 9.7 of Chapter 9.

In Figure 10.3, the utilisation and monitored efficiency of resource $R_I=4$ over a period of the turbine blade design process is shown as observed by the associated Resource Monitor.

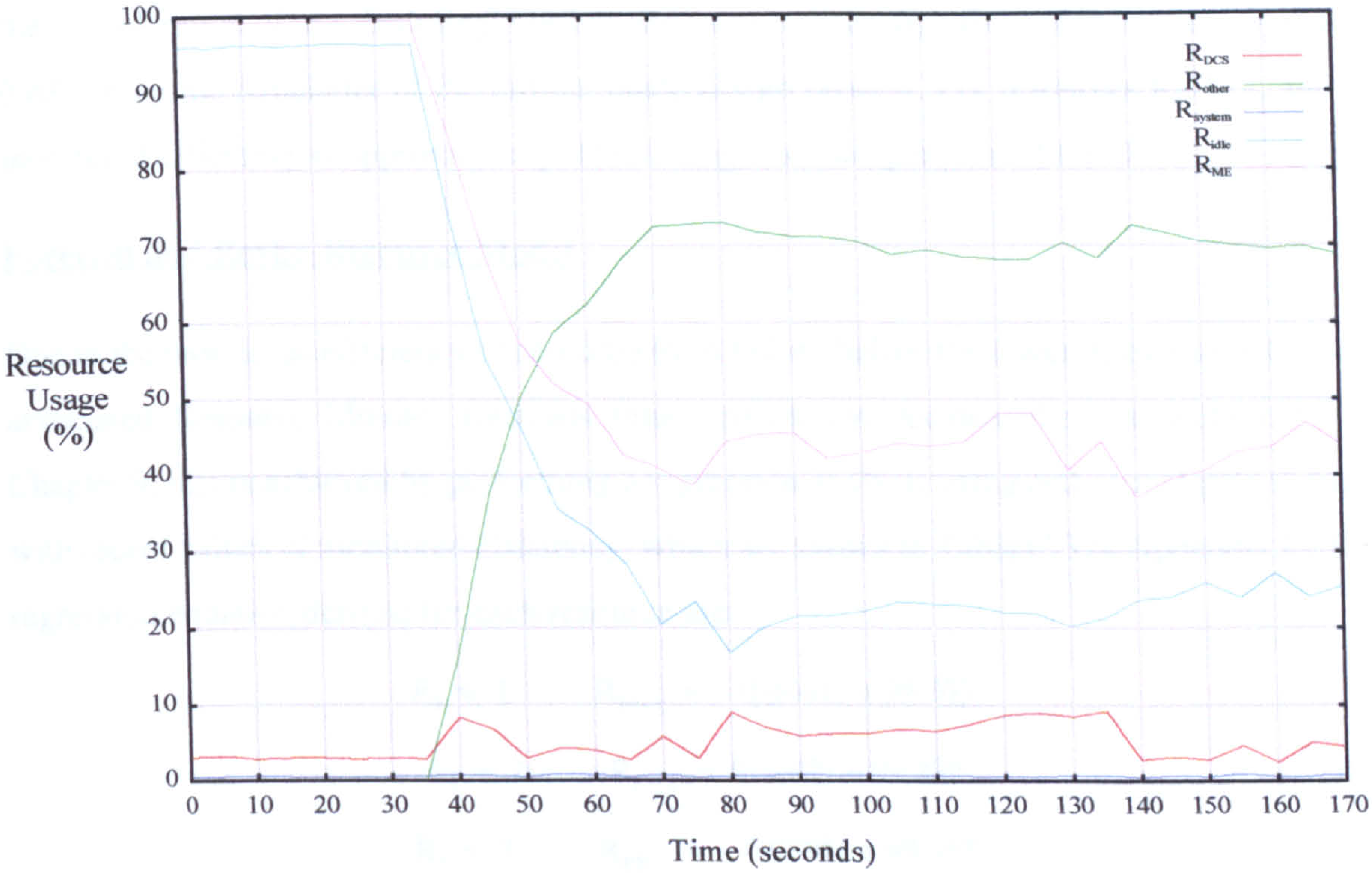

Figure 10.3 $R_I = 4$, Resource Usage versus Time

Figure 10.4 represents R_{ME} for all four resources employed over the same time period shown in Figure 10.3.

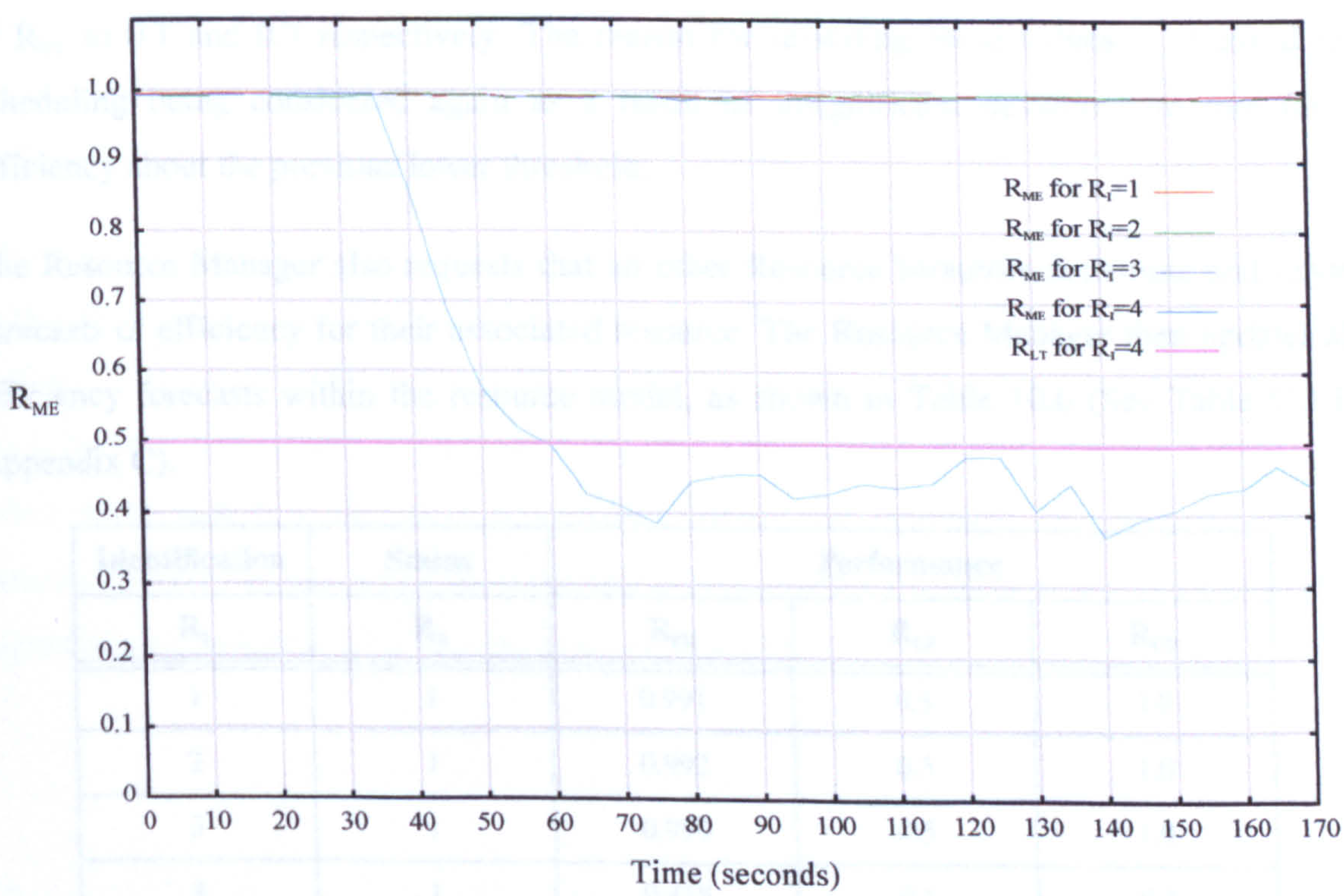

Figure 10.4 Resource Monitored Efficiency versus Time

In Figure 10.4, for resource R_I=4 it can be seen that at approximately t = 60 seconds there is a deviation in monitored efficiency that exceeds its lower threshold of R_{LT}=0.5, which instigates the consideration of re-scheduling. Further, for this resource, R_{ME} fluctuates between 0.38 and 0.48 during the remainder of the turbine blade design process. For resources R_I=1, 2, and 3, monitored efficiency is approximately 0.99 throughout the operation of the DCS.

Forecast and Revise Resource Model

Due to the monitored efficiency of resource R_I=4 falling below the lower threshold of 0.5, the associated Resource Monitor forecasts future efficiency. As described in Section 9.7 of Chapter 9, this is achieved by performing a regression analysis using orthogonal polynomials with recent values of monitored efficiency, which are shown in Table C.3 of Appendix C. The regression equation derived for each resource are:

$$R_I = 1 \qquad R_{FE,t} = -0.0441t + 99.703$$

$$R_I = 2 \qquad R_{FE,t} = 0.0007t + 99.229$$

$$R_I = 3 \qquad R_{FE,t} = -0.0392t + 99.555$$

$$R_I = 4 \qquad R_{FE,t} = -0.1979t^4 + 7.7977t^3 - 111.97t^2 + 683.18t - 1395.9$$

The Resource Monitor supplies the forecasted efficiency to the Resource Manager, which updates the resource model accordingly. The Resource Manager also re-sets the values of R_{LT} or R_{UT} to 0.1 and 0.7 respectively. The reason for re-setting these values is to avoid re-scheduling being considered again as a result of insignificant deviations in monitored efficiency about the previous lower threshold.

The Resource Manager also requests that all other Resource Monitors determine and report forecasts of efficiency for their associated resource. The Resource Manager then updates all efficiency forecasts within the resource model, as shown in Table 10.6 (See Table C.3 in Appendix C).

Identification	Status	Performance		
R_I	R_A	R_{FE}	R_{LT}	R_{UT}
1	1	0.991	0.5	1.0
2	1	0.992	0.5	1.0
3	1	0.990	0.5	1.0
4	1	0.418	0.1	0.7

Table 10.6 Revised Resource Model

Subsequently, the Resource Manager instructs the Scheduler to consider re-scheduling based on the up-to-date knowledge held within the resource model.

Derive Interim Schedule Models

In order to establish whether interim schedule models need to be derived, i.e. re-scheduling is required, the Scheduler assesses whether it is more economical time-wise to continue with the current schedule or, alternatively, re-schedule a proportion of the outstanding tasks and complete the revised schedule. During the period of re-scheduling the remainder of outstanding tasks would be able to be completed in accordance with the interim schedule models.

In order to make the decision whether or not to re-schedule, the Scheduler determines estimated times to: (i) complete the current schedule, (ii) derive a revised schedule, and (iii) complete a revised schedule. Prior to determining any of these estimated times, the Scheduler requests that each Activity Director suspend administering their associated original schedule models. At the time of suspension being requested, three of the four Activity Directors are awaiting related Task Managers to complete the task being undertaken. Due to these tasks being non pre-emptive, they are completed before the Activity Directors can suspend direction. One of the Activity Directors is awaiting the completion of another task such that it could inform a related Task Manager to undertake the pending scheduled task. As such, this Activity Director suspends administering its original schedule model immediately. Once all of the Activity Directors suspend their original schedule models, the Scheduler is able to begin determining the three time estimates.

Determining these time estimates requires the consideration of the one hundred and four outstanding tasks within the original schedule models of each Activity Director, as presented in Table 10.7. Shaded cells in Table 10.7 signify those outstanding tasks that could potentially be included within an interim schedule model since they are independent, i.e. T_N=0 at the point when the Scheduler considers re-scheduling. Further, the estimated durations of tasks are summed in order to determine the cumulative time required to complete the tasks that could potentially be included in the interim schedule models.

$R_I = 1, R_{PR} = 0.991$				$R_I = 2, R_{PR} = 0.992$				$R_I = 3, R_{PR} = 0.990$				$R_I = 4, R_{PR} = 0.418$			
T_G	T_N	T_{DD}	ΣT_{ED}	T_G	T_N	T_{DD}	ΣT_{ED}	T_G	T_N	T_{DD}	ΣT_{ED}	T_G	T_N	T_{DD}	ΣT_{ED}
72	1	1	-	76	1	1	-	28	0	1	1.01	65	0	1	2.39
37	0	1	1.01	43	0	2	2.02	86	1	1	-	83	1	1	-
130	0	11	12.11	88	0	1	3.02	74	0	1	2.02	58	0	1	4.78
17	0	1	13.12	60	0	1	4.03	34	0	1	3.03	49	0	2	9.57
9	0	1	14.13	54	0	2	6.05	64	0	1	4.04	81	0	1	11.96
114	1	1	-	53	0	2	8.07	12	0	1	5.05	68	0	1	14.35
4	0	1	15.14	24	0	1	9.07	102	1	1	-	78	1	1	-
85	2	1	-	35	0	1	10.08	39	0	1	6.06	16	0	1	16.75
112	1	1	-	33	0	1	11.09	87	0	1	7.07	118	1	1	-
7	0	1	16.15	18	0	1	12.10	21	0	1	8.08	25	0	1	19.14
103	1	1	-	19	0	1	13.11	66	0	1	9.09	92	1	1	-
115	1	1	-	109	1	1	-	31	0	1	10.10	123	1	1	-
30	0	1	17.15	22	0	1	14.11	117	1	1	-	8	0	1	21.53
36	0	1	18.16	90	2	1	-	67	1	1	-	26	0	1	23.92
113	1	1	-	108	1	1	-	15	0	1	11.11	116	1	1	-
107	1	1	-	38	0	1	15.12	105	1	1	-	129	1	1	-
106	1	1	-	128	1	1	-	94	1	1	-	14	0	1	26.32
				111	1	1	-	96	1	1	-	104	1	1	-
				121	1	1	-	59	0	1	12.12	27	0	1	28.71
				100	1	1	-	97	1	1	-	10	0	1	31.10
				99	1	1	-	61	1	1	-	32	0	1	33.49
				6	0	1	16.13	79	1	1	-	71	1	1	-
				5	0	1	17.14	23	0	1	13.13	98	1	1	-
				122	1	1	-					11	0	1	35.89
				13	0	1	18.15					101	1	1	-
				89	2	1	-					95	1	1	-
				82	1	1	-					84	1	1	-
				20	0	1	19.15					29	0	1	38.28
				120	1	1	-					127	1	1	-
				77	1	1	-					110	1	1	-
				124	1	1	-					126	1	1	-
				119	1	1	-					125	1	1	-

Table 10.7 Outstanding Tasks within Original Schedule Models

Estimated Time to Complete the Current Schedule

In order to determine the estimated time to complete the current schedule, the Scheduler supplies the relevant up-to-date forecasted efficiency to each Activity Director. The Activity Directors then apply the forecasted efficiency to the cumulative datum duration of the outstanding tasks within its original schedule models to determine an estimated time to complete the model. Table 10.8 is constructed based on Table 10.7 and shows the cumulative datum durations of outstanding tasks in each original schedule model, and the existing forecasted efficiency of the corresponding resource, which are used to determine an estimate of the time to complete the original schedule models.

R_I	ΣT_{DD} (seconds)	R_{FE}	$\Sigma T_{ED} = \Sigma T_{DD}/R_{FE}$ (seconds)
1	27	0.991	27.2
2	35	0.992	35.3
3	23	0.990	23.2
4	33	0.418	78.9

Table 10.8 Estimated Times to Complete Current Schedule Models

Each Activity Director provides the Scheduler with an estimated time to complete their associated original schedule model. The Scheduler then determines that the original schedule model with the greatest estimated completion time, indicated by the shaded cells, corresponds with resource $R_I = 4$. That is, the resource that experienced the significant reduction in forecasted efficiency from 0.916 to 0.418. Thus, if the original schedule models continue to be adhered to under the prevailing forecasted efficiency, it is estimated that they would be completed in approximately 79 seconds, i.e. $\hat{T}_{CCS} = 79$ seconds. This estimate is considered conservative since the tasks undertaken utilising resource R_I=4 may delay dependent tasks to be completed utilising other resources.

<u>Estimated Time to Derive a Revised Schedule</u>

In order to ensure that the appropriate tasks can be undertaken and completed during the period of re-scheduling, the Scheduler estimates the execution time of the MOGA based on the number of tasks and resources to be considered. At the outset of the operation of the DCS, the Scheduler was provided with knowledge of the relationships between the parameters that influence the execution time of the MOGA. Based on an empirical study, Figure 10.5 presents the relationship between the number of tasks to be scheduled, n_{TS}, for a number of resources to be utilised, n_R, and the execution time of the MOGA, $\hat{T}_{MOGA}$.

Furthermore, the information presented in Figure 10.5 was derived under conditions representative of the actual use of the MOGA during the operation of the DCS, i.e.

- the MOGA was executed on the machine that would be used for scheduling in the turbine blade design process,

- the forecasted efficiencies of the resources were all set to unity,
- the durations of the tasks and dependencies between them were set in accordance with the case study, and,
- tasks were removed from consideration for re-scheduling in a manner representative of how they would be completed in the case study.

The three curves shown in Figure 10.5 are modelled using the regression equations shown such that the Scheduler can estimate the execution time of the MOGA based on knowledge of the number of tasks to be re-scheduled. The limits of estimated execution time based on the maximum number of tasks that can be scheduled are also shown.

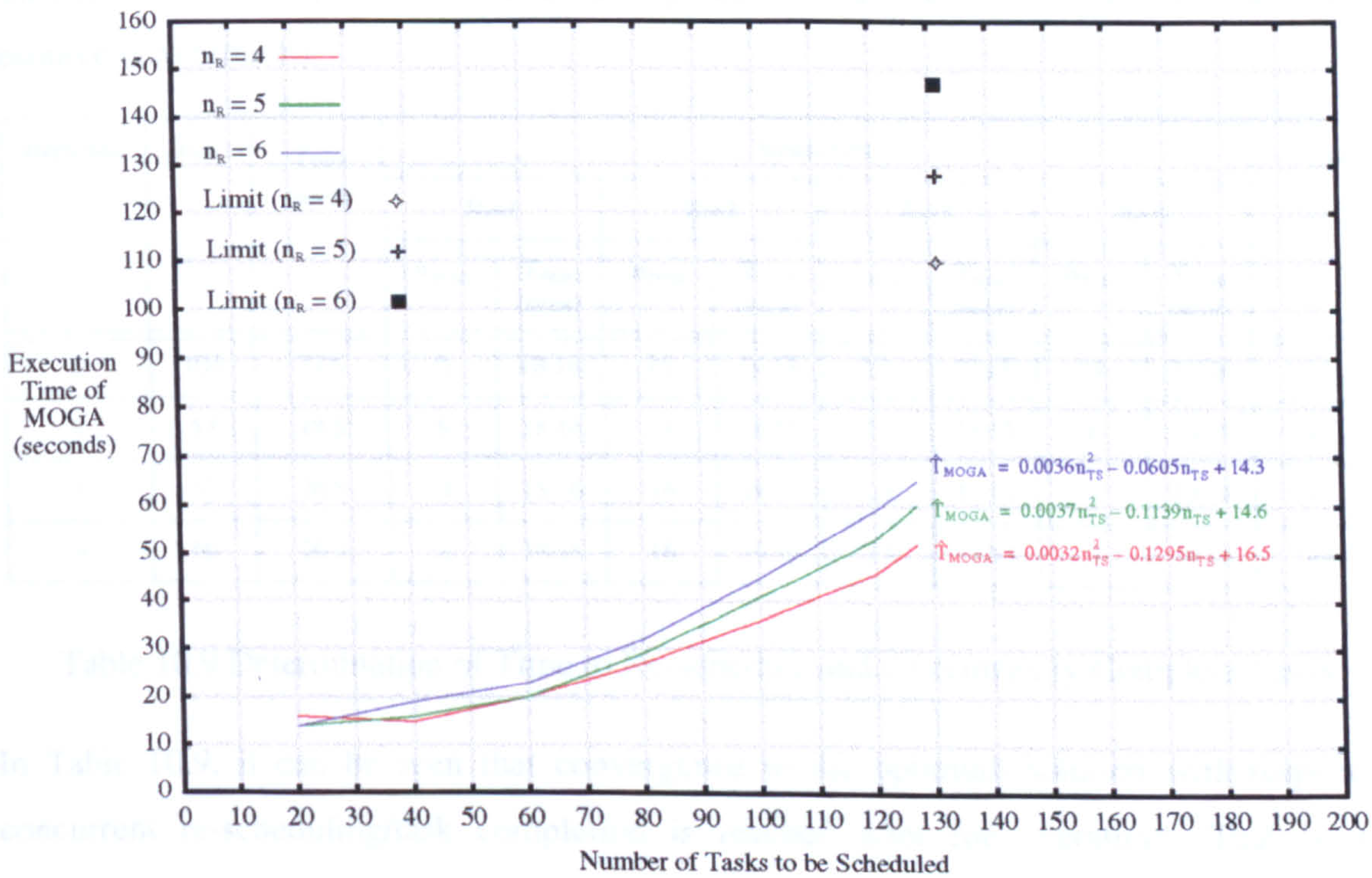

Figure 10.5 Estimated Execution Time of MOGA

In Figure 10.5, the maximum number of tasks that can be re-scheduled is 131, which corresponds to the number of analysis tool executions determined in Table 10.1. The number of tasks to be scheduled, shown on the curves in Figure 10.5, ranges from 20 to 127. Using the MOGA to re-schedule beyond these limits would be uneconomical. That is, it would be inefficient in terms of time to re-schedule less than 20 tasks. Further, the upper limit is set at 127 since the datum durations of the first four tasks to be completed are significantly greater than that of all others.

Determining the estimated time to derive a revised schedule simultaneously involves establishing the most appropriate combination of outstanding tasks to re-schedule while the remainder are completed. In order to determine the optimum number of tasks to re-schedule, a three-step iterative procedure is applied. Step 1 involves using empirically derived characteristics of the MOGA to determine its estimated execution time given the number of tasks to be re-scheduled. Based on the time estimate from Step 1, Step 2 entails using the original schedule model for each resource in order to determine the number of outstanding tasks that could be completed during re-scheduling. Step 3 involves deducting the cumulative number of outstanding tasks able to be completed utilising all resources determined in Step 2 from the number of tasks considered for re-scheduling in Step 1. The results from the application of the procedure are shown in Table 10.9. The procedure converges on the number of tasks to re-schedule such that the time taken to re-schedule them is as near-coincident as possible with the completion of the remaining outstanding tasks. Thus, the idle time of each resource is minimised.

Iteration	n_{TRS}	$\hat{T}_{DRS}$ (secs)	Resources								Σn_{TCRS}
			$R_I=1$		$R_I=2$		$R_I=3$		$R_I=4$		
			n_{TCRS}	T_{TCRS} (secs)	n_{TCRS}	T_{TCRS} (secs)	n_{TCRS}	T_{TCRS} (secs)	n_{TCRS}	T_{TCRS} (secs)	
1	104	37.6	8	18.16	16	19.15	13	13.13	14	35.89	51
2	53	18.6	8	18.16	15	18.15	13	13.13	6	16.75	42
3	62	20.8	8	18.16	16	19.15	13	13.13	7	19.14	44
4	60	20.3	8	18.16	16	19.15	13	13.13	7	19.14	44

Table 10.9 Determination of Time to Re-schedule and Concurrently Complete Tasks

In Table 10.9, it can be seen that convergence to the optimum solution with respect to concurrent re-scheduling/task completion is reached after four iterations. That is, the Scheduler should re-schedule sixty tasks, estimated to take approximately 20 seconds, i.e. $\hat{T}_{DRS}$ = 20.3 seconds, according to the regression equation associated with four resources. During the period of re-scheduling, forty four tasks are estimated as being able to be completed utilising the four resources. Based on their most recent forecasted efficiency, resources R_I=1, 2, and 4 would be utilised for approximately 19 seconds, while resource R_I=3 for approximately 13 seconds. As such, not only has the most appropriate time to re-schedule an appropriate number of outstanding tasks been determined but also the actual tasks to be completed during this period have been identified, i.e. those for inclusion within the interim schedule models. Values of T_G within the interim schedule models, based on re-scheduling sixty tasks at an estimated time of 20.3 seconds, are shown in Table 10.10.

R_I	T_G															
1	37	130	17	9	4	7	30	36								
2	43	88	60	54	53	24	35	33	18	19	22	38	6	5	13	20
3	28	74	34	64	12	39	87	21	66	31	15	59	23			
4	65	58	49	81	68	16	25									

Table 10.10 Interim Schedule Models

Furthermore, this re-scheduling/task completion results in a mean idle time of the resources of approximately 3 seconds. Since the idle time of resources is minimised, thus maintaining their optimised utilisation, then the arrival of the revised schedule is expected to be as close as possible to the completion of the interim schedule models. That is, the difference between the time for the Scheduler to re-schedule and Activity Directors to complete their respective interim schedule models is minimised.

<u>Estimated Time to Complete a Revised Schedule</u>

The Scheduler applies a three-step iterative procedure to determine the estimated time to complete a revised schedule.

<u>Step 1</u>

To determine the groups that the sixty tasks to be re-scheduled could be divided, an assessment of the tasks they are dependent on is made, i.e. whether it/they:

- was/were completed in accordance with an original schedule model,
- will be completed in accordance with an interim schedule model, and/or,
- will be re-scheduled for inclusion with a revised schedule model.

In Table C.4 of Appendix C, it can be seen that forty eight tasks would not be dependent on the completion of other tasks once re-scheduled since:

- they were never dependent on the completion of any other tasks,
- the tasks they are dependent on were completed in accordance with the original schedule models prior to the consideration of re-scheduling, and/or,
- the tasks they are dependent on will be completed in accordance with the interim schedule models during the period of re-scheduling.

Similarly, as a result of re-scheduling, only twelve tasks will be dependent on the completion of other tasks within the revised schedule models, as shown in Table C.5 of Appendix C.

Consequently, the sixty tasks to be considered for re-scheduling can be divided into two groups, i.e. one group comprising of forty eight tasks and another group consisting of twelve tasks. Further, these two groups must be completed sequentially. That is, the group of forty eight tasks must be completed prior to any of the group of twelve tasks being undertaken. However, tasks within each group may be completed in parallel since they are independent of other tasks in the same group.

Steps 2 and 3

Given that the datum duration of each outstanding task to be re-scheduled is one second, Table 10.11 presents information regarding how the two groups of tasks identified in Step 1 could be distributed amongst the four resources such that their collective time to completion is minimised.

R_I	R_{FE}	Group 1: 48 tasks		Group 2: 12 tasks		Total Time (seconds)
		Number of Tasks Assigned	$\Sigma T_{ED} = \Sigma T_{DD} / R_{FE}$ (seconds)	Number of Tasks Assigned	$\Sigma T_{ED} = \Sigma T_{DD} / R_{FE}$ (seconds)	
1	0.991	14	14.13	4	4.04	18.17
2	0.992	14	14.11	4	4.03	18.14
3	0.990	14	14.14	3	3.03	17.17
4	0.418	6	14.35	1	2.39	16.74

Table 10.11 Assignment of Re-scheduled Tasks

Based on Table 10.11, with respect to the available resources, the estimated time to complete the revised schedule, $\hat{T}_{CRS}$, is approximately 18 seconds. This corresponds to the greatest cumulative time to complete the two groups of tasks, as indicated by the shaded row of Table 10.11.

Decision to Re-Schedule

In summary, an estimated time to continue the current schedule has been calculated as approximately 79 seconds. Performing re-scheduling, while simultaneously completing interim schedule models, and the time to complete the revised schedule is estimated as approximately 38 seconds.

Thus,

$$\hat{T}_{CCS} > \hat{T}_{DRS} + \hat{T}_{CRS}$$

leading to the Scheduler taking the decision to re-schedule. Furthermore, the interim schedule models consisting of the tasks presented in Table 10.10 will be administered by the Activity Directors of the associated resources such that tasks can be completed during the period of re-scheduling.

Modify Task Model

Once the decision is made to re-schedule, the task model must be modified prior to performing re-scheduling. This is required since knowledge held in the task model is used in the derivation of the revised schedule models.

Knowledge in the task model modified by the Scheduler consists of:

- T_{AC} of those tasks to be completed in accordance with the interim schedule models, and,
- if appropriate, T_G, $T_{[T_G]}$ and T_N of outstanding tasks to be re-scheduled, i.e. the sixty tasks considered in Table 10.11.

Table 10.12 presents the modified task model with knowledge attributes T_{AC}, T_I, T_G, T_L, T_{DD}, T_N and $T_{[T_G]}$.

T_{AC}	T_I	T_G	T_L	T_{DD}	T_N	$T_{[T_G]}$	T_{AC}	T_I	T_G	T_L	T_{DD}	T_N	$T_{[T_G]}$	T_{AC}	T_I	T_G	T_L	T_{DD}	T_N	$T_{[T_G]}$
0	4	0	4	1	0	-	0	7	20	10	1	0	-	0	8	40	16	1	0	-
0	4	1	6	1	0	-	0	7	21	13	1	1	10	0	8	41	17	1	0	-
0	4	2	7	1	0	-	0	7	22	14	1	1	11	0	8	42	18	1	0	-
0	4	3	10	1	0	-	0	7	23	16	1	0	-	0	8	43	19	1	0	-
0	4	4	22	1	0	-	0	8	24	0	1	0	-	0	8	44	20	1	0	-
0	4	5	23	1	0	-	0	8	25	1	1	0	-	0	8	45	21	1	0	-
0	4	6	25	1	0	-	0	8	26	2	1	0	-	0	8	46	22	1	1	4
0	4	7	28	1	0	-	0	8	27	3	1	0	-	0	8	47	23	1	1	5
0	6	8	3	1	0	-	0	8	28	4	1	1	0	0	8	48	24	1	0	-
0	6	9	9	1	0	-	0	8	29	5	1	0	-	0	8	49	25	1	1	6
0	6	10	13	1	0	-	0	8	30	6	1	1	1	0	8	50	26	1	0	-
0	6	11	14	1	0	-	0	8	31	7	1	1	2	0	8	51	27	1	0	-
0	7	12	0	1	0	-	0	8	32	8	1	0	-	0	8	52	28	1	1	7
0	7	13	1	1	0	-	0	8	33	9	1	0	-	0	8	53	29	1	0	-
0	7	14	2	1	0	-	0	8	34	10	1	1	3	0	8	54	30	1	0	-
0	7	15	3	1	1	8	0	8	35	11	1	0	-	0	8	55	31	1	0	-
0	7	16	6	1	0	-	0	8	36	12	1	0	-	0	8	56	32	1	0	-
0	7	17	7	1	0	-	0	8	37	13	1	0	-	0	8	57	33	1	0	-
0	7	18	8	1	0	-	0	8	38	14	1	0	-	0	8	58	34	1	0	-
0	7	19	9	1	1	9	0	8	39	15	1	0	-	0	8	59	35	1	0	-

Table 10.12 Modified Task Model

Derive an Optimised Revised Schedule

In order to derive the revised schedule models, the Scheduler uses the MOGA with knowledge held within the modified task model and revised resource model. New values of T_G allocated to the re-scheduled tasks within the revised schedule models are shown in Table 10.13.

R_I	T_G																	
1	1	40	39	59	5	54	0	28	11	6	15	27	29	21	49	9	43	56
2	58	45	2	24	30	47	20	12	17	3	25	22	18	37	42	7	19	38
3	44	23	53	41	32	8	10	13	31	35	34	36	14	4	55	26	52	57
4	50	33	48	51	16	46												

Table 10.13 Revised Schedule Models

The actual duration of re-scheduling was approximately 23 seconds, which is 3 seconds greater than estimated. As such, the decision to re-schedule would not have been affected.

Previously, the estimated time to complete a revised schedule without having the schedule derived was determined to be approximately 18 seconds. Using Table 10.13, the estimated time to complete the derived revised schedule can be calculated as approximately 18 seconds.

Undertake and Complete Overlapped Tasks

While the Scheduler re-schedules, the Activity Directors orchestrate the enactment of their respective interim schedule models such that overlapped tasks can be undertaken and completed. Since all of the tasks to be undertaken and completed in accordance with the interim schedule models are independent, i.e. they are not dependent on the completion of other tasks or those tasks they are dependent on have already been completed, then the need for dependency checking is not required. The omission of dependency checking is essential since it requires Scheduler involvement, which is not possible due to this agent being occupied performing re-scheduling during the enactment of the interim schedule models.

All Activity Directors work in parallel by sequentially instructing related Task Managers to execute the associated analysis tool to complete the relevant tasks in accordance with Table 10.13.

Request, Provide and Supply Task Information

As described previously, prior to undertaking a task, Task Managers request that their related Information Manager provides any necessary information. In response, the Information Manager retrieves the necessary input files from the task information repository and then notifies the Task Manager such that it can commence with the execution of its associated analysis tool. Similarly, on the completion of each task, the Information Managers store any output files in the task information repository.

<u>Conclusion of the Turbine Blade Design Process</u>

Once re-scheduling has been performed and, simultaneously, the interim schedule models are completed, then the revised schedule models are derived as shown in Table 10.13. The turbine blade design process then progresses until all tasks have been undertaken and completed in accordance with the revised schedule models.

The case study has demonstrated the real-time operational design co-ordination part of the methodology by applying the DCS. Throughout the turbine blade design process, all agents communicated and interacted in a coherent manner such that inter-related tasks were undertaken in the right order by the appropriate agent using the right information and utilising the right resource at the right time. In addition to performing the process in a co-ordinated manner, a key feature of the methodology is that by adjusting in real-time when appropriate, benefits can be made in terms of reducing the time to complete the process. However, the magnitude of any reductions that can be achieved are dependent on the stage of completion of the turbine blade design process. With regard to the case study, by deciding to re-schedule, the turbine process was completed in approximately 38 seconds from the point in time when re-scheduling was considered whereas continuing to adhere to the original schedule models would have taken 79 seconds. As such, from the point at which re-scheduling was considered, an approximate reduction of 50% in time to complete the turbine blade design process was achieved.

In the case study, relatively significant reductions in the time to complete the turbine blade design process have been achieved as a result of applying operational design co-ordination in real-time. In order to demonstrate the methodology further in terms of scalability, it should be applied within an engineering organisation where similar significant savings in time could be achieved on a larger absolute scale, i.e. in the order of man weeks or man months.

10.3 Marine Vessel Conversion Design Programme

The case study provided by Armstrong Technology Associates is concerned with the design programme for the conversion of a LASH carrier to a mutli-role offshore support vessel. Within this company, single-skilled engineers worked within a multi-disciplinary design team.

As described in Section 8.2 of Chapter 8, the prospective operational design co-ordination part of the methodology is aimed at identifying deficiencies in the resources used in the derivation of an optimised schedule such that improvements can be proposed and assessed. As presented in Chapter 8 *(Figure 8.23, page 120)*, the prospective part of the methodology comprises five steps, the last three of which are iterated until the proposed support adequately redresses any imbalance in the original available resources with regard to the tasks to be undertaken according to the derived schedule.

Step 1: Identify deficiencies in the optimised schedule and propose support in the form of simulated resource models.

Step 2: Construct a simulated task model.

Step $3^{(n)}$: Derive an off-line optimised schedule.

Step $4^{(n)}$: Assess proposed support and record in schedule evaluation repository.

Step $5^{(n)}$: Identify the existence of deficiencies in the optimised schedule resulting from the proposed support, and, if appropriate, propose support in the form of further simulated resource models then repeat steps 3, 4 and 5.

Steps 3, 4 and 5 are iterative as denoted by the superscript *(n)*. Further, since *step 1* includes identifying deficiencies in the optimised schedule, such a schedule must first be derived.

Derive an Optimised Schedule

The derivation of an optimised schedule involves the use of knowledge of the tasks to be undertaken and resources to be utilised along with the MOGA as used in the real-time part of the methodology.

Tasks: A study of information regarding the design programme and consultation with the Senior Project Manager at Armstrong Technology Associates resulted in the composition of tasks being defined. As shown in Table 10.14, the design programme involved one hundred and thirty four tasks, which corresponded to four goals. The only knowledge required for use within the prospective part of the methodology is represented in the task model for the design programme as shown in Table C.6 of Appendix C.

Goal Identification Index (T_I)	Goal Description	Task Description	Number of Tasks
0	General	General	2
1	Naval Architecture	Classification	10
		Structure - Classification	15
		Structure - Production	17
		Outfit Design - Classification	21
		Outfit Production	23
2	Marine Engineering	Classification	4
		Production	18
3	Electrical Engineering	Classification	7
		Production	17
		Total	**134**

Table 10.14 Design Programme: Task Composition

Resources: Consultation with the Senior Project Manager also resulted in knowledge being provided regarding members of the design team, i.e. resources, to be utilised on the design programme. Resources within Armstrong Technology Associates are single-skilled within a multi-disciplinary team. Thus, each resource is only assigned a forecasted efficiency for their respective area of expertise, as shown in Table C.7 of Appendix C. Further, the forecasted efficiencies assigned correspond with the designation of the design engineers within the company. Similarly, resource cost per unit time also corresponds with designation.

Based on Table C.7, knowledge of the forecasted efficiencies within the resource model is shown in Table 10.15.

	Resource Index (R_l)	Goal Identification Index (T_l)			
		0 (General)	1 (Naval Architecture)	2 (Marine Engineering)	3 (Electrical Engineering)
Naval Architects	0	1.0	1.0	0	0
	1	1.0	1.0	0	0
	2	0.8	0.8	0	0
	3	0.8	0.8	0	0
	4	0.8	0.8	0	0
	5	0.8	0.8	0	0
	6	0.6	0.6	0	0
	7	0.6	0.6	0	0
Marine Engineers	8	1.0	0	1.0	0
	9	1.0	0	1.0	0
	10	0.8	0	0.8	0
	11	0.6	0	0.6	0
	12	0.6	0	0.6	0
Electrical Engineers	13	0.8	0	0	0.8
	14	0.8	0	0	0.8
	15	0.6	0	0	0.6

Table 10.15 Resource Model: Forecasted Efficiencies

In Table 10.15, the shaded cells indicate those resources that are able to undertake tasks of the associated goal. Cells that are not shaded signify that the resources are unable to undertake tasks of the associated goal.

Schedule: Based on knowledge held within the task model and resource model, the MOGA is employed to derive an optimised schedule. Furthermore, ten runs are carried out in order to gain confidence in the derived optimised schedules. These schedules are referred to as datum case schedules since they are derived using the original resources available within Armstrong Technology Associates.

Each datum case schedule was assessed in order to establish (i) the cumulative estimated time to complete the assigned tasks for each resource while accounting for forecasted efficiency, and (ii) the corresponding cost of utilising each resource for that cumulative estimated time, which is presented in Table C.8 of Appendix C. The mean time and mean cost of the datum case schedules are 59.5 weeks and 175222 units respectively. In Table C.8, it can be seen that in each run of the datum case all resources are to be utilised for a proportion of the estimated time to complete the schedule.

The schedule of the design programme produced by Armstrong Technology Associates had an expected duration of approximately 61 weeks. In comparison, the estimated time to complete the datum case schedule derived is within approximately 2.5% of that produced by the company. Thus, it is considered that the company design programme schedule is comparable with the datum case schedule derived using the MOGA.

Step 1: In order to identify the area in which the original resources are deficient, the cumulative time to complete the tasks associated with each goal is determined. This is achieved by assessing each datum case schedule derived and summing the estimated time for each task of like-disciplined resources while deducting the time to complete the tasks associated with the *general* goal, as shown in Table C.9 of Appendix C. The mean $\Sigma T_{ED}/\Sigma R_{FE}$ ratios presented in Table C.9 are shown in Figure 10.6 illustrating the disparity existing between the resources utilised with respect to the tasks to be completed regarding each associated goal.

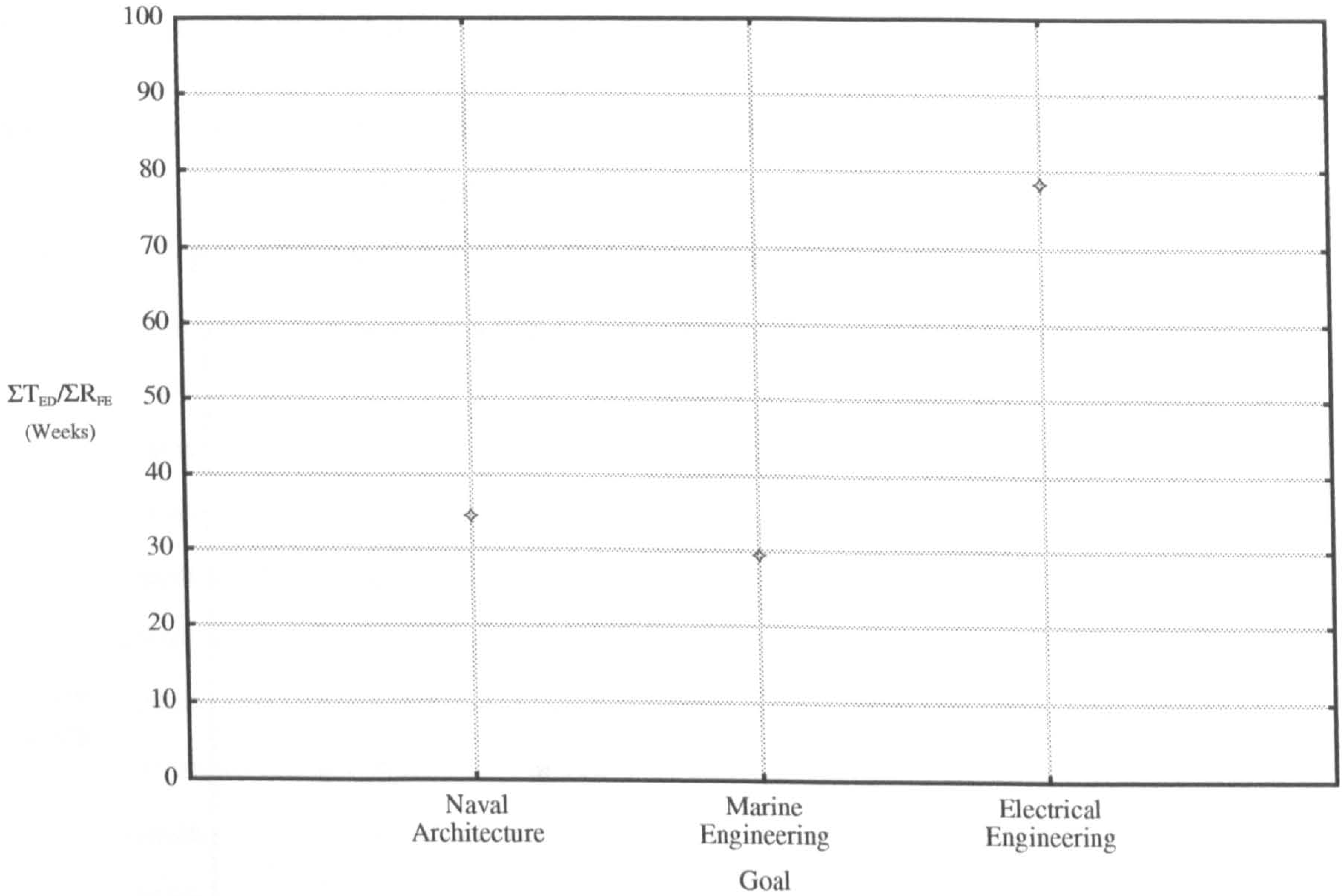

Figure 10.6 $\Sigma T_{ED}/\Sigma R_{FE}$ Ratios for each Goal

In Figure 10.6, the greatest mean $\Sigma T_{ED}/\Sigma R_{FE}$ ratio corresponds to electrical engineering. Thus, the greatest requirement for improvements within the resources is in electrical engineering. For naval architecture and marine engineering, the ratios are approximately equal indicating that the cumulative efficiency of the resources in these disciplines are proportional with respect to the cumulative estimated duration of the tasks associated with their respective goal.

Since there is a requirement for improvement within electrical engineering, three simulated resource models are proposed. That is, the original resources are extended to include an electrical engineer with the designation: (i) design engineer, (ii) senior design engineer, and (iii) consultant. The simulated resource model cases are as shown in Table 10.16.

Case	Design Engineer	Senior Design Engineer	Consultant
1.1	1	0	0
1.2	0	1	0
1.3	0	0	1

Table 10.16 Simulated Resource Model Cases

Step 2: The simulated task model corresponds to the task model used to derive optimised schedules for the datum case (See Table C.6 in Appendix C).

Step 3(1): Knowledge contained within each simulated resource model is used with the simulated task model and the MOGA in order to derive an optimised schedule. As indicated previously, ten runs of the MOGA are performed for each simulated resource model.

Step 4(1): A summary of the time and cost associated with each optimised schedule derived for Cases 1.1, 1.2, and 1.3 is presented in Table C.10 of Appendix C. Mean cost versus mean time is shown in Figure 10.7 for Cases 1.1, 1.2, 1.3 and the datum case.

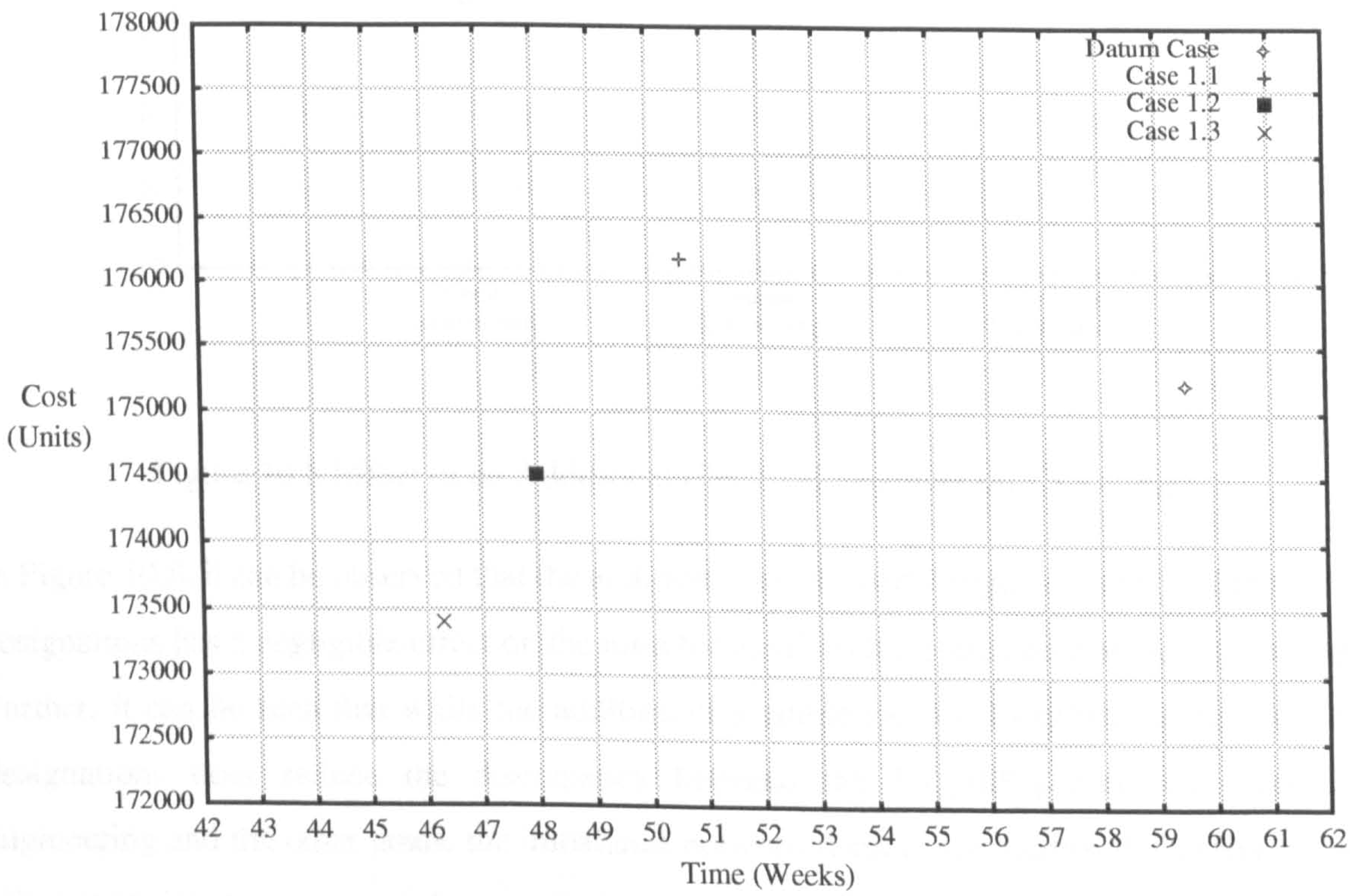

Figure 10.7 Mean Cost versus Mean Time

From Figure 10.7, it can be seen that the greatest reduction in time and cost in relation to the datum case corresponds with the addition of a consultant electrical engineer to the original resources. The reduction in time is approximately 22% whereas the reduction in cost is approximately 1%.

Step 5(1): In order to determine whether or not a further set of simulated resource models should be proposed, the schedules derived corresponding to Cases 1.1, 1.2 and 1.3 must be assessed.

Table C.11 in Appendix C presents the $\Sigma T_{ED}/\Sigma R_{FE}$ ratios, including the mean, for each of the goals within the schedules for Cases 1.1, 1.2 and 1.3. Figure 10.8 shows the mean $\Sigma T_{ED}/\Sigma R_{FE}$ ratios corresponding to the addition of an electrical engineer in each of the three designations: (i) design engineer, (ii) senior design engineer, and (iii) consultant.

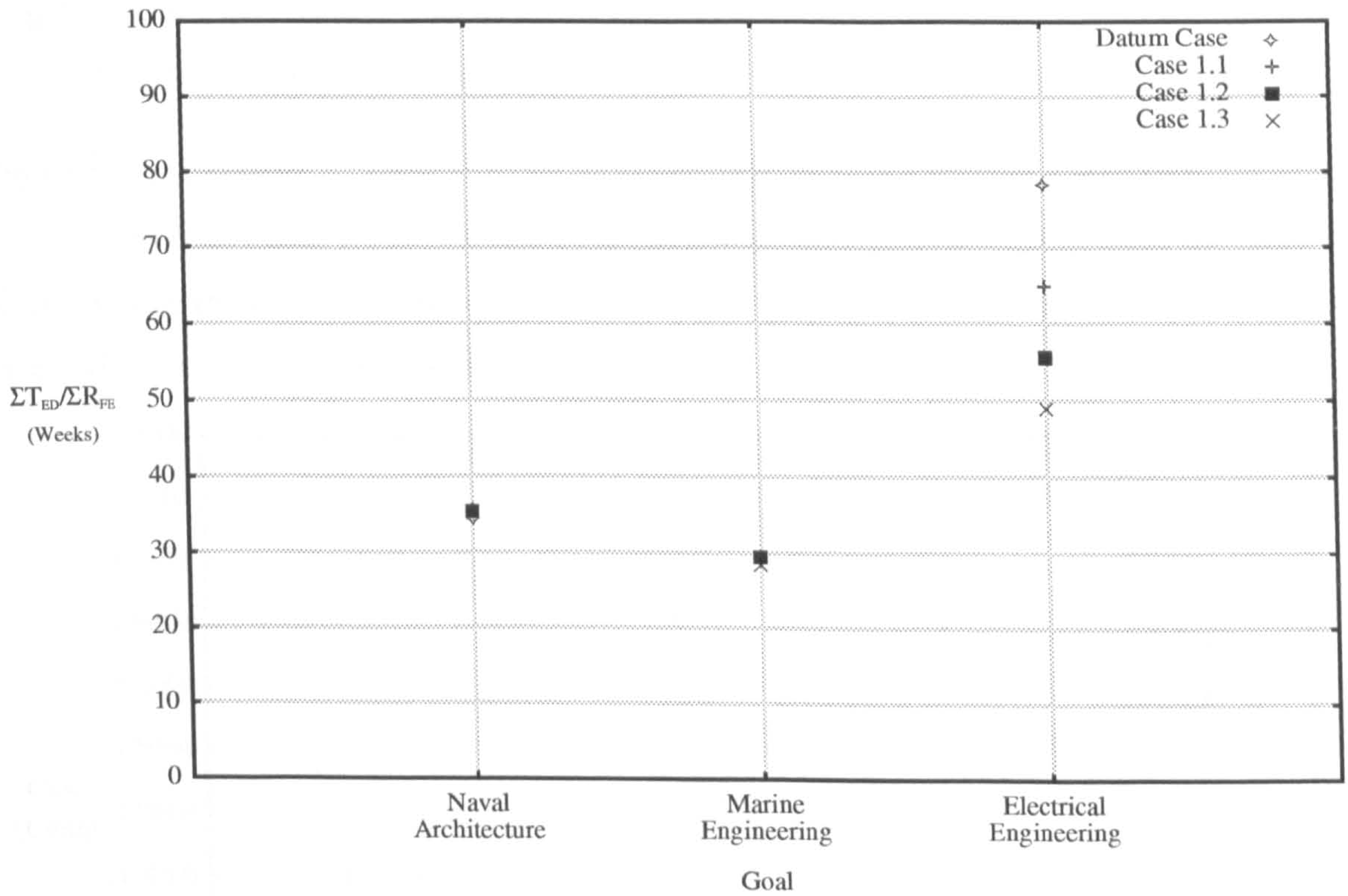

Figure 10.8 Effect of an Additional Electrical Engineer on $\Sigma T_{ED}/\Sigma R_{FE}$

In Figure 10.8, it can be observed that the addition of an electrical engineer in each of the three designations has a negligible effect on the ratio for naval architecture and marine engineering. Further, it can be seen that while the addition of a single electrical engineer at each of the designations does reduce the discrepancy between the $\Sigma T_{ED}/\Sigma R_{FE}$ ratio for electrical engineering and the other goals, the imbalance between them is not redressed. Consequently, it is appropriate to propose and assess further improvements to the resources. Specifically, all combinations of the addition of two electrical engineers to the original resources is considered in accordance with Table 10.17.

Case	Electrical Engineering		
	Design Engineer	Senior Design Engineer	Consultant
2.1	2	0	0
2.2	1	1	0
2.3	1	0	1
2.4	0	2	0
2.5	0	1	1
2.6	0	0	2

Table 10.17 Simulated Resource Model Cases

Step 3$^{(2)}$: Using each simulated resource model (*Step 5$^{(1)}$*), the simulated task model (*Step 2*) and the MOGA, ten optimised schedules are derived.

Step 4$^{(2)}$: In Appendix C, Table C.12 presents the time and cost, including the mean, for each run of each of the Cases 2.1 to 2.6. The mean time and mean cost for each of these six cases is plotted in Figure 10.9. For comparative purposes, the mean time and mean cost for the datum case and cases 1.1, 1.2, and 1.3 are also plotted.

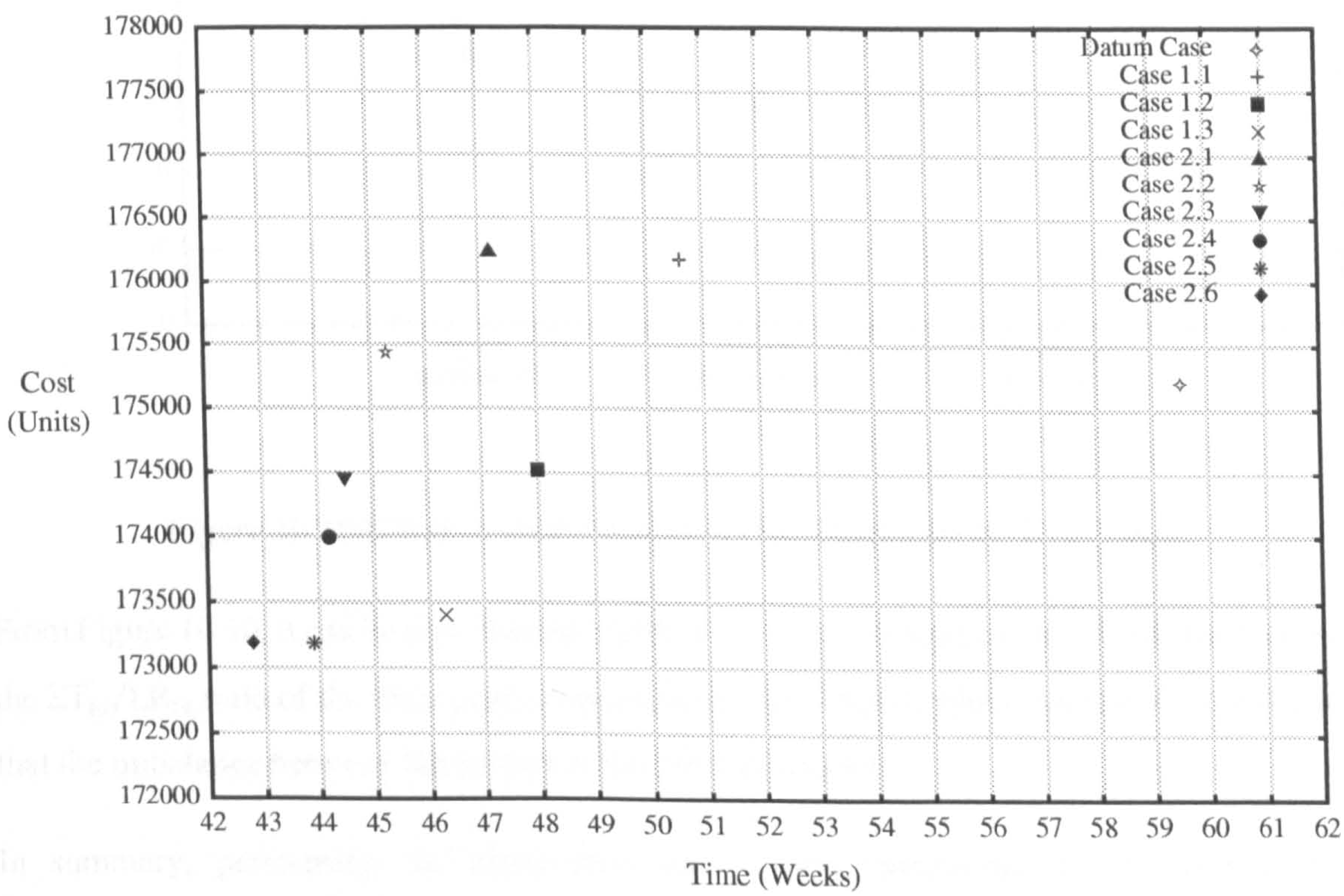

Figure 10.9 Mean Cost versus Mean Time

In Figure 10.9, the addition of two electrical engineers in the various combinations of designation can be seen to result in further reductions in the estimated time to complete the schedule. The addition of two consultant electrical engineers, i.e. Case 2.6, offers the greatest reduction in time of 28%. With regard to cost, it is noted that the range of reductions in cost for Cases 2.1-2.6 approximately correspond with those observed for Cases 1.1-1.3.

Step 5(2): To establish whether any of the six cases involving the addition of two electrical engineers to the original resources redresses the imbalance between electrical engineering and the other goals, the optimised schedules are assessed in order to evaluate the $\Sigma T_{ED}/\Sigma R_{FE}$ ratios, including the mean, as shown in Table C.13 of Appendix C.

For each of the Cases 2.1 to 2.6, the mean $\Sigma T_{ED}/\Sigma R_{FE}$ ratio is plotted in Figure 10.10. For comparative purposes, the mean $\Sigma T_{ED}/\Sigma R_{FE}$ ratio for electrical engineering, naval architecture and marine engineering for the datum case and Cases 1.1 to 1.3 are also plotted.

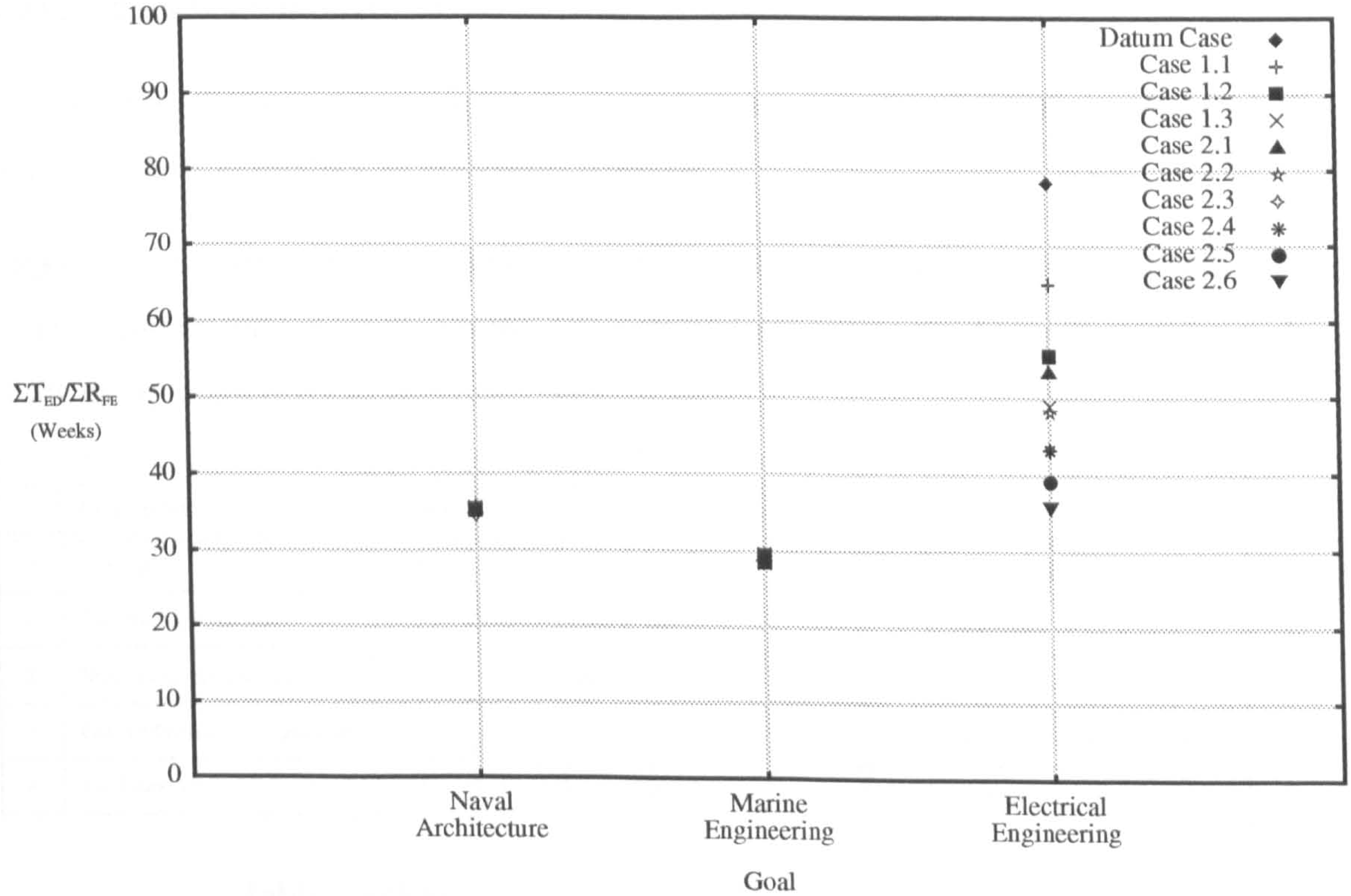

Figure 10.10 Effect of Additional Electrical Engineers on $\Sigma T_{ED}/\Sigma R_{FE}$

From Figure 10.10, it can be seen that the addition of two consultant electrical engineers causes the $\Sigma T_{ED}/\Sigma R_{FE}$ ratio of the three goals to be approximately equal, which leads to the conclusion that the imbalance between the resources has been redressed.

In summary, performing the prospective part of the operational design co-ordination methodology as presented in this section, provides the Senior Project Manager with the knowledge that an additional two consultant electrical engineers will potentially lead to a 28% time reduction in the design programme with no cost penalty being incurred in terms of utilising the resources. Indeed, the cost of the design programme attributed to the utilisation of the design team is marginally reduced, i.e. approximately 1%. Furthermore, the realisation of these time and cost benefits can be achieved by implementing the optimised schedule corresponding to Case 2.6.

10.4 Rotary Drum Dryer Design Development Phase

The case study provided by domnick hunter limited is concerned with the design development of a new product, namely a rotary drum dryer. In contrast with the previous case study, this company employed multi-skilled engineers within a multi-disciplinary design team.

The case study is conducted in accordance with the five steps of the prospective part of the methodology summarised at the beginning of Section 10.3.

Derive an Optimised Schedule

Knowledge of the tasks to be undertaken and resources to be utilised, together with the MOGA, is used in order to produce an optimised schedule.

Tasks: Discussions and correspondence with the Research and Development Manager of domnick hunter limited resulted in the definition of tasks within the design development phase of the rotary drum dryer as shown in Table 10.18.

T_I	Goal Description	No. of Tasks	T_I	Goal Description	No. of Tasks	T_I	Goal Description	No. of Tasks
0	Costing	9	5	Air Cooler	5	10	Amend Drawings	10
1	Drawings of Castings	16	6	Drum Motor	5	11	Leadtimes	23
2	Machining of Castings	21	7	Other Componentry	38	12	Revised Build	2
3	Other Machined Components	35	8	Prototype Build	2	13	Generate BOMs / Final Mods	3
4	Desiccant Drum	5	9	Review Size Build	4	14	Testing	12

Table 10.18 Design Development Phase: Task Composition

Relevant knowledge within the task model, involving 15 goals with 190 associated tasks, is presented in Table C.14 of Appendix C.

Resources: Discussions and correspondence with the Research and Development Manager also resulted in knowledge being provided regarding the multi-skilled design engineers within the multi-disciplinary design team. Each design engineer, i.e. resource, was assigned a forecasted efficiency for each type of task that they are capable of undertaking, as shown in Table 10.19.

Resource		Goal Identification Index (T_I)														
(R_I)	(R_C)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	12	0.3	0	0	0	0	0	0	0.2	0.4	0	0.1	0	0.5	0.1	0.6
1	20	0.9	0.1	0.1	0.1	0.5	0.5	0.5	0.2	0.1	0	0	0.9	0	0.1	0.1
2	20	0.7	0.1	0	0	0.8	0.5	0.5	0.2	0.7	0.8	0	0	0.7	0.1	0.7
3	15	0.5	0.9	0.9	0.9	0.1	0.5	0.3	0.7	0.5	0.6	0.8	0	0.5	0.8	0.2
4	17	0.7	1.0	0.9	0.9	0.8	0.7	0.7	0.7	0.7	0.8	0.8	0	0.5	0.8	0.2
5	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0	0	0
6	17	0.5	0.1	0	0	0	0.3	0.2	0.5	0.8	0.9	0	0	0.9	0.1	0.9
7	12	0	0	0	0.3	0.3	0	0.2	0.3	0	0	0	0	0	0	0
8	17	0.5	0.1	0	0	0	0	0.3	0	0	0	0	0	0	0	0

Table 10.19 Resource Model: Forecasted Efficiencies

In Table 10.19, the shaded cells denote those resources able to undertake tasks associated with the corresponding goal. Conversely, cells that are not shaded represent resources that are unable to undertake tasks of the corresponding goal.

<u>Schedule</u>: Using the MOGA with knowledge of tasks and resources, an optimised schedule was derived. To gain confidence in the derived optimised schedules, a number of runs of the MOGA are performed. Since these schedules are derived using the original resources, they are referred to as datum case schedules.

Datum schedule are assessed to determine their associated time and cost, as presented in Table C.15 of Appendix C. The mean time and mean cost of the datum case schedules are 64 weeks and 223554 units respectively. The schedule of the design development phase produced by domnick hunter limited had an expected duration of approximately 59 weeks. As such, with respect to the datum schedule and that produced by the company, an 8% discrepancy existed in terms of estimated duration to complete the design development phase. Knowledge of this discrepancy enables any reductions in duration made, as a result of applying the methodology, to be offset accordingly.

On inspection of Table C.15, it can be seen that all resources are to be utilised in each run of the datum case schedules.

<u>Step 1</u>: An assessment of the datum case schedule, i.e. the 3rd schedule since it most closely represents the mean time and mean cost, is conducted in order to identify any areas of deficiency within the resources with respect to the tasks associated with each goal. The assessment of the 3rd datum case schedule is presented in Tables C.16 and summarised in Table C.17 of Appendix C.

The assessment entails identifying the resource allocated to each task, and then dividing the datum duration of the task by corresponding forecasted efficiency. For each goal, the estimated durations are then summed and divided by the cumulative forecasted efficiencies of the resources allocated to the associated tasks.

Based on this assessment, the $\Sigma T_{ED}/\Sigma R_{FE}$ ratios shown in Table C.17 are illustrated in Figure 10.11.

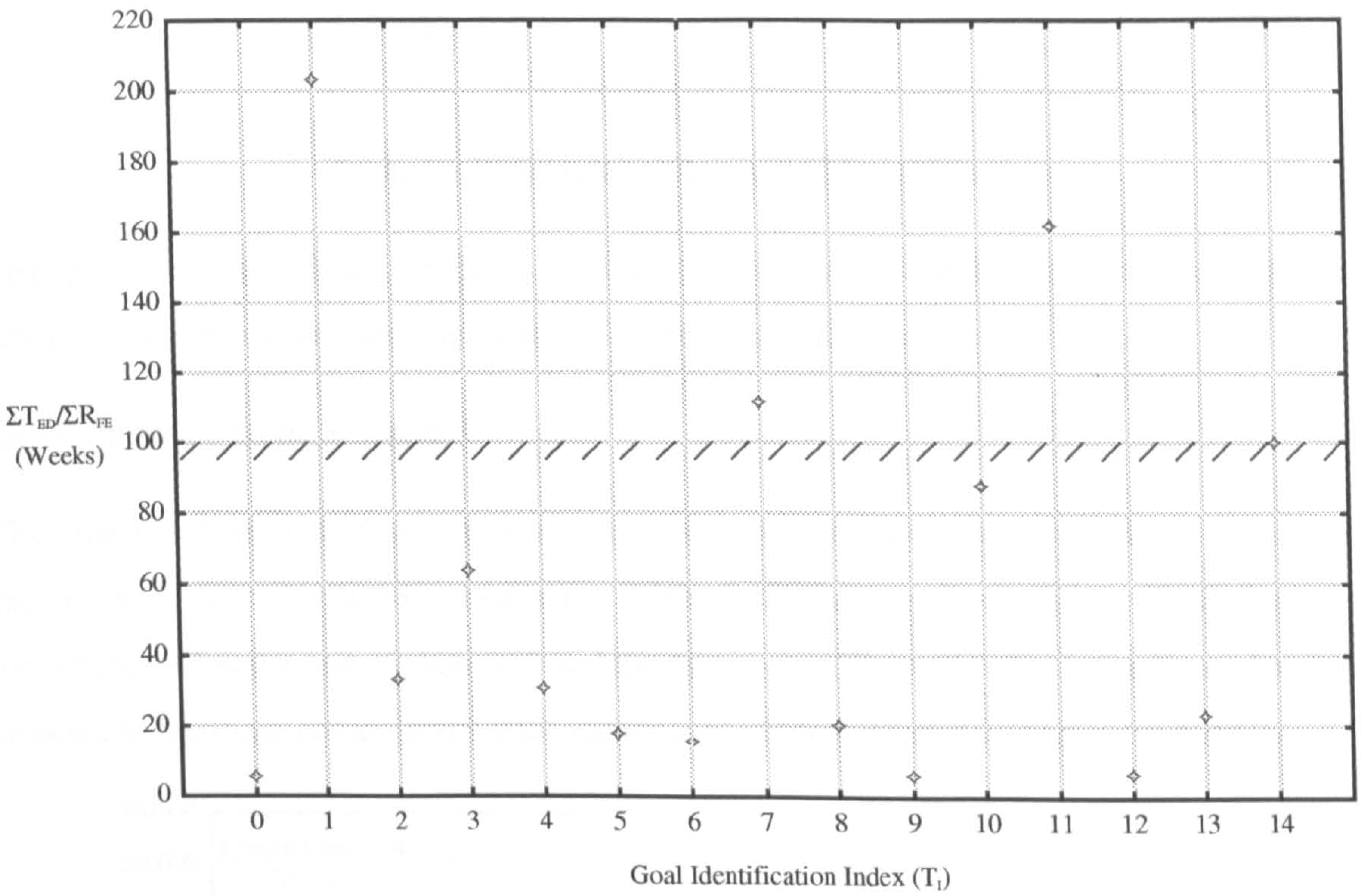

Figure 10.11 $\Sigma T_{ED}/\Sigma R_{FE}$ Ratios for each Goal - Datum Case (3rd Schedule)

In Figure 10.11, a $\Sigma T_{ED}/\Sigma R_{FE}$ ratio greater than or equal to 100 is shown for four of the goals, i.e. $T_I = 1, 7, 11$ and 14. From Table C.17 in Appendix C, it can be seen that with respect to three of these four goals, i.e. $T_I = 1, 7$ and 11, all available resources are utilised to some degree whereas for $T_I = 14$ they are not. Thus, goals with $T_I = 1, 7$ and 11 are considered for improvement in terms of resources that are able to complete the associated tasks. In order to assess the effect of the all of the various combinations of additional resources for the three goals under consideration, seven cases are considered, i.e. $2^{n_G} - 1$ where n_G is the number of goals. This number of cases corresponds with each additional resource having only a single value of R_{FE}, i.e. 1. As such, the proposed simulated resource models are defined in Table 10.20.

Case	Goal Identification Index (T_I)		
	1	7	11
1.1	1.0	0	0
1.2	0	1.0	0
1.3	0	0	1.0
1.4	1.0	1.0	0
1.5	1.0	0	1.0
1.6	0	1.0	1.0
1.7	1.0	1.0	1.0

Table 10.20 Simulated Resource Model Cases

<u>**Step 2:**</u> The simulated task model is equivalent to the task model used to derive optimised schedules for the datum case (See Table C.14 in Appendix C).

<u>**1st Iteration of Steps 3, 4 and 5**</u>

The time and cost, including the mean, associated with each optimised schedule derived for each of the Cases 1.1 to 1.7 is presented in Table C.18 of Appendix C. Figure 10.12 shows the mean time and mean cost of each case and the datum case.The scale used in the figure has been selected to facilitate comparisons with subsequent proposed simulated resource models.

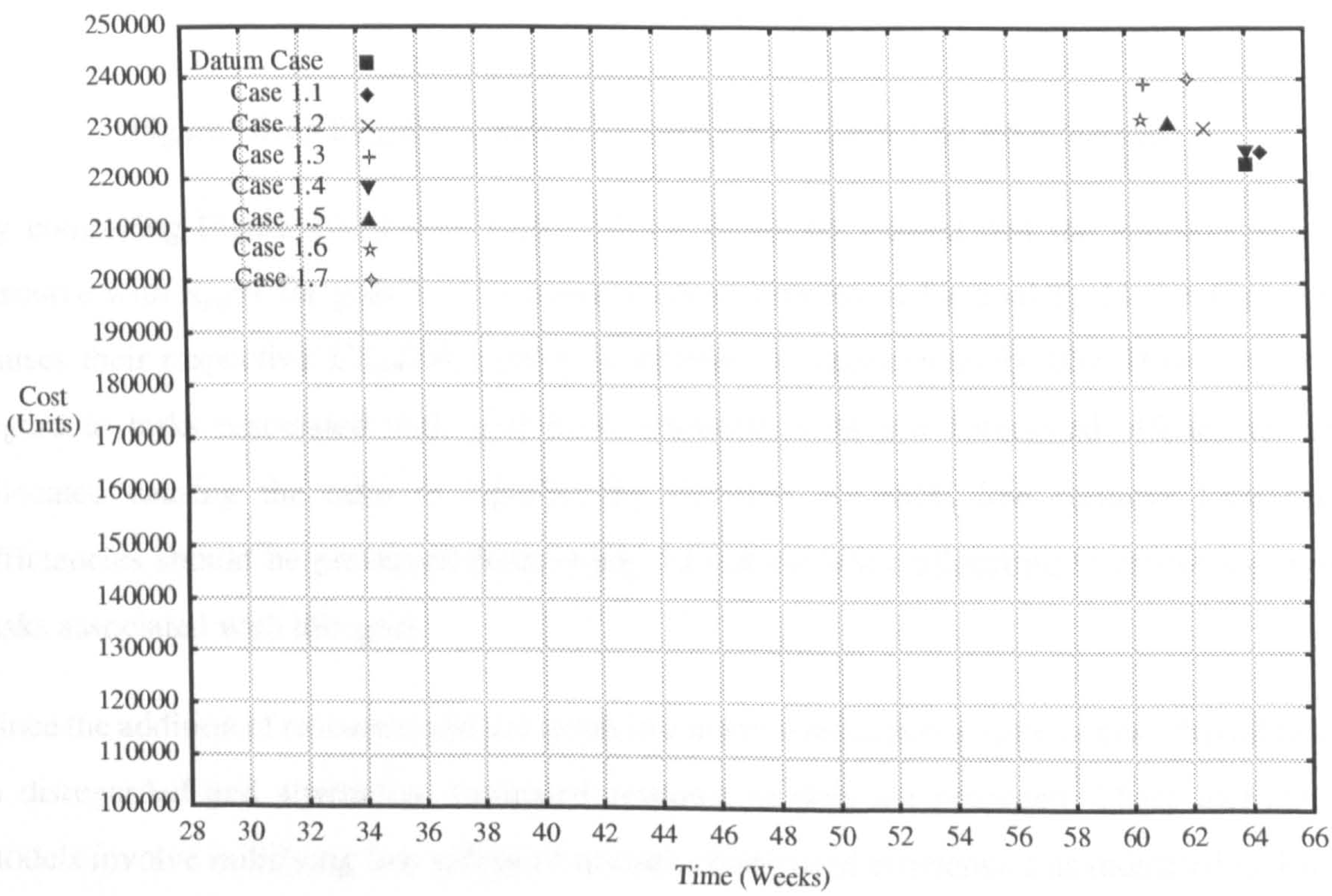

Figure 10.12 Mean Cost versus Mean Time

Figure 10.12 indicates that Case 1.6 provides the least expected time to complete the design development phase. However, with respect to the datum case, all cases exhibit an increase in cost. Specifically, Case 1.6 corresponds to an approximate 5% reduction in time and a 4% increase in cost. Since Case 1.6 offers the greatest reduction in time, in order to establish if any further improvements can be made, an assessment is made of an optimised schedule that most closely represents the mean time and mean cost for this case. Thus, an assessment of the 3rd optimised schedule of Case 1.6 is shown in Table C.19 and summarised in Table C.20 in Appendix C. The $\Sigma T_{ED}/\Sigma R_{FE}$ ratios calculated in Table C.20 are illustrated in Figure 10.13.

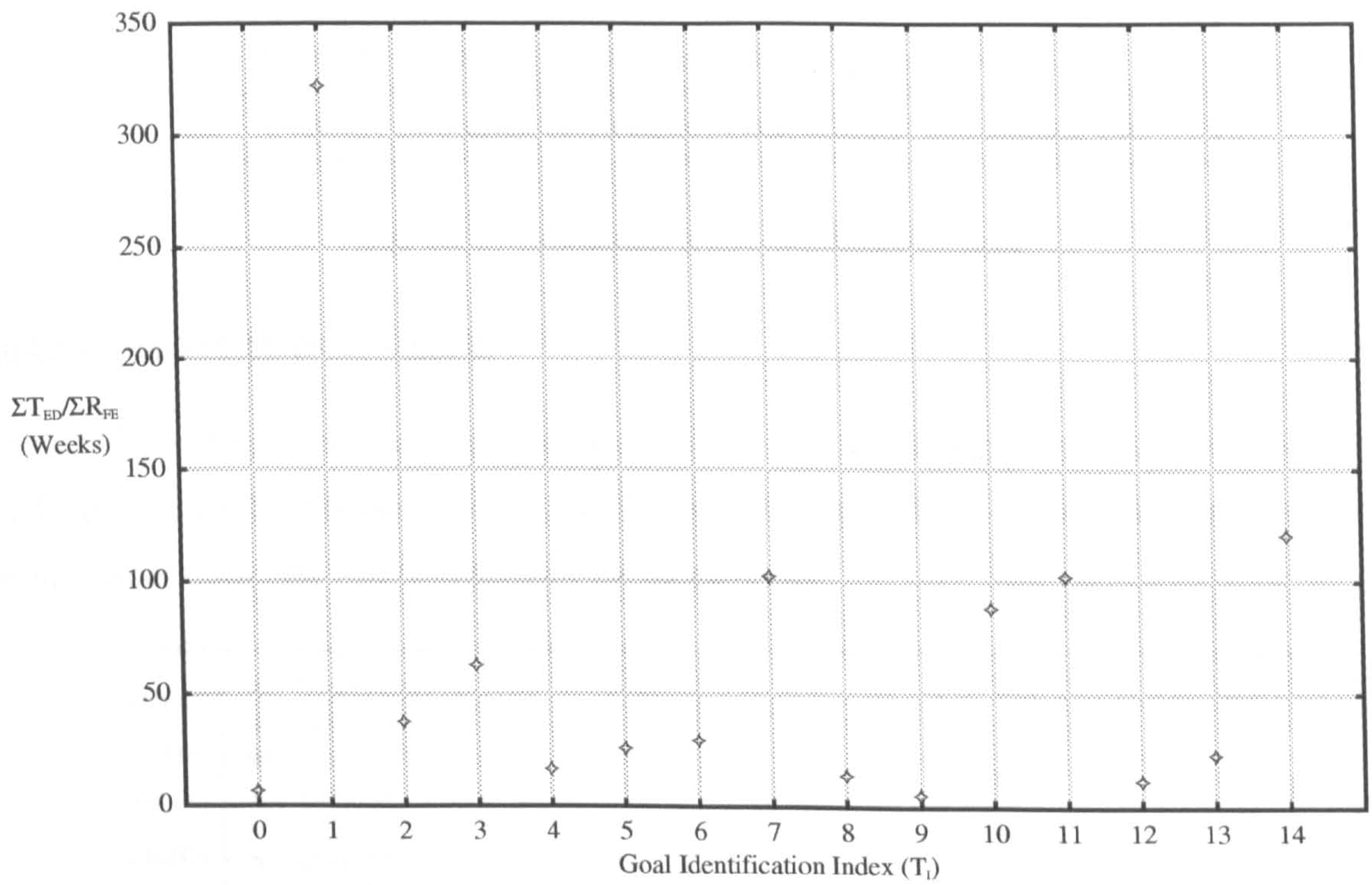

Figure 10.13 $\Sigma T_{ED}/\Sigma R_{FE}$ Ratios for each Goal - Case 1.6 (3rd Schedule)

By comparing Figure 10.13 with Figure 10.11, it can be viewed that the addition of one resource with R_{FE}=1 for goal T_I=7 and one resource with R_{FE}=1 for goal T_I=11, i.e. Case 1.6, causes their respective $\Sigma T_{ED}/\Sigma R_{FE}$ ratios to decrease to approximately 100. However, with regard to tasks associated with goal T_I=1, resources with low forecasted efficiencies are allocated causing the ratio to significantly increase. As such, low resource forecasted efficiencies should be prevented from being considered when allocating to resources to the tasks associated with this goal.

Since the addition of resources did not result in a notable reduction in time or cost, this addition is disregarded and alternative simulated resource models are proposed. These alternative models involve nullifying low values of resource forecasted efficiencies as indicated in Table 10.21. That is, the resource themselves are not removed, rather their low values of forecasted efficiency are set to zero for the purpose of deriving schedules. Forecasted efficiencies greater than 0.6 are not nullified since this would leave the resources unable to undertake tasks associated with goals T_I = 5, 6 and 7.

Case	Description
2.1	Nullify forecasted efficiencies of 0.1
2.2	Nullify forecasted efficiencies of 0.1 and 0.2
2.3	Nullify forecasted efficiencies of 0.1, 0.2 and 0.3
2.4	Nullify forecasted efficiencies of 0.1, 0.2, 0.3 and 0.4
2.5	Nullify forecasted efficiencies of 0.1, 0.2, 0.3, 0.4 and 0.5
2.6	Nullify forecasted efficiencies of 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6

Table 10.21 Simulated Resource Model Cases

2nd Iteration of Steps 3, 4 and 5

Table C.21 in Appendix C summarises the time and cost, including the mean, associated with each optimised schedule derived for Cases 2.1 to 2.6. Figure 10.14 shows the mean time and mean cost of each case and, in addition, the datum case.

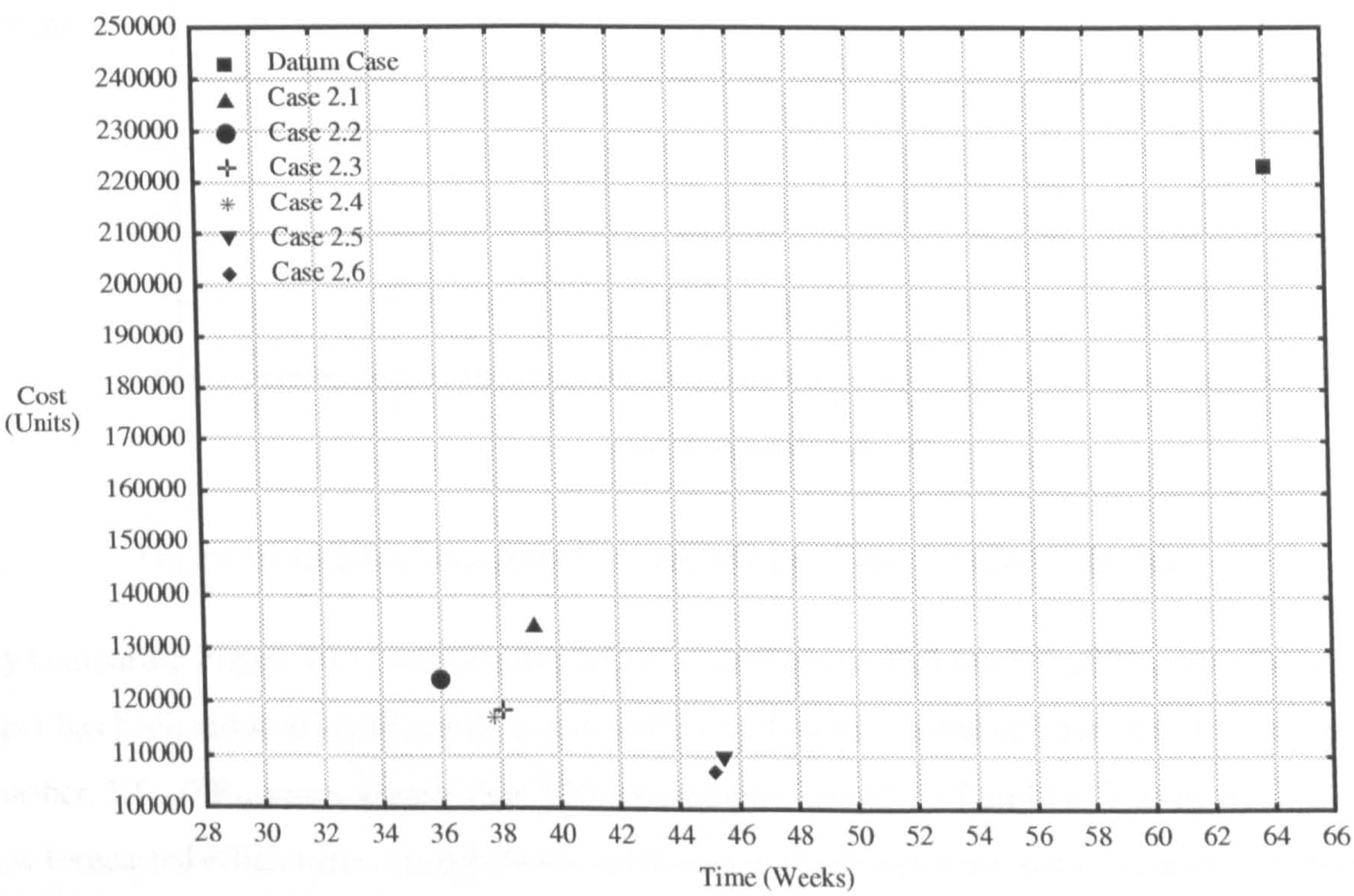

Figure 10.14 Mean Cost versus Mean Time

With respect to the datum case, nullifying resource efficiencies of less than or equal to 0.2, i.e. Case 2.2, provides the greatest reduction in time. In Case 2.2, the design development phase can be scheduled to be completed in approximately 36 weeks as opposed to 64 weeks in the datum case. In addition to this 44% reduction in time, Case 2.2 also offers a 44% reduction in cost.

The time and cost differences between Cases 2.3 and 2.4 is marginal since only one resource had a forecasted efficiency of 0.4. Similarly, the difference between Cases 2.5 and 2.6 is marginal due to only two resources having a forecasted efficiency of 0.6.

To establish if any further improvements can be made, an assessment is made of an optimised schedule that closest reflects the mean for Case 2.2. Thus, an assessment of the 2nd derived schedule of Case 2.2 is shown in Table C.22 and summarised in Table C.23 of Appendix C. The $\Sigma T_{ED}/\Sigma R_{FE}$ ratios calculated in Table C.23 are plotted in Figure 10.15.

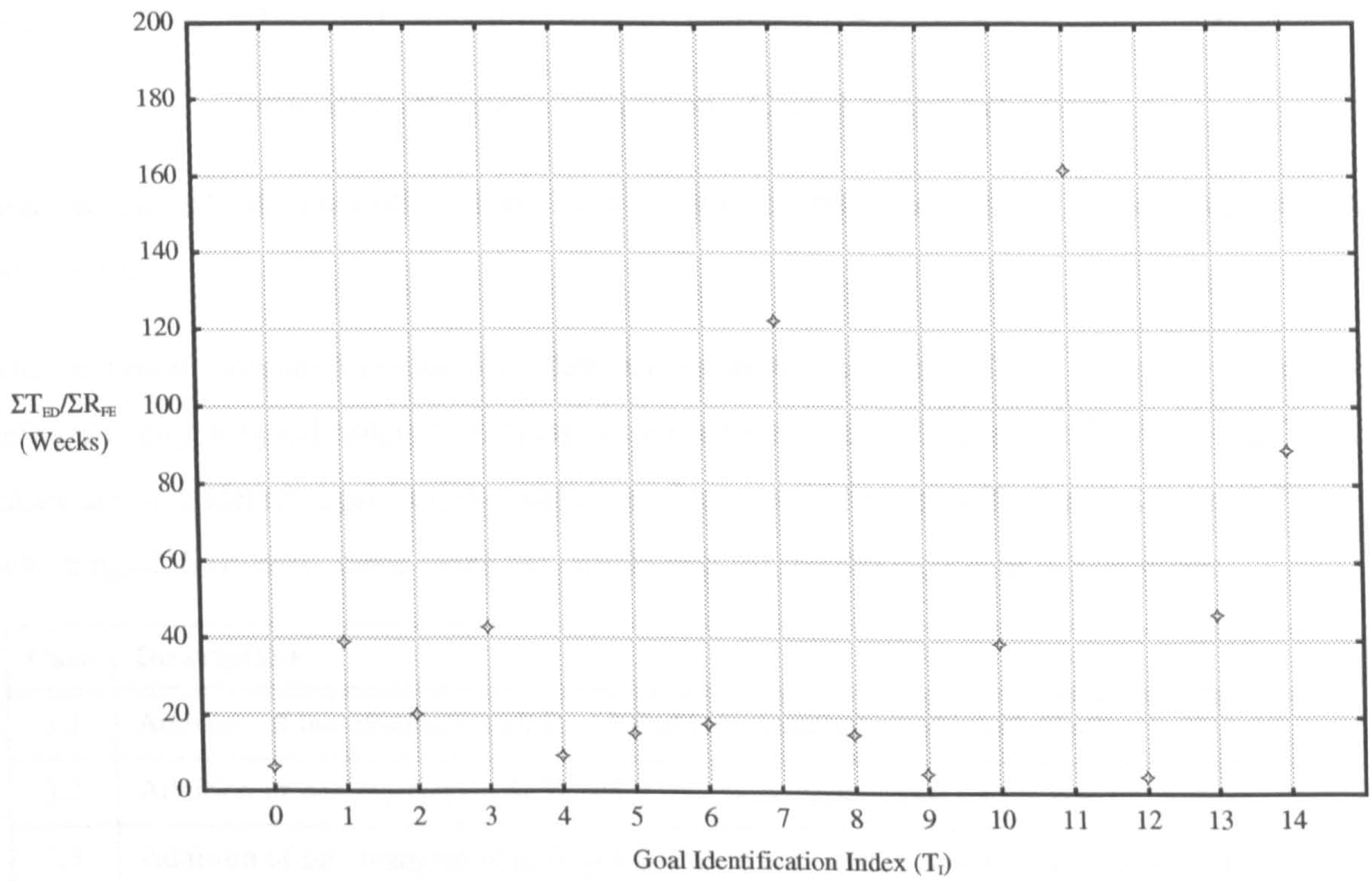

Figure 10.15 $\Sigma T_{ED}/\Sigma R_{FE}$ Ratios for each Goal - Case 2.2 (2nd Schedule)

By comparing Figure 10.11 with Figure 10.15, it can be seen that the $\Sigma T_{ED}/\Sigma R_{FE}$ ratio for goal T_I=1 has been reduced significantly due to nullifying low forecasted efficiencies of resources. Further, $\Sigma T_{ED}/\Sigma R_{FE}$ ratios greater than 100 correspond to goals T_I=7 and 11. Despite nullifying low forecasted efficiencies, an imbalance still exists in the design team with respect to the tasks of the associated goals.

Since the first iteration of the prospective part of the methodology showed that the addition of engineers had negligible effect in terms of reducing time and cost, then rather than only choosing to add resources, existing resources are also modelled as being developed by increasing their forecasted efficiency in the deficient areas identified, i.e. goals T_I=7 and 11.

As shown in Table 10.19, with regard to T_I=11, the only two resources able to complete tasks associated with this goal are resources R_I=1 and R_I=5 with R_{FE} values of 0.9 and 1.0 respectively. Thus, the scope to develop these resources is relatively small and, as such, another resource must be selected.

On inspecting the assessment of the 2nd schedule of Case 2.2 shown in Table C.22 of Appendix C, it can be derived that the utilisation of resources R_I=0 and R_I=8 are 0% and 1% respectively. The utilisation of all nine resources in this schedule are shown in Table 10.22.

Resource, R_I	0	1	2	3	4	5	6	7	8
Utilisation (%)	0	88.3	67.2	97.2	83.3	88.9	91.1	83.9	1.1

Table 10.22 Resource Utilisation - Case 2.2 (2nd Schedule)

Since resource R_I=0 is not utilised and R_I=8 is significantly under utilised, they are selected to be developed.

The proposed simulated resource models are as shown in Table 10.23, in which each case reflects changes in addition to nullifying resource forecasted efficiencies of 0.1 and 0.2. Three cases are considered regarding the addition of resources for goals T_I=7 and 11, i.e. $2^{n_G} - 1$ where n_G=2. Similarly, three cases are considered for the development of resources.

Case	**Description**
3.1	Addition of one resource with R_{FE}=1.0 able to undertake tasks with T_I=7
3.2	Addition of one resource with R_{FE}=1.0 able to undertake tasks with T_I=11
3.3	Addition of one resource with R_{FE}=1.0 able to undertake tasks with T_I=7 and T_I=11
3.4	Develop resource R_I=0 and R_I=8 to R_{FE}=1.0 able to undertake tasks with T_I=7
3.5	Develop resource R_I=0 and R_I=8 to R_{FE}=1.0 able to undertake tasks with T_I=11
3.6	Develop resource R_I=0 and R_I=8 to R_{FE}=1.0 able to undertake tasks with T_I=7 and T_I=11

Table 10.23 Simulated Resource Model Cases

3rd Iteration of Steps 3, 4 and 5

A summary is presented in Table C.24 of Appendix C regarding the time and cost associated with each optimised schedule derived for Cases 3.1 to 3.6. Figure 10.16 shows the mean time and mean cost of each case and, in addition, the datum case.

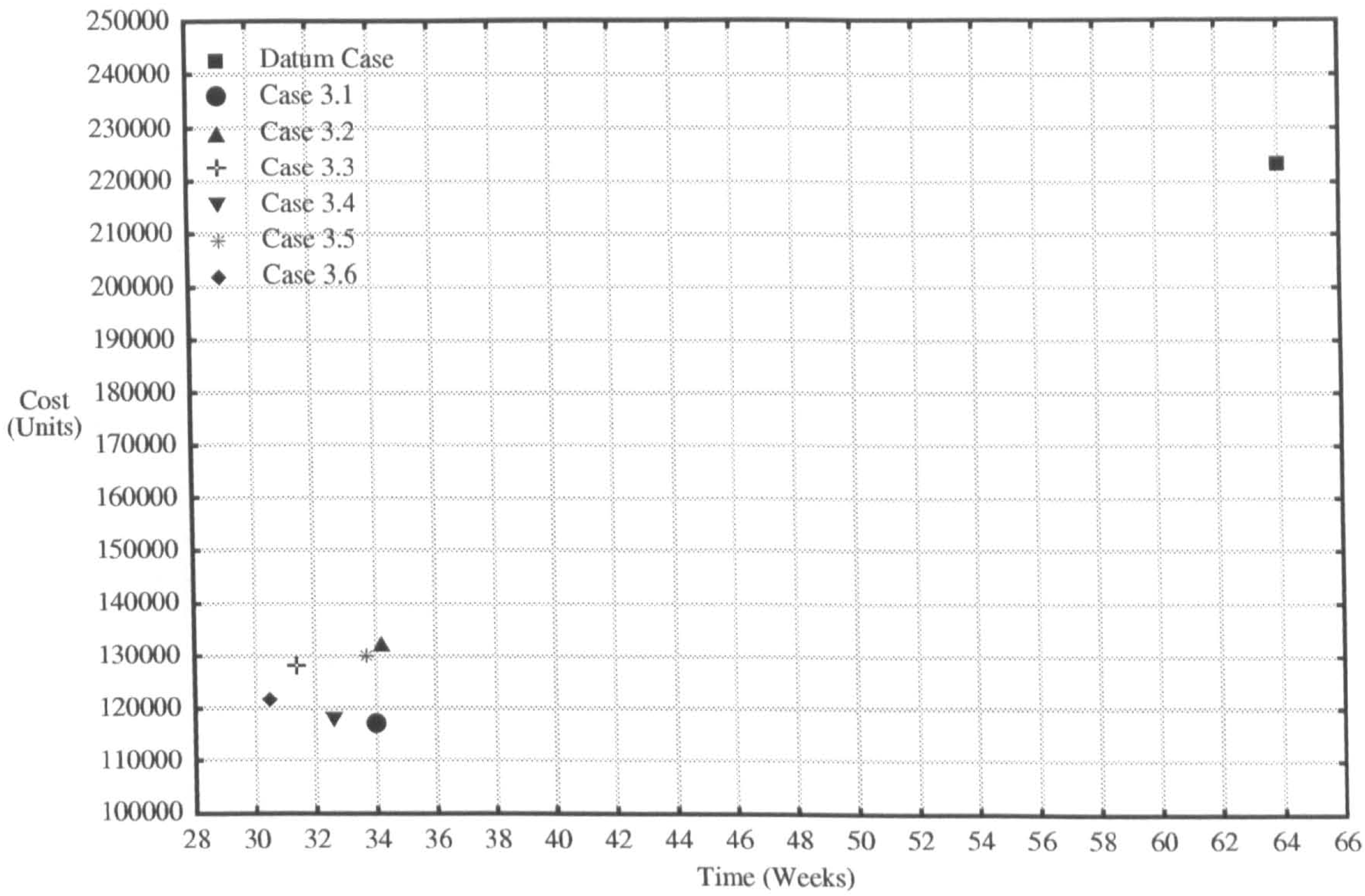

Figure 10.16 Mean Cost versus Mean Time

In Figure 10.16, the addition and development of resources has resulted in further reductions in time and cost. The lowest expected time to complete the design development phase corresponds with Case 3.6, which involves improving the forecasted efficiencies of existing resources rather than adding resources. Specifically, Case 3.6 corresponds to a 52% reduction in time and 45% reduction in cost.

In order to establish whether or not any further improvements can be made, an assessment is made of an optimised schedule that most closely represents the mean time and mean cost for Case 3.6. Thus, an assessment of the 4th derived optimised schedule of Case 3.6 is shown in Table C.25 and summarised in Table C.26 of Appendix C. The $\Sigma T_{ED}/\Sigma R_{FE}$ ratios calculated in Table C.26 are illustrated in Figure 10.17.

In Figure 10.17, all of the $\Sigma T_{ED}/\Sigma R_{FE}$ ratios are less than 80. While the resources have not been completely balanced, the difference between the $\Sigma T_{ED}/\Sigma R_{FE}$ ratios has significantly diminished. That is, the most prominent discrepancies in the $\Sigma T_{ED}/\Sigma R_{FE}$ ratios has been removed leading to the conclusion that the imbalance within the resources has been largely redressed.

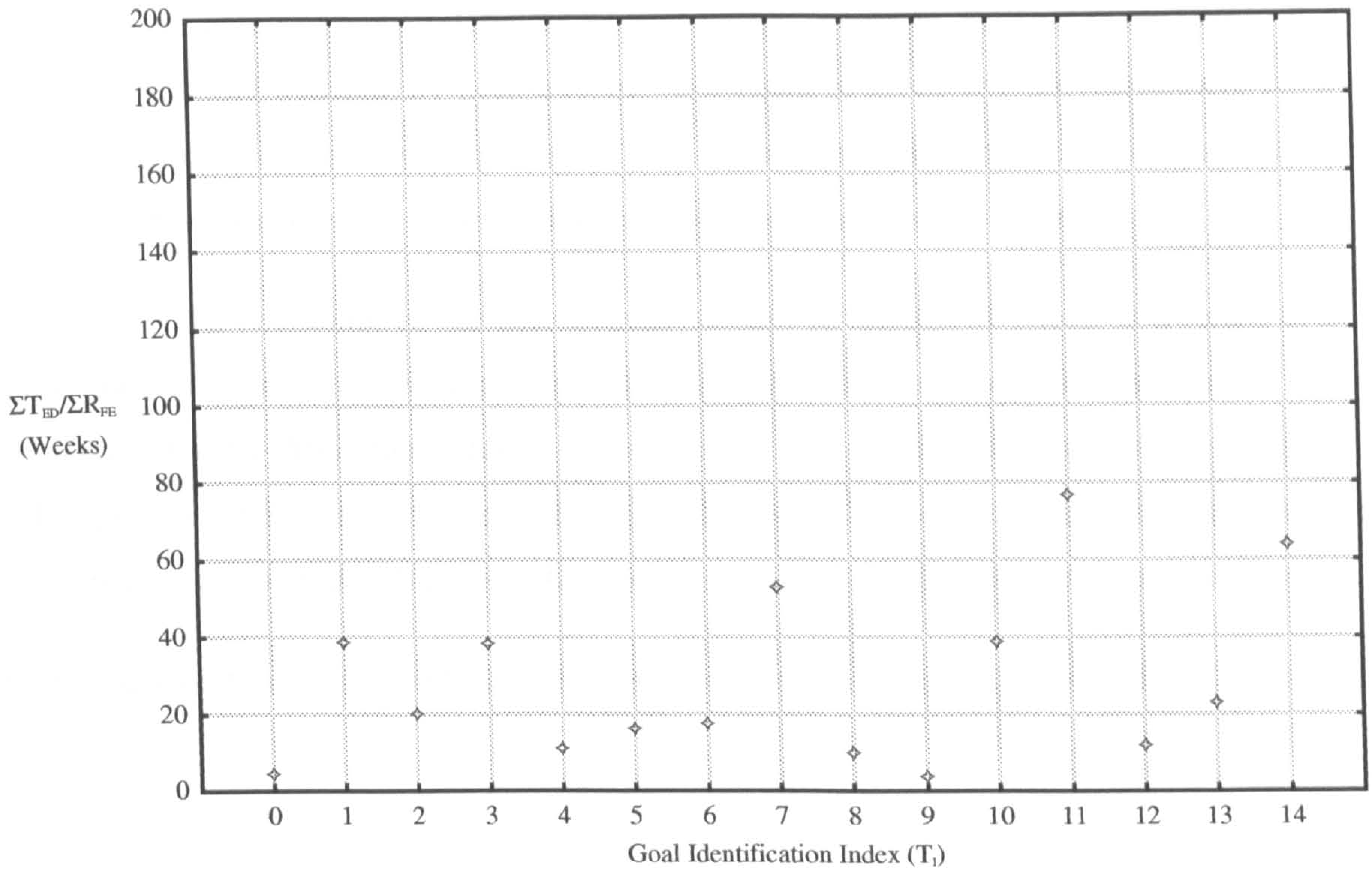

Figure 10.17 $\Sigma T_{ED}/\Sigma R_{FE}$ Ratios for each Goal - Case 3.6 (4th Schedule)

In summary, as a result of excluding resource forecasted efficiencies of less than 0.3, and developing the existing resources R_I=0 and R_I=8 with regard to their ability to undertake tasks associated with goals T_I=7 and T_I=11, it has been shown that the estimated time to complete the design development phase can be reduced by 52%. In addition, an associated cost reduction of 45% can be achieved. As such, a proposed resource model is shown in Table C.27 of Appendix C.

10.5 Summary

Real-time operational design co-ordination, implemented within the Design Co-ordination System, has been applied to a case study involving the turbine blade design process provided by Siemens Power Generation Limited. The case study has demonstrated the various features of the real-time operational design co-ordination part of the methodology. In particular, coherent task, resource and schedule management has enabled the turbine blade design process to be performed in an operationally co-ordinated manner in real-time. Further, from the point when considered, co-ordinated adjustment in real-time resulted in excess of a 50% reduction in the time to complete the turbine blade design process. However, this reduction reflected the stage of completion of the turbine blade design process when adjustment was considered.

Prospective operational design co-ordination has been applied to two industrial case studies provided by Armstrong Technology Associates and domnick hunter limited.

At the outset of a marine vessel conversion design programme, Armstrong Technology Associates are able to identify deficiencies and assess proposed improvements within their single-skilled multi-disciplinary design team. As a result of proposing the recruitment of two additional consultant electrical engineers, a 28% reduction in the estimated time to complete the design programme could be achieved with no cost penalty being incurred.

Similarly, at the beginning of the new product design development phase of a rotary drum dryer, domnick hunter limited are able to determine the most appropriate modelling of their multi-skilled multi-disciplinary design team. Further, the development of existing designers with regard to specific skills was established leading to a 52% reduction in the estimated time to complete the design development phase with an associated 45% reduction in resource cost.

An evaluation of the approach to operational design co-ordination is presented in Chapter 11.

11 Evaluation of the Approach

The aim of this chapter is to evaluate the approach in terms of the requirements of operational design co-ordination by examining its application to the practical case studies presented in Chapter 10.

An evaluation, including company feedback, of the real-time and prospective parts of the methodology within the approach, and where appropriate the support provided by the knowledge modelling formalism, are presented in Sections 11.1 and 11.2 respectively. Further, based on the evaluation, each section highlights the strengths and weaknesses of the respective parts of the methodology. Finally, the chapter is summarised in Section 11.3.

11.1 Real-Time Operational Design Co-ordination

In order to evaluate the real-time part of the methodology, the Design Co-ordination System (DCS) was applied to the turbine blade design process case study. This involved the use of a suite of analysis tools as used by the engineers within Siemens Power Generation Limited.

11.1.1 Turbine Blade Design Process

As stated in the correspondence from the company presented in Appendix D, "traditionally, the simulation tools are executed sequentially by the designer using a single computer". Further, while the obvious benefits of using the DCS were recognised, it was stated that "it is the underlying real-time operational design co-ordination methodology and the work in setting up the architecture for this that is of key importance". In addition, it is stated that "enabling the turbine blade design process to be continuously co-ordinated in real-time, while being responsive to changes in the environment such that the process is performed in an optimised way, is a considerable achievement of your research". With regard to the methodology, and its implementation within the DCS, the belief was expressed that "the principles involved provide an improvement to current approaches aimed at managing / co-ordinating and engineering design".

<u>Task Management</u>

In Chapter 3, task management was defined as "the organisation and control of tasks, and the dependencies between them, such that they can be undertaken and completed in a structured manner".

<u>Construction of the Task Model: Establishing, Maintaining and Managing Tasks</u>

The construction of the task model, and the subsequent management of the knowledge held within it, provided the basis for enabling the structured undertaking and completion of tasks in real-time. That is, each task to be undertaken was assigned values to knowledge attributes for inclusion within the task model. These values assisted the management of tasks in terms of their enactment and, in addition, scheduling/re-scheduling.

Initially, the tasks to be undertaken within the turbine blade design process were established based on knowledge provided by the designer regarding the analysis tools to be used.

In order to identify tasks, they were assigned indices to allow the appropriate task to be scheduled/re-scheduled, undertaken and completed to accomplish goals. The global task identification index was used for scheduling / re-scheduling purposes. This index was dynamic within the task model since in the event of re-scheduling, only outstanding tasks were considered and, as such, their global task identification indices needed to be re-set. The static goal and local task identification indices were used for task enactment purposes.

Knowledge of the datum duration was used such that, once scheduled, the estimated duration of the task could be determined based on the corresponding forecasted efficiency of the resource to which it was assigned.

Progress knowledge was required for purposes of re-scheduling. That is, once a task was completed, this knowledge attribute was re-set within the task model such that it could not be considered again for re-scheduling.

Preparation for re-scheduling involved the task model being modified such that only the tasks to be included within the revised schedules would be re-scheduled. Further, knowledge attributes were modified pertaining to these tasks, and the tasks they were dependent on such that revised schedules would accurately reflect the outstanding tasks. In addition, although not yet undertaken, progress knowledge was modified regarding the tasks to be completed during re-scheduling in accordance with the interim schedule models.

Within the DCS, tasks were defined as executions of analysis tools and, as such, once started they could not be interrupted, i.e. the tasks were non pre-emptive. Thus, in terms of re-scheduling, tasks could only be one of two states, i.e. completed or outstanding. The scenario of a task being only partially completed was not able to be considered. As such, the concept of re-scheduling proportions of tasks could not be tested. Further, within the case study, despite analysis tools involving stress and vibration calculations regarding the turbine blades, tasks of only one type could be undertaken in the DCS, i.e. executing an analysis tool.

In order to undertake tasks in a structured manner, dependencies between them were established and maintained. Establishing this knowledge required the construction of a dependency matrix by comparing the input requirements of each task with the output requirements of all others. Based on these requirements, the task model included knowledge of the number of tasks that each task was dependent on and their global task identification index/indices. During the enactment of the tasks within the turbine blade design process, dependency knowledge was checked where appropriate such that tasks could only be undertaken if any tasks they were dependent on had been completed.

Information Management

Within the DCS, the organisation, provision and storage of task input/output information was supported such that tasks could be undertaken when required.

A consequence of task dependency management was the assurance that in the event of a task being required to be undertaken, any necessary information was available. When a Task Manager requested information such that a task could be undertaken, the necessary inputs were retrieved from the task information repository and provided by the related Information Manager. On completion of the task, the resulting output was supplied by the Task Manager to the related Information Manager such that it could be stored and retrieved in the future if needed. This process of requesting, providing and supplying task information was carried out for every task to be undertaken within the turbine blade design process. As a result of managing information in this manner, in no case did, or could, information fail to be provided on request due to not being available.

Resource Management

In Chapter 3, resource management was described as "organising and controlling resources to enable their continuous optimised utilisation throughout a changeable design development process". In order to assess the utilisation of the resources throughout the turbine blade design process, it is appropriate to divide the process into a number of logical sections. Since resources were allocated for utilisation according to schedule models, the turbine blade design process can be divided according to these models, i.e. original, interim and revised.

It is noted that prior to the original schedule models being derived, the resources were only utilised for initial agent activity rather than undertaking tasks. This period of resource inactivity is a consequence of only allowing tasks to be undertaken once scheduled.

Resource Utilisation during the Enactment of the Original Schedule Models

In order to facilitate the optimised utilisation of the resources, they were initially assigned forecasted efficiencies such that, as a result of scheduling, the appropriate type and number of tasks would be assigned to them. In the methodology presented in Chapter 8, forecasted efficiencies were described as being assigned for the range of tasks able to be undertaken by the resources. Since the tasks within the turbine blade design process were all defined as executions of analysis tools then only a single forecasted efficiency existed for each resource. Similarly, only a single upper and lower monitored efficiency threshold was used for each resource.

The DCS supported the forecasting of resource efficiency to aid the derivation of appropriate schedules such that resources utilisation could be optimised. Forecasting enabled a prediction of future efficiency of the resources to be determined, such that the appropriate tasks could be assigned to them. Each Resource Monitor used regression analysis and orthogonal polynomials with past monitored efficiencies in order to calculate a forecasted efficiency at one step ahead, i.e. t+1. A limitation of only forecasting one step ahead is that in reality the forecast is intended to be applicable over a greater period of time. While it is acknowledged that all predictions may not always be accurate, some level of confidence must be gained by aiming to forecast over the long-term rather than the short-term.

Initially, resources were utilised in an optimised manner for a proportion of the estimated duration of the enactment of the original scheduled models. However, at a certain point in time, the monitored efficiency of one of the resources began to decrease. Since monitoring was supported, this was observed by the Resource Monitor associated with the resource. Due to the nature of the operating environment of the DCS, the monitored efficiency of each resource was directly proportional to the progress of their respective original schedule model. As such, only resources were monitored.

A period of time elapsed before the monitored efficiency of the resource exceeded its specified lower threshold. As such, while the monitored efficiency of three of the four resources closely adhered to their respective forecasted efficiency, the resource with the decreasing monitored efficiency started to affect their optimised utilisation. That is, due to the decrease in monitored efficiency, tasks expected to be undertaken and completed were delayed. Consequently, any tasks dependent on the completion of these delayed tasks were delayed themselves, thus affecting the utilisation of all resources. Thus, while the resource with decreasing monitored efficiency continued to be utilised, re-scheduling needed to be considered and, if appropriate, performed to avoid any further delays being encountered. Monitoring resources enabled the timely recognition of a monitored efficiency threshold being exceeded, and new forecasted efficiencies being calculated, leading to the consideration of re-scheduling (see schedule management).

Resources were utilised in an optimised manner according to the proportion of the original schedule models that were enacted. However, the timely recognition of the need to consider re-scheduling ensured the future utilisation of resources was also optimised.

Resource Utilisation during the Enactment of the Interim Schedule Models

In considering whether or not to re-schedule, interim schedule models were derived by applying a three-step procedure. The application of this procedure resulted in tasks being included within the interim schedule models that would ensure, as near as possible, resources would be utilised in an optimised manner during re-scheduling. The interim schedule models reflected the workload able to be completed by each of the resources taking into account their respective newly forecasted efficiencies (see schedule management). That is, the cumulative datum duration of the tasks assigned to each resource were directly proportional to the forecasted efficiencies.

Since re-scheduling was performed (see schedule management), the interim schedule models enabled the continuation of optimised resources utilisation during this period.

Resource Utilisation during the Enactment of the Revised Schedule Models

As with the interim schedule models, the tasks within the revised schedule models reflected the workload able to be completed by each of the resources considering their respective forecasted efficiencies. In the application of the DCS, the revised schedule models were completed in the time estimated since the forecasts of efficiency approximately reflected those subsequently monitored. As such, resources were utilised in an optimised manner during the enactment of the revised schedule models.

Schedule Management

In Chapter 3, schedule management was described as "managing the planning and dynamic assignment of tasks to resources, and the enactment of the resulting schedules, throughout a changeable design development process". As such, an aim of the real-time part of the methodology is to ensure that dynamic scheduling occurs when appropriate during the turbine blade design process. Further, that all schedules are derived using appropriate task and resource knowledge and, subsequently, their enactment is managed.

Planning and Dynamic Scheduling

Within the DCS, planning involves accessing appropriate task and resource knowledge for use with the MOGA. This knowledge was maintained within the respective models throughout the operation of the DCS. Thus, when planning was performed followed by scheduling/re-scheduling, the resulting schedules ensured that tasks were undertaken in a structured manner and resource utilisation was optimised.

Schedule Enactment / Pending Scheduled Tasks

In order to facilitate the co-ordinated undertaking and completion of tasks, the enactment of schedules was supported by managing and maintaining dependencies between tasks. During the turbine blade design process, three types of schedule were derived, i.e. original, interim, and revised. The procedure for enacting the original and revised schedule models was identical. That is, the relevant agents ensured that the task could be undertaken by checking dependencies and providing the required information (see task management). However, in situations where tasks could not be undertaken when scheduled, due to the tasks they are dependent on not yet being completed, the pending schedule task repository provided support by ensuring that they were only undertaken when appropriate. Thus, on the completion of every task, in addition to updating progress knowledge in the task model (see task management), the pending scheduled task repository was checked such that, if appropriate, any awaiting tasks could be undertaken. As such, throughout the turbine blade design process, no situation occurred in which a task was attempted to be undertaken when it was not possible.

The procedure for enacting the interim schedule models differed from that of the original and revised schedule models in that task dependency checking was not required. The reason for omitting task dependency checking was that interim schedule models only included independent tasks. By omitting this checking during the enactment of the interim schedule models, (i) the Scheduler was free to perform re-scheduling uninterrupted, and (ii) the task model was not altered such that it would effect the enactment of the revised schedule models.

Decision-Making with regard to Re-Scheduling

Prior to making the decision regarding whether or not to re-schedule, the Scheduler instructed each Activity Director to suspend their associated original schedule model. At the point in time when suspension was requested, three tasks were being undertaken and one was pending. Due to tasks being non pre-emptive, the three tasks being undertaken had to be completed. However, the pending task was not undertaken. As a result, knowledge of this task was removed from the pending scheduled task repository. This removal was required since failure to do so would cause deadlock on the enactment of the following interim/revised schedule models. Once all Activity Directors had suspended the enactment of their associated original scheduled models, of the one hundred and thirty one tasks involved in the turbine blade design process, twenty seven had been completed while one hundred and four remained outstanding.

In order to ensure that re-scheduling was only undertaken if appropriate, i.e. would lead to a reduction in the time taken to complete the turbine blade design process, estimations were determined for the time taken to: (i) complete the current, i.e. original, schedule, (ii) derive the revised schedule, and (iii) complete the revised schedule.

The procedure of determining the estimated time taken to complete the original schedule involved summing the datum durations of the outstanding tasks within each respective original schedule model and dividing by the newly forecasted efficiency of the associated resource. The estimated time taken to complete the original schedule corresponded to the greatest estimated time to complete the original schedule model associated with the resource that caused re-scheduling to be considered, i.e. approximately 79 seconds. The accuracy of this estimate could only ever be assessed if the decision was made not to perform re-scheduling, nor at any other point during the process, since the enactment of the original schedule models would be resumed through to completion.

The estimated time to derive a revised schedule was made based on empirically derived characteristics of the MOGA. For the number of resources to be utilised, a regression equation was used such that based on the number of tasks to be re-scheduled, an estimation of the time taken to re-schedule could be made. As described in Chapter 10, the empirical characteristics of the MOGA were based on a number of assumptions regarding its use and the nature of the tasks to be re-scheduled. While some of these assumptions were true of any use of the MOGA within the context of the DCS, a number were also particular to the turbine blade design process. A more detailed assessment of the influence of certain parameters used as input for the MOGA would yield more generic characteristics in terms of obtaining an accurate estimation of the time to re-schedule.

While empirically derived characteristics of the MOGA were used to determine an estimated execution time, a three-step iterative procedure was applied to ensure that the optimum number of tasks were re-scheduled and the utilisation of the resources was optimised during re-scheduling. The procedure involved adjusting the number of tasks to be re-scheduled and, each time, estimating the time to re-schedule them. Subsequently, the tasks that could be completed during this period were determined. After four iterations, the procedure converged on the solution that sixty tasks should be re-scheduled for inclusion within the revised schedule models, while, simultaneously, forty four tasks were undertaken and completed in accordance with the interim schedule models. Using empirically derived information regarding the

MOGA, re-scheduling sixty tasks was estimated to take approximately 20 seconds. Proportioning tasks in this manner was not only expected to facilitate the optimised utilisation of the four resources according to the interim schedule models during re-scheduling but, in addition, afterwards in the enactment of the revised schedule models. That is, the idle time of the resources was minimised in the transition between adjacent schedules. In determining the optimum estimated time to re-schedule, the estimated mean idle time of the resources was calculated to be approximately 3 seconds.

While the estimated time taken to complete the original schedule involved assessing the original schedule models, the estimated time taken to complete the revised schedule was obtained without the use of any schedule models. A three-step iterative procedure was employed involving grouping tasks according to future dependency relationships and assigning them to resources such that the estimated time to complete them was minimised. The application of this procedure resulted in an estimated time to complete the revised schedule of approximately 18 seconds.

As a result of determining the three estimated times discussed, by re-scheduling it was estimated, that from the point when re-scheduling was considered, the turbine process could be completed in 38 seconds whereas continuing to adhere to the original schedule models would have taken 79 seconds. As such, these estimations provided in excess of a 50% reduction in time to complete the turbine blade design process from the point at which re-scheduling was considered. This key feature of the methodology demonstrates that by adjusting in real-time when appropriate in a co-ordinated manner, benefits can be made in terms of reducing the time to complete the process. However, the magnitude of any reductions that can be achieved are dependent on the stage of completion of the process.

Within the operating environment of the DCS, the time taken to make the decision to re-schedule does not influence the decision itself. However, within an engineering company consisting of many multi-skilled resources and numerous inter-related tasks, the time taken to determine the estimates discussed in order to make the decision may have a bearing on the decision to re-schedule.

Optimised Concurrent Re-Scheduling and Undertaking Tasks

An outcome of determining the estimated time to derive a revised schedule was the identification of those tasks that could be undertaken during the period of re-scheduling. In addition to the identification of these tasks, the DCS supported their undertaking during the period of re-scheduling. Due to the procedure used to determine the tasks for inclusion within the interim schedule models, their completion occurred within several seconds prior to the arrival of the revised schedule. This near co-incident occurrence leads to the conclusion that the empirically derived characteristics of the MOGA and the three-step iterative procedure used are reliable.

11.1.2 Strengths and Weaknesses

Based on the evaluation presented in Section 11.1.1, this section highlights the strengths and weaknesses of this part of the methodology that have been identified. In addition, this section is presented in terms of task, resource, and schedule management, which reflects the requirements of operational design co-ordination.

<u>Task Management</u>

The DCS is able to organise and control tasks, and the dependencies between them, such that they can be undertaken and completed in a structured manner in real-time.

<u>Strengths</u>

- Tasks, and the dependencies between them, were established, maintained and managed.
- Knowledge of tasks was modelled that enables the undertaking and scheduling/re-scheduling of tasks to be managed.
- Information used to undertake tasks is managed such that prior to any task being undertaken, the requested information was able to be provided, and on the completion of each task, any resulting information was maintained such that it could be retrieved in the event of being required as input for another task.

<u>Weaknesses</u>

- Tasks were non pre-emptive, thus simplifying the problems associated with managing the progress of a task.
- While tasks involved various calculations of the stresses and vibrations regarding turbine blades, in reality they were only of one type due to the nature of the operating environment.

<u>Resource Management</u>

The DCS supports the organisation and control of resources to enable their continuous optimised utilisation throughout a changeable process.

Strengths

- Resources are modelled such that each resource is assigned an efficiency forecast with regard to the type of tasks they can be utilised to undertake and complete, which could be used to assist in their appropriate allocation for utilisation.
- Resource forecasting is supported such that in the event of any threshold being exceeded, resource knowledge can be updated to reflect the prevailing efficiency of the resources. That is, future efficiency is forecasted such that if it is decided that an appropriate course of action would be to re-schedule, then any resulting derived schedule will enable the optimised allocation and utilisation of resources.
- Resource monitoring is supported in order to detect if any defined efficiency thresholds are exceeded.

Weaknesses

- Resources are not utilised to undertake tasks prior to the derivation of the original schedule.
- Since only one type of task existed, only a single forecasted efficiency and associated monitored efficiency upper and lower threshold was assigned.
- The forecasting technique used was only able to make a prediction of resource forecasted efficiency one step ahead.

Schedule Management

The DCS supports the management of planning and the dynamic assignment of inter-related tasks to the most appropriate resources throughout a changeable process. In addition, the management of the enactment of the resulting schedule is supported.

Strengths

- Planning is supported, which involves preparation of task and resource knowledge for scheduling.
- Dynamic scheduling is supported such that, if appropriate, revised schedules can be derived that reflect the current state of affairs in terms of the tasks to be undertaken and the resources to be utilised.
- Schedule enactment, involving the management of dependencies between scheduled tasks, is supported using a pending scheduled task repository.

- Decision-making is supported with regard to re-scheduling such that it is only performed if beneficial to the overall performance of the process, i.e. will result in the process being completed in less time than if re-scheduling were not performed.
- Optimised concurrent re-scheduling and undertaking tasks is supported.

Weaknesses

- Schedule monitoring is not supported within the application of the DCS since the progress of the schedule models was proportional to the monitored efficiency of the resource. As such, only resource monitoring is supported.
- Interim schedule models only consist of tasks that are independent at the time of being considered for inclusion.
- The empirically derived characteristics of the MOGA were obtained based on a number of assumptions that were specific to the turbine blade design process case study.
- The decision-making process regarding re-scheduling does not account for the time taken to make the decision itself.

11.2 Prospective Operational Design Co-ordination

As indicated in Chapter 10, Armstrong Technology Associates and domnick hunter limited each provided a practical case study in order to enable the prospective part of the methodology to be evaluated. Two case studies have been used since the design teams within each company are modelled differently. Armstrong Technology Associates employ single-skilled engineers within a multi-disciplinary design team. In contrast, domnick hunter limited utilise multi-skilled engineers within a multi-disciplinary design team.

Throughout both case studies, the composition of tasks was static. As such, every off-line schedule derived was based on the same set of tasks as originally defined within the respective case studies. The role of schedule management involved the derivation of off-line schedules to enable the identification of deficiencies in terms of resources. As in the real-time part of the methodology, the MOGA was used to derive schedules. In both case studies, resource management focused on the modelling of resource forecasted efficiency with respect to the tasks associated with each goal such that improvements could be proposed and assessed.

Initially, the prospective part of the methodology involves identifying deficiencies in the original resources with respect to the datum schedule and, consequently, proposing support in the form of improvements to the resources. This proposed support is then assessed in terms of time and cost. Further, the existence of any deficiencies are identified in this proposed support.

If deficiencies are found to exist, then further support is proposed. Since the prospective part of the methodology is iterative, the assessment of proposed support, identification of any deficiencies, and proposal of further support is repeated until the appropriate improvements to the resources are deemed to have been made.

11.2.1 Marine Vessel Conversion Design Programme

As indicated in the correspondence from Armstrong Technology Associates in Appendix D, the application of the methodology to the case study "identified, at the outset of the design programme, the specific areas within our organisation in which it would have been beneficial to allocate additional skilled personnel". Further, it was stated that "the findings suggest that the methodology applied is an effective feature of engineering management" and that "the methods employed are practical and of considerable value, and would improve the management of future design programmes".

The Senior Project Manager within the company supplied knowledge of the design programme in terms of tasks and design team members, i.e. resources. Task knowledge comprised of the number of tasks, their datum durations, and dependencies between them. Resource knowledge consisted of forecasted efficiency, with respect to the tasks associated with each goal (discipline), that corresponded with their respective resource designations, i.e. consultant, senior design engineer and design engineer. Resource cost per unit time was also supplied and assigned in accordance with these respective designations. In addition to the knowledge provided by the Senior Project Manager, tasks and resources were assigned further knowledge attributes such that they could be considered within the prospective part of the methodology.

Identify any Deficiencies in the Original Resources and Propose Support

Based on the datum schedule derived, the estimated duration of all one hundred and thirty four tasks associated with all goals was determined. This involved dividing the datum duration of each task by the forecasted efficiency of the resource to which it was assigned according to the schedule. Since resources were single-skilled, they were only assigned tasks associated with the goal that corresponded with the resource's discipline. Ratios were then determined for each goal by dividing the cumulative estimated duration of the tasks associated with the goal by the cumulative forecasted efficiency of the resources assigned these tasks. The ratios provided a measure of the duration of tasks associated with each goal per unit of allocated forecasted efficiency. In practice, the ratios calculated revealed that electrical engineering was deficient in terms of the resources utilised in the derived schedule. Further, ratios for naval architecture and marine engineering were observed as being approximately equal. An incremental approach, including all combinations, was taken with regard to proposing support in the form of simulated resource models. Thus, one additional electrical engineer in each of the three designations was proposed, i.e. consultant, senior design engineer, and design engineer.

Assess Support, Identify any Deficiencies, Propose further Support

An assessment of these additions indicated that an additional consultant electrical engineer provided the greatest reduction of approximately 22% in estimated time to complete the schedule and a 1% reduction in cost. It was also indicated that the imbalance was not sufficiently redressed between the ratio for electrical engineering and that of naval architecture and marine engineering. Consequently, the addition of two electrical engineers was proposed in all combinations of the three designations stated earlier.

A further iteration of the methodology indicated that two additional consultant electrical engineers resulted in the greatest reductions of 28% and 1% in time and cost respectively. Also, this addition redressed the imbalance in the resources.

In summary, with regard to the finding of recommending to improve the design team by adding two consultant electrical engineers, as indicated in the correspondence in Appendix D, it is stated that "the findings of the case study are in agreement with the final allocation of resources as implemented in practice" and, furthermore, "this finding corroborates with our decision to allocate two additional electrical engineers to the design programme". Also, in relation to the decision made by the company, it was said that "the decision was determined during the design programme rather than at the outset as would have been indicated had we applied your methodology". In fact, the company recruited two electrical engineers in the final third of the design programme. However, these additions did not prevent the design programme from over-running.

11.2.2 Rotary Drum Dryer Design Development Phase

From the correspondence provided by domnick hunter limited in Appendix D, it was stated that "the work offers an advanced methodology to modelling and managing the engineers within our research and development department". Further, it was said that "the work provides a very useful technique for assessing our personnel requirements prior to starting the design development phase involving our multi-disciplinary, multi-skilled design team".

As in the previous case study, knowledge of the tasks to be undertaken and the design team to be utilised within the design development phase was provided by the company's Research and Development Manager. Due to the multi-skilled multi-disciplinary nature of the design team, each member, i.e. resource, was assigned a forecasted efficiency for a range of goals with associated tasks. Again, as in the previous case study, in addition to the knowledge provided by the Research and Development Manager, further knowledge attributes were assigned to tasks and resources enabling them to be considered within the prospective part of the methodology.

Identify any Deficiencies in the Original Resources and Propose Support

The assessment of each schedule involved dividing the datum duration of each of the one hundred and ninety tasks by the forecasted efficiency of the resource to be utilised for the corresponding goal associated with that particular task. The resulting estimated duration of the tasks associated with each goal was then summed. To obtain the required ratios, this estimated duration was then divided by the cumulative forecasted efficiency of the resources allocated to be utilised to undertake these tasks.

Four goals were identified as having ratios greater than or equal to 100. The significance of this value was that it provided a threshold leaving a manageable number of goals in terms of proposed improvements in the form of simulated resource models. On consideration of the actual deployment of available resources with regard to the tasks associated with these four goals, it was found that not all resources were utilised that were able to undertake tasks of one of the goals. As a result, only three goals were considered for improvement in terms of resources able to complete the associated tasks. Support was proposed in the form of adding a single resource with a forecasted efficiency of unity for each of the three goals in turn. Further, combinations of adding two and three resources were proposed with respect to the three goals under consideration. That is, a full factorial technique was used based on the expression $2^{n_G} - 1$, where n_G is the number of goals considered. As such, for three goals, seven combinations of resource improvement were proposed.

Assess Support, Identify any Deficiencies, Propose further Support

An assessment of the proposed support showed that the greatest reduction in estimated time to complete the schedule was approximately 5% with an associated 4% increase in cost. Furthermore, the ratio of one of the goals was observed to increase significantly as a result of the improvements to the resources. The reason for this increase was attributed to tasks being assigned to resources with low forecasted efficiencies for the associated goal. Since the addition of resources did not notably reduce time and, in fact, increased cost, as well as having an adverse effect on the ratio of one particular goal, the initial proposed support was disregarded. Further, based on the original resources, the incremental nullification of low forecasted efficiencies was proposed. Specifically, forecasted efficiencies were set to zero in increments of 0.1 until any further nullification would result in the design team being unable to complete all of the tasks.

The next iteration of the methodology showed that the proposed support of nullifying forecasted efficiencies of less than 0.3 resulted in the greatest reductions of 44% in both time and cost. Despite these reductions, the proposed support was shown not to satisfactorily redress the imbalance in the resources. That is, the ratios of two goals remained in excess of 100. Previously, initial support in the form of the addition of resources had been shown to only marginally reduce time and actually increase cost, and thus was disregarded. As such, based on the original resources with forecasted efficiencies of less than 0.3 being nullified, further support was proposed by developing as well as adding extra resources. In particular, the addition and development of resources able to complete tasks associated with the two goals with ratios greater than 100. Two resources were chosen to be developed in terms of forecasted efficiency since they were significantly under utilised in the schedule corresponding to the previous proposed support, i.e. nullifying forecasted efficiencies of less than 0.3. This proposed support involved combinations of adding and developing resources with regard to the two goals mentioned.

An assessment of this proposed support showed that developing two resources each able to complete tasks associated with one of the goals resulted in a 52% reduction in time and a 45% reduction in cost. Further, the imbalance within the resources was deemed to be significantly redressed.

In summary, from the correspondence in Appendix D, it was indicated that the non-trivial and complex nature of managing the design development phase was emphasised since, in contrast to the traditional project management technique of adding extra personnel, the findings of applying the methodology advised that the solution was to model people's capabilities more appropriately and then develop them. With regard to the 52% and 45% reductions achieved in time and cost respectively, in their correspondence the company stated that "figures of this order need to be realised in order for companies, such as domnick hunter limited, to be successful in the future". As such, it was indicated that the methodology was extremely useful and provided the company with a new technique to manage their technical personnel. Further, it was stated that "the generic nature of your methodology should make it applicable elsewhere within our company as well as within our supplier chain companies who are increasingly becoming key members of our new product development programmes".

11.2.3 Strengths and Weaknesses

As a result of the evaluation of the prospective operational design co-ordination part of the methodology presented in Sections 11.2.1 and 11.2.2, this section highlights the strengths and weaknesses that have been identified.

Strengths

- The use of ratios involving the cumulative estimated duration of tasks associated with a particular goal and the cumulative forecasted efficiencies of resources allocated provide a means of identifying where resource improvements could be made. In other terms, areas of deficiency can be identified.
- The assessment of support involved determining the estimated time to complete the design programme or design development phase from the schedule, and then costing the utilisation of the resources for the schedule.

Weaknesses

- Since the prospective part of the methodology was not applied in conjunction with the real-time part, a static task model was considered.
- Companies had not conceived of modelling the efficiencies of their design engineers and as such lack formal methods on how to do so.
- Once deficiencies in the resources were identified, no formal method was provided regarding the selection of where improvements should be made, nor the magnitude or level of such improvements.

11.3 Summary

This chapter has presented an evaluation of the approach to operational design co-ordination. The real-time part of the methodology has been evaluated by applying the DCS to the turbine blade design process case study. The prospective part of the methodology has been applied to a marine vessel conversion design programme and a rotary drum dryer design development phase. In each case study, the knowledge modelling formalism has supported the respective parts of the methodology. Based on the evaluations, and with regard to the requirements of operational design co-ordination, strengths and weaknesses have been identified for both parts of the methodology.

As such, support has been provided to enable the structured undertaking and completion of tasks, and resource utilisation to be optimised through the coherent, timely and appropriate communication and interaction between the various agents in the DCS, with designated responsibilities, operating in real-time. That is, throughout the turbine blade design process, it has been ensured that the right tasks are undertaken using the right information when appropriate while utilising the right resource at the right time.

Further, support has been provided to facilitate the identification of deficiencies in resources with respect to scheduled tasks. Based on these deficiencies, considered improvements have been proposed in terms of resources. An assessment of these proposals has enabled their effects to be determined in terms of estimated time to complete the design programme or design development process, resource utilisation cost, and the degree to which any imbalance in the resources has been redressed.

12 Discussion

In Section 12.1, the research methodology used to conduct the work presented in this thesis is summarised. In Section 12.2, the techniques used within the approach are discussed. In Section 12.3, recommendations are made for future work based on the evaluation of the approach presented in Chapter 11 and industrial feedback given in Appendix D. In addition, the future direction of design co-ordination research is considered. Finally, Section 12.4 summarises the chapter.

12.1 Research Methodology

The research presented in this thesis has been conducted in accordance with the methodology presented by Duffy and O'Donnell [Duffy & O'Donnell, 1998] as illustrated in Figure 1.1, Chapter 1. Based on the methodology, the research has been divided into three parts:

- ***research problem formalisation***, i.e. design problem, hypothesis and research problem,
- ***an approach to operational design co-ordination***, i.e. solution, and,
- ***evaluation and discussion***, i.e. formal evaluation.

While dividing the research in this manner has provided a useful guide for conducting the work and presenting it in this thesis, it has also enabled the relationships between the three parts to be identified more easily than had it not been used. In Chapter 13, the constituents of each of the parts and the dependencies between them are illustrated in Figure 13.1.

In the remainder of this section, the positive aspects of conducting the research and an area of possible improvement are summarised.

Dissemination

During the course of this research, a number of papers related to this work have been published in relevant journals and conferences. In addition, a number of contributions have been made to a book to be published that focuses on design co-ordination theory and practice. Other contributors to this book include industrialists and academics from across Europe that lead research in the area of design co-ordination. A full list of publications related to the work presented in this thesis is given in Appendix E.

Further, the work has been presented at three international conferences, and two workshops of the design co-ordination sub-group of the thematic network mentioned in Chapter 3, called Integration In Manufacturing and Beyond. At these workshops, the work has received positive feedback from fellow researchers in this field.

Industrial Collaboration

A benefit of working in the Engineering Design Centre (EDC) at the University of Newcastle upon Tyne is that the research has been presented to a wide variety of industrialists from throughout the United Kingdom. Industrial involvement has provided in-situ feedback as the research progressed and an approach was developed. The main outcome is that this industrial involvement has proved useful in obtaining suitable practical case studies that have enabled the approach to be evaluated.

Academic Collaboration

A further benefit of conducting research within the EDC is that their exists the potential for collaborative research links with other work being carried out in the Centre. In this respect, this research has proven to be particularly useful. That is, the operational design co-ordination research has been linked with several other areas of work, namely: (i) robust concept exploration [Whitfield et al., 1998], (ii) strategic design co-ordination [Whitfield et al., 2000a], (iii) design integration, and (iv) multi criteria decision making. These academic collaborative links serve to emphasise that operational design co-ordination is applicable to a variety of areas of engineering design research.

Improvement

Despite following the methodology stated earlier, the manner in which the research has been conducted could have been improved through more effective time management.

Throughout the period of research, best estimates have been made regarding the intended progress of the work. Despite this conscious management of time, the research and writing of this thesis has taken several months longer than anticipated. In hindsight, more attention should have been paid to planning and monitoring the progress of the research throughout the programme of work. Thus, realistic time management is an important aspect of conducting research that should be given careful consideration continuously.

12.2 The Approach: Techniques Used

The aim of this section is to discuss the techniques used in the approach, and system, in terms of their suitability with respect to their intended purpose. Two techniques are discussed:

- the multi objective genetic algorithm, and,
- regression analysis using orthogonal polynomials and analysis of variance.

Multi Objective Genetic Algorithm

The earliest work on genetic algorithms was conducted by Holland [Holland, 1975] and DeJong [DeJong, 1975]. Genetic algorithms have been described as directed random search procedures based on the Darwinian theory of evolution, i.e. the mechanics of natural selection and genetics [Goldberg, 1989]. These algorithms differ from most optimisation methods by searching from one group, known as a population, of solutions to another, rather than from one solution to another as in the case of simulated annealing. Alongside genetic algorithms, simulated annealing is perhaps one of the most prominent contemporary optimisation techniques, which was introduced by Kirkpatrick et al. [Kirkpatrick et al., 1983]. Within genetic algorithms, although the population is placed randomly within the search space, the solutions evolve adaptively over a number of generations of populations. Thus, subsequent populations are fitter and more adapted to their environment. For this reason, genetic algorithms have been described as having the ability to outperform more conventional search techniques since they lack robustness when confronted with highly complex problems [Goldberg, 1989]. That is, genetic algorithms have a high probability of locating a global optimal solution, whereas traditional methods can become trapped in a local optimal solution. The characteristic of robustness makes genetic algorithms well suited for multi-objective optimisation, which is often a characteristic of scheduling problems.

Reeves conducted performance comparisons between the genetic algorithm procedure and the simulated annealing procedure based on the standard of the solution obtained from combinatorial problems after a fixed time had elapsed [Reeves, 1995]. It was reported that both procedures produce comparable results for relatively small problems. However, as the size of the problem increased, the performance of the genetic algorithm based procedure was said to be relatively better then the simulated annealing procedure, and a near-optimal solution was located more quickly. Keane also carried out a comparison of some evolutionary optimisation methods, including genetic algorithms and simulated annealing [Keane, 1996]. The main finding of this comparison was that genetic algorithms outperformed the others considered.

Based on the reasons discussed, in this research, a multi objective genetic algorithm (MOGA) has been employed, which was produced by Todd [Todd, 1997]. The use of the MOGA has been adapted for use within the Design Co-ordination System and, as such, a number of developments have been made with regard to its use:

- dynamic and automated scheduling in an appropriate manner,
- dynamically determined and generated input,

- results generation and interpretation (selection), and,
- optimised use and performance tuning.

Regression Analysis using Orthogonal Polynomials and Analysis of Variance

In Chapter 3, the Network Weather Service (NWS) [Wolski, 1997] and the Network Status Predictor (NSP) [Kim & Lilja, 1998] were described as stand-alone computer network monitoring systems. Both of these systems employed a number of numerical models to predict future expected network performance at one step ahead, i.e. t+1. In order to justify the choice of forecasting method used within the Design Co-ordination System, it is appropriate to first briefly discuss the methods employed, and the manner in which they are used, within the NWS and NSP. As such, limitations of these systems can be identified.

In order to predict a single value at t+1, the NWS used running averages and sliding windows and the mean and median of a subset of values with mean and median based methods, in addition to adaptations of these methods. After each measurement was recorded, a prediction was obtained using each forecasting model. As a result of generating a forecast each time a measurement was taken, Wolski stated that the NWS was restricted to forecasting methods of limited computational complexity. Further, it was recognised that more computationally complex methods would be feasible when forecasts were requested rather than continuously disseminated. Rather than making the difficult decision as to which forecasting method to use a priori, the NWS generates a prediction using all of them. Subsequently, the best prediction is chosen according to that closest to the actual measurement taken at the previous time step.

The NSP also used sliding windows and a number of mean, standard deviation and median values with a number of prediction models, such as maximum-minimum, standard deviation, confidence intervals and weighted based, and standard deviation to predict upper and lower bounds at t+1. A sliding window was used to accommodate the changing level of importance of past measurements. Within the NSP, prediction boundaries were selected based on the accuracy of the forecasts determined by calculating the errors expressed as a percentage. A limitation of representing an error as a percentage is that a lower error will be reported for a large measured value and small forecasted value, whereas, a large error will be reported for a small measured value and large forecasted value. Since, error was not expressed as a percentage in the NWS, it is assumed that this limitation was appreciated.

Statistical regression analysis has been reported as being used for prediction/forecasting purposes [Montgomery & Johnson, 1976; Graybill & Iyer, 1994; Draper & Smith, 1998]. Graybill and Iyer stated that "regression analysis is a commonly used method for obtaining a prediction function". Within the DCS, forecasts of resource efficiency were determined using statistical regression analysis using orthogonal polynomials and analysis of variance (ANOVA). Since the order of the polynomial that best represented historical data was not known prior to the regression analysis being performed, the use of orthogonal polynomials and ANOVA enabled the best fitting polynomial to be determined. As such, the model was dynamically generated as opposed to using pre-defined prediction models as within the NWS and NSP. Further, by dynamically generating a prediction model, rather than using a number of pre-defined models and selecting the forecast with the least error, forecasting is more efficient and less intrusive to computation. The issue of being less intrusive toward computation is also addressed by the manner in which forecasting is carried out within the DCS. That is, forecasting is only performed when necessary according to defined monitored efficiency thresholds being exceeded rather than each time a new measurement was taken as within the NWS and NPS.

Finally, regression analysis using orthogonal polynomials accounts for the order in which measurements are made. As such, the polynomial produced reflects the trend of the historical data, which is of obvious importance and significance. In contrast, within the NWS and NSP, by only considering, for example, the mean and median of measurements within a sliding window, the order in which the measurements were recorded is not reflected.

12.3 Future Work

Based on the weaknesses established in the evaluation of the approach presented in Chapter 11, and industrial feedback stated in the correspondence from the companies given in Appendix D, areas of future work have been identified as:

- theoretical improvements to the approach,
- further development of the Design Co-ordination System, and,
- further applications of the approach.

Furthermore, the direction of future research in the field of design co-ordination is considered.

Theoretical Improvements to the Approach to Operational Design Co-ordination

Real-Time Operational Design Co-ordination Methodology

At the outset of the operation of the real-time part of the methodology, while an original schedule is being derived, resources are not utilised to undertake tasks. It can be viewed that failure to utilise resources during this period of scheduling is a squandered opportunity in terms of contributing to the improvement in the performance of the design development process. As such, an aspect of possible future work could be focused toward developing a means of utilising resources prior to the original schedule being derived say, for example, in accordance with a preliminary schedule.

In order to ensure that resource utilisation is optimised during the period of re-scheduling, interim schedule models are constructed that consist of knowledge of tasks that can be undertaken while the revised schedule models are derived. Tasks included within the interim schedule models are independent at the time at which re-scheduling is considered. In order to overcome this weakness of the approach, there is a need to develop a method that manages the highly complex issues involved in constructing interim schedule models that include dependent tasks.

The decision-making process regarding whether or not re-scheduling is appropriate involves determining three time estimates, i.e. time to complete the current schedule, time to derive a revised schedule, and time to complete a derived schedule. Within the DCS operating environment, these estimates are calculated almost instantaneously. However, within a company setting, the time taken to determine these estimates may not be negligible. As such, a means of estimating the time taken to make the decision itself would be beneficial since it may influence the outcome.

Prospective Operational Design Co-ordination Methodology

With regard to the case studies concerning prospective operational design co-ordination, both companies expressed a difficulty in determining knowledge of the efficiency of each design engineer. As such, the Senior Project Manager at Armstrong Technology Associates elected to assign efficiencies according to designation. The Research and Development Manager at domnick hunter limited did make a judgement regarding the efficiency of each design engineer with respect to each goal in the design development phase. However, it was stressed that an ad-hoc technique was used based on knowledge of the team member's performance in the past. In addition to emphasising the difficulty in establishing and assigning efficiencies to design engineers, discussions with the companies revealed that a major obstacle in doing this is as much a cultural problem as being complex. Due to the difficulty stated, it is recognised that companies require formalised methods enabling them to assess and assign efficiencies to their resources. A possible starting point in this area could be to develop a method to determine efficiencies based on resource attributes such as experience, qualifications, personality and knowledge held. While this area of future work has been recognised as a result of discussions with the companies regarding the prospective part of the methodology, it is considered equally applicable to the real-time part of the methodology.

The proposal of support in the case studies involved the incremental consideration of all combinations of resource improvements in light of the areas of deficiency identified. Further, with regard to the rotary drum dryer design development phase case study, the magnitude of proposed support was extreme in that additional or developed resources were considered to have the greatest permissible value of efficiency. Based on these weaknesses, it would be useful to develop a method of determining realistic improvements to the resources more efficiently. A benefit of an efficient method would be that a greater number of improvements would be able to be considered.

Further Development of the Design Co-ordination System

In addition to the DCS being developed to incorporate the relevant theoretical improvements of the approach discussed, there are a number of other enhancements that are recommended for future work.

As discussed in Section 12.2, the forecasting technique employed within the DCS has a number of advantages over related work in this area. However, a weakness of the technique used in the DCS, and other dedicated forecasting systems, is related to the period of prediction. Currently, forecasts are made at a single time step ahead. However, the periodicity, i.e. the duration between time steps, can be controlled by the user of the DCS. As such, increasing the interval between successive time steps will result in a greater forecast period. Despite this ability to control the length of time between time steps, it is viewed that further work could be conducted with regard to establishing longer range forecasts.

As described in Chapter 10, the empirically derived characteristics of the MOGA are based on a number of assumptions, several of which are related to its application to the case study considered. As such, it is recommended that more generic characteristics of the MOGA be derived such that its use is process independent.

While the two areas of future work regarding the development of the DCS were recognised as a result of the its application to the turbine blade design process case study, it is viewed that further developments could be made.

Presently, the DCS can only operate on a local area network of UNIX workstations. Within engineering companies, their computer networks often include machines being used on a variety of platforms. Thus, the implementation of the real-time part of the methodology in a platform independent language, such as Java, would enable computers across different platforms to be harnessed. Such a development would allow the DCS to operationally co-ordinate greater resources than is currently achievable and, consequently, potentially lead to further reductions in process time.

A limitation of the DCS is that it does not exhibit any user-friendly facilities. As such, use of the DCS is limited to a handful of people who have considerable knowledge of its operation. Based on this limitation, it would be desirable for a front-end graphical user interface to be developed to broaden the use of the system.

The DCS currently facilitates the operational co-ordination of software agents in real-time. A useful development of the system would be to include the operational co-ordination of design engineers. For instance, such a development could be achieved through electronic mail invocation. That is, rather than a software agent executing an analysis tool, a human could be instructed to undertake certain tasks using certain information between defined time intervals. This area of work is related to computer supported co-operative work (See Chapter 2).

Further Applications of the Approach

Siemens Power Generation Limited

As a result of applying the real-time part of the methodology to the turbine blade design process case study, Siemens Power Generation Limited expressed their interest in further work. In the correspondence in Appendix D, it was indicated that the scope and applicability of the real-time operational design co-ordination methodology could be demonstrated further through its application to other case studies. Further, an interest was expressed in the application of the real-time operational design co-ordination methodology "to a project, which involves human resources and the complexities of multi-disciplinary design activity".

Armstrong Technology Associates

Two areas of further work were highlighted from this company in the correspondence in Appendix D. Firstly, it was stated that "it would be useful to apply your methodology to a multi-project environment in which design is usually carried out, since the management of resources in these situations proves immensely difficult" and "such an approach would present companies such as ours with a powerful approach to design management/co-ordination". Secondly, it was suggested that "the hierarchical nature of the design tasks should be more rigorously modelled such that the methodology would be able to further identify more specific improvements in terms of resources, e.g. differentiating between concept/embodiment/detail design".

domnick hunter limited

While not explicitly requesting further work, it was indicated that the methodology should be "applicable elsewhere within our company as well as within our supplier chain companies who are increasingly becoming key members of our new product development programmes".

With regard to the further applications of the respective parts of the methodology suggested by the companies, the approach is well positioned to be applied in the scenarios named. Future collaboration with these companies has been discussed and it is intended that further work will be conducted in the application areas suggested.

In addition to the applications mentioned, others are recommended aimed at overcoming the weaknesses identified in Chapter 11 not already discussed.

Related to the suggestion made by Siemens Power Generation Limited, a future application of the approach should include both the real-time and prospective parts of the methodology within a single case study involving human resources in an engineering company. As such, whenever re-scheduling is considered, appropriate changes in the resources could be identified such that, if implemented, they would facilitate even further improvements in the performance of the design development process to be achieved than that as a result of real-time operational design co-ordination alone. In addition, such an application would involve: (i) a variety of pre-emptive tasks being considered, (ii) multiple forecasted efficiencies being assigned to resources corresponding to different goals, (iii) schedules being monitored as well as resources, and (iv) the prospective part of the methodology being applied to a dynamic, rather than static, task model.

With regard to the case studies, the application of the prospective part of the methodology has been aimed at identifying improvements in the resources to further improve the performance of the design programme and design development phase. A variation on the application of prospective operational design co-ordination could be oriented toward determining improvements to the resources required to enable slippage of a project to be redeemed and, thus, the original deadline to be maintained.

The Future Direction of Design Co-ordination Research

As indicated in Chapter 2, design co-ordination can be applied at a strategic and operational level of management. While the work presented in this thesis has been aimed at the operational level only, the future direction of *design co-ordination* research is discussed here since it encompasses both levels of management.

It is considered that the future direction of research in the field of design co-ordination should advance in two complimentary directions.

The first of these direction is focused toward the engineering design community. Future work should be aimed at developing the research in the context of the realisation of the ultimate goal of engineering design management, i.e. the optimisation of the design development process. In Section 3.2 of Chapter 3, it was indicated that the starting point of the research presented in this thesis was the Design Co-ordination Framework (DCF). This framework is the main outcome of European funded collaborative research effort into design co-ordination. Specifically, the approach to operational design co-ordination developed in this thesis has concentrated on three of the eleven DCF frames. As such, in the forthcoming years, it is recommended that design co-ordination research aims to develop approaches that address the fundamental issues involved in linking together other frames of the DCF. Ultimately, all of the frames should be integrated within a design co-ordination environment in order to achieve the optimisation of the design development process.

The second direction of research is oriented more toward the broader area of co-ordination rather than design co-ordination. As indicated in Chapter 3, co-ordination is an area of research that has been identified as being of fundamental importance within a number of domains. As well as those named in Chapter 3, co-ordination has been recognised as of key significance in other domains. As such, complimentary to the first direction of future research indicated, it is suggested that an initiative should be launched that facilitates academics, industrialists and researchers worldwide, with a shared interest in co-ordination, to collaborate with the aim of contributing further to understanding and knowledge in this area. Thus, in the future, a collective and unified generic theory of co-ordination may be able to be established that could be applicable within a variety of domains.

12.4 Summary

A number of aspects of the work presented in this thesis have been discussed in this chapter.

The research methodology used to conduct the research has been summarised. Also, the techniques used within the approach, and system, have been discussed. Finally, future work has been discussed.

13 Conclusion

In this thesis, a novel, integrated and holistic approach to operational design co-ordination has been developed that improves the performance of the design development process. This has been achieved by the approach through exercising real-time and prospective operational design co-ordination. Figure 13.1 provides a summary of the work presented in the thesis indicating the contributions to knowledge made and dependencies between them. In addition, an indication is given regarding the chapters and parts of the thesis corresponding to each aspect of the work.

Part I: Research Problem Formalisation

Engineering Management

In an increasingly aggressive global market, competitive advantage can be achieved and maintained through effective engineering management. Improvements in engineering management need to be made in order to (i) increase the competitiveness of companies by contributing towards the delivery of quality products in shorter timescales at an acceptable cost, (ii) cope with the increasing complexity of contemporary engineering processes and products, and (iii) complement and facilitate the best use of rapidly advancing technology. Based on a review of contemporary approaches to engineering management, knowledge of the importance and pervasiveness of co-ordination was identified. However, despite being cited as a characteristic of these approaches, it was also identified that there exists a broad and varied understanding of co-ordination. As a result of co-ordination being recognised as important and pervasive within a number of existing approaches to engineering management, it is proposed as the foundation for an improved and more comprehensive approach. That is, design co-ordination offers a more comprehensive approach to engineering management than currently exists with an emphasis on timeliness and appropriateness. Specifically, design co-ordination at an operational level of management was identified as the focus of such an approach.

The Nature and Key Issues of Operational Design Co-ordination

In order to identify the nature of operational design co-ordination, perceptions from existing approaches to engineering management were used as a starting point. In addition, while the emphasis was toward operational co-ordination of engineering design, other areas were considered in which co-ordination has been recognised as relevant and important, i.e. organisational theory and distributed artificial intelligence. Based on a review of literature dedicated to co-ordination, knowledge of the key issues of operational design co-ordination was established: coherence, communication/interaction, task management, schedule management, resource management, and real-time support.

Coherence was reported as the integrating, or linking together, of resource effort and tasks within an organisation in a harmonious manner to avoid chaos. Communication/interaction was described as the interaction involving the exchange of structured and meaningful data, information and knowledge. Task management was defined as the organisation and control of tasks, and the dependencies between them, such that they can be undertaken and completed in a structured manner. Resource management was stated as organising and controlling resources to enable their continuous optimised utilisation throughout a changeable design development process. Schedule management was expressed as managing the planning and dynamic assignment of tasks to resources, and the enactment of the resulting schedules, throughout a changeable design development process. Real-time support was identified as how to manage and adapt to a changeable, i.e. dynamic and unpredictable, design development process.

Critical Review / Limitations of Existing Approaches

In order to identify the need for further research in the area of operational design co-ordination, existing approaches related to operational engineering management have been critically reviewed. Specifically, the most relevant approaches in the areas of design management and project management have been critiqued with respect to the key issues of operational design co-ordination.

As a result of a critical review, it has been identified that none of the existing approaches address all of the identified key issues of operational design co-ordination. Further, again with respect to operational design co-ordination, knowledge of the limitations that these approaches exhibit was established, i.e. they do not provide operational knowledge regarding (i) how to perform management activities appropriately to enable coherent working, (ii) how to manage tasks to enable their structured undertaking, (iii) how to manage resources such that their utilisation can be optimised, (iv) how to manage dynamic scheduling, (v) how to manage the enactment of schedules, and, (vi) how to enable real-time support.

Consequently, it has been identified that there is scope for an integrated and holistic approach to operational design co-ordination that addresses the key issues and overcomes the limitations stated.

Requirements of Operational Design Co-ordination

Based on consideration of the key issues and overcoming the limitations of existing approaches, the requirements of operational design co-ordination have been discussed leading to the identification that an approach is required to consist of:

- A methodology that exercises:
  - real-time operational design co-ordination in order to improve the performance of a changeable design development process, and,
  - prospective operational design co-ordination to facilitate further potential improvements in the performance of the design development process.
- A knowledge modelling formalism that supports the methodology.

Further, specific requirements of an approach to operational design co-ordination have been identified as integrating:

- Methodology
  - Task Management that supports: (i) the managing of tasks and their dependencies, and (ii) task information management.
  - Resource Management that supports: (i) the assignment of expected resource performance, (ii) monitoring, (iii) forecasting, and (iv) identification of deficiencies, and proposal and assessment of improvements.
  - Schedule Management that supports: (i) planning, (ii) dynamic scheduling, (iii) schedule enactment, (iv) monitoring, (v) re-scheduling decision-making, and (vi) optimised concurrent re-scheduling and undertaking of tasks.
- Knowledge Modelling Formalism
  - Task representation of: (i) identification, (ii) time, (iii) progress, and (iv) dependencies.
  - Resource representation of: (i) identification, (ii) status, (iii) performance, and (iv) cost.
  - Schedule representation of scheduled tasks, as described for tasks, including additional time and progress knowledge.

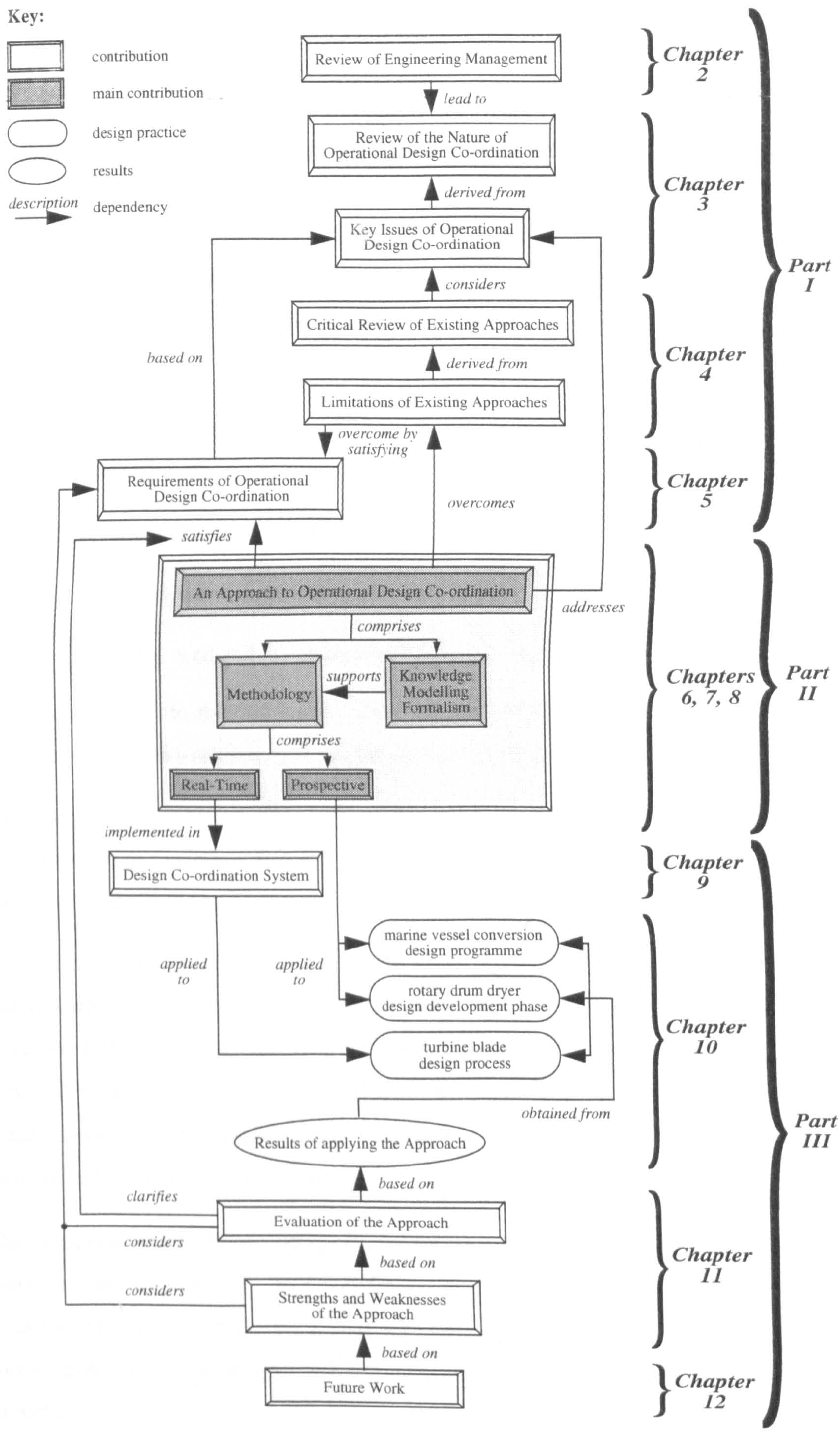

Figure 13.1 Summary of the Work

Part II: An Approach to Operational Design Co-ordination

A novel, integrated and holistic approach to operational design co-ordination is the main contribution of the work presented in this thesis.

The approach is founded on a more comprehensive set of key issues of operational design co-ordination than previously identified. Furthermore, for the first time, these key issues have been addressed within a single integrated approach. As such, the approach provides an original and significant contribution to knowledge in the field of operational engineering management, specifically operational design co-ordination.

The approach provides knowledge of the constituent techniques of operational design co-ordination and an understanding of their inter-relationships. Specifically, the approach provides knowledge of:

- the techniques involved in operational design co-ordination,
- the links and dynamic interactions between the techniques, and,
- the knowledge used and maintained within and between the techniques.

As such, not only do the individual techniques themselves define the approach, but more significantly the links and interactions that enable them to be integrated.

The approach to operational design co-ordination comprises two components: a methodology and a knowledge modelling formalism. Furthermore, the methodology consists of two parts: real-time and prospective.

The real-time operational design co-ordination part of the methodology enables the coherent undertaking and completion of inter-related tasks in a structured manner, by maintaining and managing task dependency relationships, while continuously optimising the utilisation of the allocated resources in accordance with dynamically generated schedules. Carrying out the dynamic and unpredictable design development process in such an appropriate and timely fashion leads to improved performance.

The prospective operational design co-ordination part of the methodology facilitates the identification of deficiencies in the resources with respect to the derived schedule such that improvements can be proposed and assessed. Appropriate adjustments in the resources enable further potential improvements to be made in the performance of the design development process.

The knowledge modelling formalism represents tasks, resources and schedules in order to comprehensively support the real-time and prospective parts of the methodology. Task knowledge modelled includes attributes regarding identification, time, progress and dependencies that support the structured undertaking of tasks. Resource knowledge modelled consists of identification, status, performance and cost. This modelled knowledge provides support such that resources can be continuously utilised in an optimised manner and deficiencies in the resources can be identified and assessed. Schedule modelled knowledge comprises additional task knowledge attributes to support scheduled tasks to be managed in accordance with dynamically derived schedules.

Part III: Evaluation and Discussion

The Design Co-ordination System

A prototype agent-oriented computer-based system, called the Design Co-ordination System (DCS), has been developed in order to facilitate the evaluation of the real-time part of the methodology.

The DCS architecture provides knowledge of how the real-time part of the methodology is realised within an agent-oriented environment. That is, knowledge is provided regarding how task, resource and schedule management responsibilities are attributed amongst the agents within the DCS, and, further, how the agents communicate and interact enabling a process to be performed in a coherent and operationally co-ordinated manner.

The DCS has been written in the C++ programming language and developed on a Sun Ultra 10 workstation. The operation of the DCS was performed on a number of Sun workstations within a local area network.

Evaluation of the Approach

Three practical case studies from engineering industry have been used to evaluate the approach to operational design co-ordination. Based on the evaluation, knowledge has been derived regarding how well the approach has satisfied the requirements of operational design co-ordination.

The real-time part of the methodology, using the Design Co-ordination System, has been applied to a turbine blade design process case study. The application of the DCS has been shown to support the continuous utilisation of the resources throughout the changeable turbine blade design process. This is achieved by monitoring the resources and, if appropriate, adjusting their utilisation according to predictions of future performance. Tasks are managed throughout the turbine blade design process such that they can be undertaken and completed in a structured manner. This is enabled through continuously managing and maintaining task knowledge and information. Based on knowledge of the tasks to be undertaken and the resources to be utilised, the methodology has been shown to support the dynamic derivation of suitable schedules at appropriate times during the turbine blade design process, and their enactment. The application of the approach demonstrated that adjusting in real-time in a co-ordinated manner enabled in excess of a 50% reduction in time to complete the process to be achieved from the point when re-scheduling was considered. As a result of real-time operational design co-ordination, it is recognised that the magnitude of any reductions in time achieved is dependent on the stage of the process when adjustment is considered.

The prospective part of the methodology was applied to case studies regarding a marine vessel conversion design programme supplied by Armstrong Technology Associates, and the design development phase of a rotary drum dryer provided by domnick hunter limited.

With regard to the marine vessel conversion design programme case study, it was shown that for a low number of design goals and single-skilled multi-disciplinary design team, the methodology enabled improvements in time and cost to be made, and the imbalance in the design team to be redressed. That is, the recruitment of two additional consultant electrical engineers resulted in a 28% reduction in the estimated time to complete the design programme and a 1% reduction in cost.

In relation to the rotary drum dryer design development phase case study, a greater number of design goals and a multi-skilled multi-disciplinary design team provided a more complex problem. However, suitable improvements in the resources, i.e. appropriate modelling and developments, resulted in significant time and cost reductions, i.e. 52% and 45% respectively.

Strengths and Weaknesses of the Approach

Based on an evaluation of the approach, and reflecting the requirements of operational design co-ordination, the strengths and weaknesses have been discussed. The features of the approach that distinguish it from other approaches are:

- *Real-Time Operational Design Co-ordination Support*

  This part of the methodology is based on a more comprehensive consideration of the relevant issues of operational design co-ordination than has previously been undertaken. Consequently, it enables the right resources to be utilised to undertake the right tasks using the right information at the right time within a changeable design development process in real-time. This has been achieved through the coherent alignment and interactions between task, resource and schedule management.

- *Prospective Operational Design Co-ordination Support*

  Consideration of the scheduled tasks to be undertaken with respect to the capabilities of the resources available facilitates the appropriate proposal and assessment of resource adjustments. This leads to further potential improvements in the performance of the design development process that are beyond that currently achievable.

- *Knowledge Modelling Formalism Capability*

  The approach provides the capability to represent knowledge of tasks, resources and schedules that comprehensively supports the real-time and prospective parts of the methodology. Continuously maintaining this modelled knowledge serves to support both parts of the methodology enabling the design development process to be co-ordinated at an operational level.

Future Work

Based on the weaknesses identified in the evaluation of the approach and feedback from industry, recommendations for future work are made. In addition, the direction of future research in design co-ordination is considered.

Theoretical improvements to the approach have been suggested regarding the real-time and prospective parts of the methodology: With respect to real-time operational design co-ordination, future work could be directed at: (i) enabling co-ordinated utilisation of resources prior to the derivation of an original schedule, (ii) developing a method to manage the complexities involved in enabling inter-dependent tasks to be undertaken and completed during re-scheduling, and (iii) accounting for the duration of the re-scheduling decision-making process within a company environment. With regard to prospective operational design co-ordination, future work could focus on: (i) developing a formal method to determine resource efficiencies, and (ii) developing an efficient method to determine realistic improvements to the resources.

Further developments to the DCS are proposed as: (i) providing a means of forecasting over longer ranges, (ii) empirically deriving process independent characteristics regarding the use of the multi objective genetic algorithm, (iii) re-implementation in a platform independent language to enable multi-platform operational design co-ordination, (iv) development of a graphical user interface, and (v) broadening its use to enable humans, as well as software agents, to be operationally co-ordinated in real-time.

Based on company feedback, further applications of the approach are suggested: (i) in a company setting involving human resources and multi-disciplinary design activity, (ii) in a multi-project environment involving the problems of resource contention, (iii) more rigorous modelling of design tasks in terms of identifying specific areas of improvement within the different stages of the design process. Additional applications could include: (i) both the real-time and prospective parts of the methodology within a single case study in an engineering company, and (ii) the prospective part of the methodology to redeem project deadline slippage.

With respect to the future direction of design co-ordination research, two suggestions are made: (i) aim to develop a design co-ordination environment aimed at optimising the design development process, and (ii) facilitate collaboration between academics, industrialists and researchers with an interest in co-ordination in order to establish a generic theory of co-ordination.

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Appendix A

Agents and Multi-Agent Systems

Agents

The notion of an agent is a relatively new concept within computer science. Despite the short period of time in which the agent-oriented paradigm has existed, it has already been the focus of much research. The history of agent research and development presented by Jennings et al. [Jennings et al., 1998] provides a useful starting point for someone embarking on research in this area.

An acknowledged and unresolved issue within the agent research community is that there remains no widely accepted definition of an agent [Jennings, 1999]. Indeed, Chauhan indicated that the term agent has been used "unsparingly to refer to any software system which has an attribute of intelligence" [Chauhan, 1997]. Further, Wallace and Boldyreff stated that "a survey of the literature on agents rapidly reveals there are as many definitions and opinions as there are agents" [Wallace & Boldyreff, 1999].

Franklin and Graesser noted a variety of definitions for agents and declared that "an autonomous agent is a system situated within, and a part of, an environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future" [Franklin & Graesser, 1996]. Jennings and Wooldridge defined an agents as "a computer system situated in some environment that is capable of autonomous action in this environment to meet its design objective" [Jennings & Wooldridge, 1996]. From the numerous definitions available, two extreme views of an agent have emerged [Franklin & Graesser, 1996; Wallace & Boldyreff, 1999]. At one extreme, agents are said to be conscious entities with emotions and perceptions similar to humans. At the other extreme, agents are described as being autonomous and behaving as programmed. Based on these extremes, an agent may exhibit a number of properties.

The main properties that agents may exhibit, along with a brief description of their meanings, are:

- **Adaptive,** an agent that continuously changes state according to its environment.
- **Autonomous,** an agent that exhibits independent behaviour, having control over its own actions.

- **Character**, an agent possessing a personality and an emotional state.
- **Continuous**, an agent that is a continuous process rather than one that undertakes a particular task then terminates.
- **Learning**, an agent that alters its behaviour based on previous experience.
- **Mobile**, an agent able to transfer itself around a network.
- **Pro-Active**, an agent able to act independently to initiate changes in its environment.
- **Reactive**, an agent that monitors and reacts to changes in its environment.
- **Sociable**, an agent that communicates with other agents, and possibly humans.

This summary provides an introduction to agent properties. More detailed explanations can be obtained from a number of sources within the Distributed Artificial Intelligence (DAI) community [Wooldridge & Jennings, 1995; Chauhan, 1997; FIPA, 1999; Wallace & Boldyreff, 1999]. In addition to agent properties, Chauhan discussed a variety of agent types and their applications [Chauhan, 1997].

In order to be classed as an agent, only a subset of the properties named need to be exhibited. Indeed, this is true of many agent systems.

Multi-Agent Systems

Used synonymously with the term Distributed Artificial Intelligence, the term Multi-Agent System (MAS) is the area of research concerned with systems comprising of multiple agents. Originally, DAI was divided into two sub-areas known as Distributed Problem Solving (DPS) and Multi-Agent Systems [Bond & Gasser, 1988]. The term MAS is now used to describe all systems comprising multiple agents. Collectively, agents within a MAS are often termed the society or community of agents [Wooldridge & Jennings, 1995].

Lesser defined a MAS as "a computational system in which two or more agents interact or work together to perform some set of tasks or to satisfy some set of goals" [Lesser, 1999]. Durfee and Montgomery defined a MAS as "a loosely-coupled network of problem solvers that work together to solve problems that are beyond their individual capabilities" [Durfee & Montgomery, 1989].

Wooldridge and Jennings offer the rationale behind the agent paradigm as autonomous agents and MASs appear suitable for constructing systems in which (a) data, control, expertise, or resources are distributed, (b) agents provide a natural metaphor for delivering system functionality (c) a number of legacy systems must be made to interwork [Wooldridge &

Jennings, 1999]. Jennings et al. also name robustness and efficiency as reasons for using agents and MASs [Jennings et al., 1998].

The advantages of using agent-based systems have been identified as: (i) fault tolerance, (ii) modular/scaleable architecture, (iii) self-configuring systems, (iv) reduced software costs, (v) reduced hardware costs, (vi) faster problem solving through concurrency, (vii) decreased communication, and (viii) flexible systems [Chauhan, 1997].

In summary, the previous discussion has intended to provide a brief introduction to the term agent and multi-agent systems.

Appendix B

Activities and Tasks

Author(s)	Activities			Tasks		
	Executed	Performed	Carried Out	Executed	Performed	Carried Out
[Andreasen et al., 1996]	✗	✗	✗	✗	✗	✓
[Bendeck et al., 1998]	✗	✓	✗	✗	✗	✗
[Brazier et al., 1996]	✗	✓	✗	✗	✓	✗
[Cantamessa et al., 1999]	✗	✗	✗	✗	✗	✓
[Crabtree et al., 1997]	✗	✗	✓	✗	✗	✗
[Dellen & Maurer, 1996]	✗	✗	✓	✗	✗	✗
[Duffy et al., 1993]	✗	✗	✓	✓	✗	✓
[Duffy et al., 1994]	✗	✗	✓	✗	✗	✗
[Duffy, 1995]	✗	✗	✓	✗	✓	✓
[Duffy et al., 1995]	✓	✗	✗	✓	✗	✗
[Duffy, 1998]	✗	✗	✓	✗	✗	✗
[Duffy et al., 1999]	✗	✓	✓	✗	✗	✓
[Eppinger et al., 1990]	✗	✗	✗	✗	✓	✗
[Eppinger, 1991]	✗	✓	✗	✓	✓	✗
[Eppinger et al., 1994]	✓	✓	✗	✗	✓	✗
[Girod, 1997]	✓	✗	✓	✗	✗	✗
[Goldmann, 1996]	✗	✗	✗	✗	✓	✗
[Khanna et al., 1998]	✗	✗	✗	✓	✗	✗
[Kusiak & Park, 1990]	✗	✓	✗	✗	✗	✗
[Kusiak & Wang, 1991]	✗	✓	✗	✗	✓	✗
[MacCallum & Liu, 1995]	✗	✗	✓	✗	✗	✗
[Maurer, 1996]	✗	✗	✗	✓	✗	✗
[Pourbabai & Pecht, 1994]	✗	✓	✗	✗	✗	✗
[Prasad et al., 1998]	✗	✗	✗	✗	✗	✓

Table B.1 Perceptions of Activities and Tasks

Further verbs have been used throughout the publications named such as activities/tasks being done, solved, accomplished, completed.

Appendix C

Practical Case Studies

The approach to operational design co-ordination is evaluated using three practical case studies from engineering industry, which are presented in Chapter 10. These case studies are titled:

- Turbine Blade Design Process
- Marine Vessel Conversion Design Programme
- Rotary Drum Dryer Design Development Phase

This appendix supports the practical case studies by presenting tables referred to in Chapter 10.

C.1 Turbine Blade Design Process

List of Tables

T_I	T_L	T_G	T_{DD}	T_{AC}	$T_{[TIn]}$	$T_{[TOut]}$	T_N	$T_{[TG]}$
0	0	0	97	0	hp1.760.inp	hp1.760.out hp1.bld	0	-
1	0	1	6	0	hp1.bld	hp1.b2d	1	0
2	0	2	6	0	hp1.b2d	hp1.720.inp	1	1
3	0	3	14	0	hp1.720.inp	hp1.720.ben hp1.720.out hp1.720.sls	1	2
4	0-35	4-39	1	0	hp1.b2d hp1.720.ben	hp1.0α.843.inp	2	1, 3
5	0-17	40-57	2	0	hp1.b2d	hp1.0β.024.inp hp1.0β.062.inp	1	1
6	0-17	58-75	1	0	hp1.0β.062.inp	hp1.0β.062.out hp1.0β.024.mat	1	(T_G-16)
7	0-17	76-93	1	0	hp1.0β.024.inp hp1.0β.024.mat	hp1.0β.024.out	2	(T_G-36), (T_G-16)
8	0-35	94-129	1	0	hp1.720.ben hp1.0α.843.inp	hp1.0α.843.out	2	3, (T_G-90)
9	0	130	11	0	hp1.b2d hp1.720.sls	hp1.b3d	2	1, 3

Table C.1 A Summary of the Task Model

With respect to Table C.1, α and β are two-digit integers, where $\alpha = T_L+1$ and $\beta = 2T_L+2$.

R_I	T_G															
2	0	41	57	52	73	46	42	76	43	88	60	54	53	24	35	33
	18	19	109	22	90	108	38	128	111	121	100	99	6	5	122	13
	89	82	20	120	77	124	119									
3	44	62	80	55	3	28	86	74	34	64	12	102	39	87	21	66
	31	117	67	15	105	94	96	59	97	61	79	23				
4	51	45	75	93	69	63	65	83	58	49	81	68	78	16	118	25
	92	123	8	26	116	129	14	104	27	10	32	71	98	11	101	95
	84	29	127	110	126	125										

Table C.2 Tasks within Original Schedule Models for Resources R_I = 2, 3 and 4

Time Step (n)	Resource			
	R_I=1	**R_I=2**	**R_I=3**	**R_I=4**
1	99.5	99.2	99.3	n/a
2	99.6	99.1	99.4	n/a
3	99.6	99.4	99.4	n/a
4	99.7	99.3	99.5	n/a
5	99.4	99.0	99.5	n/a
6	99.5	99.0	99.5	n/a
7	99.4	99.4	99.3	99.4
8	99.5	99.6	99.3	85.4
9	99.2	99.4	99.2	69.4
10	99.4	99.3	99.4	57.7
11	99.1	98.9	98.9	52.1
12	99.1	99.2	98.9	49.4
R_{FE}	**99.1**	**99.2**	**99.0**	**41.8**

Table C.3 Monitored Efficiencies and Forecasted Efficiency

T_G	T_{TG}	OSM	ISM	RSM	T_G	T_{TG}	OSM	ISM	RSM	T_G	T_{TG}	OSM	ISM	RSM	T_G	T_{TG}	OSM	ISM	RSM	T_G	T_{TG}	OSM	ISM	RSM
8	1	✓	×	×	71	53	×	✓	×	94	3	✓	×	×	107	3	✓	×	×	118	3	✓	×	×
	3	✓	×	×	72	54	×	✓	×		4	×	✓	×		17	×	✓	×		28	×	✓	×
10	1	✓	×	×	76	40	✓	×	×	95	3	✓	×	×	108	3	✓	×	×	120	3	✓	×	×
	3	✓	×	×		58	×	✓	×		5	×	✓	×		18	×	✓	×		30	×	✓	×
11	1	✓	×	×	77	41	✓	×	×	96	3	✓	×	×	109	3	✓	×	×	121	3	✓	×	×
	3	✓	×	×		59	×	✓	×		6	×	✓	×		19	×	✓	×		31	×	✓	×
14	1	✓	×	×	78	42	✓	×	×	97	3	✓	×	×	110	3	✓	×	×	123	3	✓	×	×
	3	✓	×	×		60	×	✓	×		7	×	✓	×		20	×	✓	×		33	×	✓	×
26	1	✓	×	×	82	46	✓	×	×	99	3	✓	×	×	111	3	✓	×	×	124	3	✓	×	×
	3	✓	×	×		64	×	✓	×		9	×	✓	×		21	×	✓	×		34	×	✓	×
27	1	✓	×	×	83	47	✓	×	×	102	3	✓	×	×	112	3	✓	×	×	125	3	✓	×	×
	3	✓	×	×		65	×	✓	×		12	×	✓	×		22	×	✓	×		35	×	✓	×
29	1	✓	×	×	84	48	✓	×	×	103	3	✓	×	×	113	3	✓	×	×	126	3	✓	×	×
	3	✓	×	×		66	×	✓	×		13	×	✓	×		23	×	✓	×		36	×	✓	×
32	1	✓	×	×	86	50	✓	×	×	105	3	✓	×	×	114	3	✓	×	×	127	3	✓	×	×
	3	✓	×	×		68	×	✓	×		15	×	✓	×		24	×	✓	×		37	×	✓	×
61	43	×	✓	×	92	56	✓	×	×	106	3	✓	×	×	115	3	✓	×	×	128	3	✓	×	×
67	49	×	✓	×		74	×	✓	×		16	×	✓	×		25	×	✓	×		38	×	✓	×
																				129	3	✓	×	×
																					39	×	✓	×

Table C.4 Independent Tasks within the Revised Schedule

Key
OSM Task(s) dependent on was/were completed in original schedule model
ISM Task(s) dependent on will be completed in interim schedule model
RSM Task(s) dependent on will be re-scheduled for inclusion within revised schedule model

T_G	$T_{[T_G]}$	Was/Were Completed in Original Schedule Model	Will be Completed in Interim Schedule Model	Will be Re-scheduled for inclusion within Revised Schedule Model
79	43	✗	✓	✗
	61	✗	✗	✓
85	49	✗	✓	✗
	67	✗	✗	✓
89	53	✗	✓	✗
	71	✗	✗	✓
90	54	✗	✓	✗
	72	✗	✗	✓
98	3	✓	✗	✗
	8	✗	✗	✓
100	3	✓	✗	✗
	10	✗	✗	✓
101	3	✓	✗	✗
	11	✗	✗	✓
104	3	✓	✗	✗
	14	✗	✗	✓
116	3	✓	✗	✗
	26	✗	✗	✓
117	3	✓	✗	✗
	27	✗	✗	✓
119	3	✓	✗	✗
	29	✗	✗	✓
122	3	✓	✗	✗
	32	✗	✗	✓

Table C.5 Dependent Tasks within the Revised Schedule

C.2 Marine Vessel Conversion Design Programme

List of Tables

T_I	T_L	T_G	T_{DD}	T_N	$T_{[TG]}$	T_I	T_L	T_G	T_{DD}	T_N	$T_{[TG]}$	T_I	T_L	T_G	T_{DD}	T_N	$T_{[TG]}$	T_I	T_L	T_G	T_{DD}	T_N	$T_{[TG]}$	T_I	T_L	T_G	T_{DD}	T_N	$T_{[TG]}$
0	0	0	3	0	-	1	25	27	12	1	22	1	52	54	10	1	53	1	79	81	12	0	-	2	20	108	25	1	107
0	1	1	5	1	0	1	26	28	16	1	20	1	53	55	5	1	53	1	80	82	6	1	80	2	21	109	50	0	-
1	0	2	15	0	-	1	27	29	8	1	28	1	54	56	5	1	52	1	81	83	2	0	-	3	0	110	20	0	-
1	1	3	10	1	2	1	28	30	8	1	29	1	55	57	15	1	56	1	82	84	8	1	83	3	1	111	80	1	110
1	2	4	11	1	3	1	29	31	8	1	23	1	56	58	3	0	-	1	83	85	5	0	-	3	2	112	15	0	-
1	3	5	10	0	-	1	30	32	8	1	31	1	57	59	20	1	58	1	84	86	10	0	-	3	3	113	15	1	112
1	4	6	15	1	5	1	31	33	12	1	26	1	58	60	10	0	-	1	85	87	6	1	72	3	4	114	30	0	-
1	5	7	10	1	6	1	32	34	20	1	20	1	59	61	10	0	-	2	0	88	10	0	-	3	5	115	5	1	114
1	6	8	5	1	7	1	33	35	4	1	33	1	60	62	10	0	-	2	1	89	15	1	88	3	6	116	20	1	91
1	7	9	20	1	8	1	34	36	8	1	16	1	61	63	10	1	62	2	2	90	5	1	89	3	7	117	35	0	-
1	8	10	35	1	9	1	35	37	8	1	35	1	62	64	10	1	63	2	3	91	60	1	88	3	8	118	60	0	-
1	9	11	10	0	-	1	36	38	8	1	37	1	63	65	20	0	-	2	4	92	40	0	-	3	9	119	60	0	-
1	10	12	5	0	-	1	37	39	6	1	38	1	64	66	8	1	65	2	5	93	15	1	89	3	10	120	5	1	117
1	11	13	10	1	12	1	38	40	6	1	39	1	65	67	15	0	-	2	6	94	5	1	93	3	11	121	15	1	120
1	12	14	10	0	-	1	39	41	24	1	38	1	66	68	3	1	66	2	7	95	20	1	94	3	12	122	10	1	121
1	13	15	10	1	14	1	40	42	4	1	28	1	67	69	2	0	-	2	8	96	20	1	95	3	13	123	10	0	-
1	14	16	30	0	-	1	41	43	8	1	41	1	68	70	3	0	-	2	9	97	15	1	95	3	14	124	20	1	123
1	15	17	5	1	22	1	42	44	66	0	-	1	69	71	8	1	70	2	10	98	40	0	-	3	15	125	50	0	-
1	16	18	10	1	12	1	43	45	20	0	-	1	70	72	2	1	69	2	11	99	15	0	-	3	16	126	10	1	121
1	17	19	10	1	14	1	44	46	10	0	-	1	71	73	4	1	72	2	12	100	5	1	99	3	17	127	10	1	126
1	18	20	10	1	19	1	45	47	15	1	45	1	72	74	10	1	64	2	13	101	20	1	100	3	18	128	30	0	-
1	19	21	10	1	20	1	46	48	10	0	-	1	73	75	3	1	74	2	14	102	20	1	101	3	19	129	45	1	119
1	20	22	15	1	21	1	47	49	19	1	47	1	74	76	6	1	75	2	15	103	15	1	101	3	20	130	15	1	126
1	21	23	15	1	21	1	48	50	15	1	48	1	75	77	2	1	71	2	16	104	20	0	-	3	21	131	30	1	130
1	22	24	15	1	20	1	49	51	10	0	-	1	76	78	8	1	77	2	17	105	15	0	-	3	22	132	20	1	133
1	23	25	10	1	19	1	50	52	9	1	46	1	77	79	6	1	67	2	18	106	20	0	-	3	23	133	35	1	126
1	24	26	10	1	22	1	51	53	10	0	-	1	78	80	8	1	78	2	19	107	30	1	106						

Table C.6 Task Model

Goal	Resource			
	Designation	R_I	R_{FE}	R_C (units)
Naval Architecture	Consultant	0, 1	1.0	10
	Senior Design Engineer	2, 3, 4, 5	0.8	8.5
	Design Engineer	6, 7	0.6	7
Marine Engineering	Consultant	8, 9	1.0	10
	Senior Design Engineer	10	0.8	8.5
	Design Engineer	11, 12	0.6	7
Electrical Engineering	Senior Design Engineer	13, 14	0.8	8.5
	Design Engineer	15	0.6	7

Table C.7 Resource Knowledge

In Table C.7, values of R_{FE} and R_C have been assigned in accordance with their respective designation. For reasons of confidentiality, the values related to cost are relative.

Resource (R_I)	Expected Time to Complete Optimised Schedules (Weeks) - Datum Case									
	1	2	3	4	5	6	7	8	9	10
0	26.2	14.6	30.0	37.0	29.4	22.2	23.6	27.2	24.4	25.6
1	38.6	31.0	25.2	28.8	26.6	22.4	46.0	40.8	16.4	23.8
2	18.2	18.0	30.6	23.6	39.4	19.2	33.8	22.4	23.8	28.4
3	27.4	33.0	29.0	34.6	23.0	50.2	20.4	26.2	23.4	25.0
4	27.8	31.2	15.8	25.6	26.0	14.4	8.6	20.0	43.8	32.6
5	35.8	30.8	34.8	13.6	32.6	17.6	32.8	34.2	51.6	22.6
6	26.4	38.2	23.6	39.8	32.6	42.2	43.6	15.2	24.8	51.6
7	27.6	39.8	42.8	28.8	20.2	55.4	21.2	41.4	22.8	27.0
8	30.0	30.0	19.0	18.0	38.0	29.0	37.0	17.0	31.0	31.0
9	25.0	5.6	25.0	17.0	20.6	12.0	26.0	34.0	22.0	16.0
10	17.2	12.4	29.6	23.6	18.4	19.8	9.8	5.0	40.6	26.2
11	28.0	51.2	6.6	49.6	3.2	6.6	11.6	19.2	6.6	31.2
12	16.6	33.0	42.4	19.8	34.6	58.0	29.8	49.8	11.4	15.0
13	59.4	59.0	59.0	58.6	54.6	60.0	60.4	58.0	59.6	57.0
14	58.0	59.4	58.2	59.0	60.4	58.0	57.2	58.4	58.0	59.2
15	56.2	56.4	56.6	56.2	59.8	56.2	57.2	58.2	56.0	59.6
Cost (Units)	**174156**	**176580**	**175220**	**175820**	**174448**	**176720**	**174612**	**175292**	**173839**	**175532**
Time (Weeks)	**59.4**	**59.4**	**59.0**	**59.0**	**60.4**	**60.0**	**60.4**	**58.4**	**59.6**	**59.6**

Table C.8 Datum Case: Time and Cost associated with each Schedule

Goal	Optimised Schedule Number	ΣT_{ED}^* (Days)	ΣR_{FE}^* (Total)	ΣT_{ED} (Days)	ΣR_{FE} (Used)	$\Sigma T_{ED} / \Sigma R_{FE}$
Naval Architects	1	228.0	6.4	218.0	6.4	34.1
Marine Engineers		116.8	4.0	116.8	4.0	29.2
Electrical Engineers		173.6	2.2	173.6	2.2	78.9
Naval Architects	2	236.6	6.4	236.6	6.4	37.0
Marine Engineers		132.2	4.0	129.2	4.0	32.3
Electrical Engineers		178.8	2.2	172.55	2.2	78.4
Naval Architects	3	231.8	6.4	231.8	6.4	36.2
Marine Engineers		122.6	4.0	112.6	4.0	28.2
Electrical Engineers		173.8	2.2	173.8	2.2	79.0
Naval Architects	4	231.8	6.4	220.55	6.4	34.5
Marine Engineers		128.0	4.0	128.0	4.0	32.0
Electrical Engineers		173.8	2.2	173.8	2.2	79.0
Naval Architects	5	199.8	6.4	191.47	6.4	29.9
Marine Engineers		114.8	4.0	111.8	4.0	28.0
Electrical Engineers		174.8	2.2	174.8	2.2	79.5
Naval Architects	6	243.6	6.4	237.35	6.4	37.1
Marine Engineers		125.4	4.0	125.4	4.0	31.4
Electrical Engineers		174.2	2.2	170.45	2.2	77.5
Naval Architects	7	230.0	6.4	221.67	6.4	34.6
Marine Engineers		114.2	4.0	114.2	4.0	28.6
Electrical Engineers		174.8	2.2	169.8	2.2	77.2
Naval Architects	8	227.4	6.4	222.4	6.4	34.8
Marine Engineers		125.0	4.0	120.0	4.0	30.0
Electrical Engineers		174.6	2.2	174.6	2.2	79.4
Naval Architects	9	231.0	6.4	227.25	6.4	35.5
Marine Engineers		111.6	4.0	103.27	4.0	25.8
Electrical Engineers		173.6	2.2	173.6	2.2	78.9
Naval Architects	10	207.6	6.4	203.85	6.4	31.9
Marine Engineers		119.4	4.0	119.4	4.0	29.9
Electrical Engineers		175.8	2.2	169.55	2.2	77.1

Table C.9 Datum Case: $\Sigma T_{ED} / \Sigma R_{FE}$ Ratios

*: includes the tasks associated with the *general* goal.

Case		Optimised Schedules - Addition of one Electrical Engineer										
		1	2	3	4	5	6	7	8	9	10	Mean
1.1	Cost (Units)	176548	175304	176328	176384	176568	175680	176112	176136	175996	176820	176188
	Time (Weeks)	52.2	51.2	51.0	49.6	49.8	51.4	50.8	50.0	50.2	49.8	50.6
1.2	Cost (Units)	173644	175616	174180	173900	174448	174432	173168	174052	175716	176072	174523
	Time (Weeks)	47.0	46.8	48.4	49.2	48.4	47.2	48.2	48.0	48.4	48.4	48.0
1.3	Cost (Units)	174244	173360	174280	172708	172580	173248	174220	173488	172844	173084	173406
	Time (Weeks)	45.6	45.4	47.4	45.8	46.2	44.8	47.4	46.8	47.6	46.0	46.3

Table C.10 Cases 1.1 - 1.3: Time and Cost associated with each Schedule

The shaded cells in Table C.10 signify that the optimised schedule produced was done so using only 16 of the 17 available resources. Specifically, one of the design engineers from the marine engineering discipline was not utilised. This fact reinforces that with respect to the marine engineering tasks to be undertaken, the resource structure exhibits an adequate pool of engineers in that discipline. Indeed, it appears that the marine engineering discipline is positioned such that any additional marine engineers would not necessarily result in any reductions in time taken to complete the associated tasks.

Case	T_I	Optimised Schedule										
		1	2	3	4	5	6	7	8	9	10	Mean
1.1	1	35.6	36.0	36.3	36.1	35.4	35.1	35.1	34.9	36.2	36.1	**35.7**
	2	31.0	27.8	27.1	28.3	30.5	34.0	30.8	29.9	27.7	30.3	**29.7**
	3	64.5	63.6	65.9	65.9	65.4	65.4	64.2	65.6	64.7	64.5	**65.0**
1.2	1	35.2	36.3	35.9	34.8	36.0	34.8	33.5	36.3	35.8	36.5	**35.5**
	2	29.2	30.0	27.2	30.3	27.9	29.2	28.3	31.7	30.0	32.2	**29.6**
	3	54.3	56.9	57.1	53.4	55.3	56.9	56.7	54.7	57.3	54.5	**55.7**
1.3	1	36.5	35.6	34.4	35.1	35.6	34.6	35.7	36.8	34.7	35.7	**35.5**
	2	29.2	26.2	31.2	26.7	27.3	28.8	31.2	27.1	28.5	28.7	**28.5**
	3	48.5	50.5	49.8	49.7	48.3	50.1	47.5	49.2	48.0	47.9	**49.0**

Table C.11 Cases 1.1 - 1.3: $\Sigma T_{ED} / \Sigma R_{FE}$ Ratios

Case		Optimised Schedules - Addition of two Electrical Engineers										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Mean**
2.1	Cost (Units)	176756	175204	176008	177280	174980	176956	175264	176640	176780	176568	**176244**
	Time (Weeks)	48.0	46.0	45.0	50.0	47.6	46.4	47.4	49.4	45.8	46.8	**47.2**
2.2	Cost (Units)	174752	174564	175784	174668	175388	177048	175176	175936	175420	175700	**175444**
	Time (Weeks)	44.8	43.4	46.0	45.0	44.4	44.8	44.8	47.0	47.0	45.6	**45.3**
2.3	Cost (Units)	173124	175920	175084	174040	175196	173172	173352	176132	174216	174144	**174438**
	Time (Weeks)	44.2	44.6	44.4	43.8	43.6	44.4	44.8	44.6	44.4	46.6	**44.5**
2.4	Cost (Units)	173220	173552	174812	173496	173892	173416	174152	175192	173416	174833	**173998**
	Time (Weeks)	42.0	44.8	43.0	45.2	44.6	44.6	44.8	43.6	44.6	44.6	**44.2**
2.5	Cost (Units)	173404	173088	173656	173704	173036	172224	174616	171104	173484	173580	**173190**
	Time (Weeks)	46.0	42.8	44.8	42.6	43.2	46.0	42.8	43.4	44.8	42.6	**43.9**
2.6	Cost (Units)	172704	174064	173464	172992	173604	173292	173076	173976	172596	172196	**173196**
	Time (Weeks)	41.8	43.2	43.4	44.6	44.8	43.4	41.0	41.2	41.8	43.0	**42.8**

Table C.12 Cases 2.1 - 2.6: Time and Cost associated with each Schedule

As described previously, the shaded cells in Table C.12 signify that the optimised schedule produced was done so using only 17 of the 18 available resources, i.e. one of the design engineers from the marine engineering discipline was not utilised.

Case	T_I	Optimised Schedule										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Mean**
2.1	1	36.6	33.5	35.0	36.8	34.8	36.5	35.6	36.6	34.3	35.3	**35.5**
	2	30.0	29.5	29.6	30.6	28.2	29.4	27.5	28.4	31.7	30.2	**29.5**
	3	52.2	53.2	54.4	52.0	52.4	54.4	53.3	54.8	54.5	54.2	**53.5**
2.2	1	35.6	35.7	36.2	35.6	35.7	36.3	36.3	35.6	36.2	34.9	**35.8**
	2	28.4	27.4	31.0	28.7	28.3	31.4	25.7	30.6	29.3	31.8	**29.3**
	3	48.1	48.6	46.2	47.6	49.2	49.0	50.3	48.6	48.0	48.2	**48.4**
2.3	1	34.5	35.1	35.1	36.4	36.7	34.4	34.0	35.7	35.5	35.1	**35.3**
	2	28.3	32.0	29.8	28.0	30.2	27.2	29.5	31.0	29.3	28.9	**29.4**
	3	42.3	45.3	45.3	42.2	42.0	43.9	43.6	44.2	42.6	44.0	**43.5**
2.4	1	35.7	33.9	34.7	34.4	36.0	34.3	35.3	36.3	34.3	36.7	**35.2**
	2	27.7	29.5	31.1	27.3	27.4	28.5	29.2	31.6	28.5	30.6	**29.1**
	3	42.1	44.1	43.9	45.0	43.3	44.2	43.9	42.2	44.2	41.5	**43.4**
2.5	1	36.5	34.4	36.3	34.3	34.8	35.1	35.9	34.5	35.4	35.1	**35.2**
	2	26.9	28.2	29.7	30.6	29.2	26.3	31.2	26.1	29.1	29.4	**28.7**
	3	39.2	40.3	37.6	40.1	39.5	39.4	39.7	38.1	39.1	39.5	**39.3**
2.6	1	35.3	36.8	35.1	35.5	35.9	34.9	35.5	35.8	35.7	35.3	**35.6**
	2	30.1	30.5	31.5	28.9	30.5	30.8	28.3	31.3	28.8	27.4	**29.8**
	3	34.1	36.0	35.9	36.0	35.7	36.0	36.3	36.1	35.6	36.2	**35.8**

Table C.13 Cases 2.1 - 1.6: $\Sigma T_{ED} / \Sigma R_{FE}$ Ratios

C.3 Rotary Drum Dryer Design Development Phase

List of Tables

T_I	T_L	T_G	T_{DD}	T_N	T_I	T_L	T_G	T_{DD}	T_N	T_I	T_L	T_G	T_{DD}	T_N	T_I	T_L	T_G	T_{DD}	T_N	T_I	T_L	T_G	T_{DD}	T_N	T_I	T_L	T_G	T_{DD}	T_N
0	0	0	1	0	3	13	32	1	0	10	1	64	5	1	2	13	96	1	4	0	8	128	1	0	5	4	160	3	1
0	1	1	1	4	3	14	33	1	0	10	2	65	5	1	3	17	97	3	0	1	10	129	5	0	6	4	161	2	1
0	2	2	1	0	3	15	34	2	15	10	3	66	5	1	3	18	98	2	1	1	11	130	5	0	7	25	162	1	0
1	0	3	5	0	3	16	35	1	1	11	0	67	10	1	3	19	99	1	1	1	12	131	5	0	7	26	163	1	0
1	1	4	5	0	4	0	36	3	0	11	1	68	5	1	4	3	100	3	0	1	13	132	5	0	7	27	164	1	0
1	2	5	5	0	4	1	37	2	0	11	2	69	5	0	5	3	101	3	1	1	14	133	5	0	7	28	165	1	0
1	3	6	5	0	4	2	38	1	2	11	3	70	5	1	6	3	102	2	0	1	15	134	2	0	7	29	166	1	0
1	4	7	5	0	5	0	39	3	0	11	4	71	5	1	7	16	103	2	0	10	8	135	5	0	7	30	167	2	1
1	5	8	2	0	5	1	40	5	1	11	5	72	30	0	7	17	104	10	1	10	9	136	5	1	7	31	168	10	1
1	6	9	2	0	5	2	41	1	1	11	6	73	20	0	7	18	105	1	1	2	14	137	3	0	7	32	169	1	1
2	0	10	3	0	6	0	42	2	0	11	7	74	20	0	7	19	106	1	1	2	15	138	3	0	7	33	170	10	1
2	1	11	3	0	6	1	43	2	1	12	0	75	3	1	7	20	107	10	1	2	16	139	1	0	7	34	171	3	0
2	2	12	1	0	6	2	44	1	1	9	1	76	2	1	7	21	108	3	0	2	17	140	1	0	7	35	172	1	1
2	3	13	1	0	7	0	45	1	0	13	0	77	10	1	7	22	109	1	1	2	18	141	1	0	7	36	173	1	1
2	4	14	1	0	7	1	46	1	0	14	0	78	20	0	7	23	110	1	1	2	19	142	1	0	7	37	174	10	1
2	5	15	1	0	7	2	47	1	0	14	1	79	2	0	7	24	111	10	1	2	20	143	1	0	11	14	175	10	7
2	6	16	1	0	7	3	48	1	0	14	2	80	10	1	10	4	112	5	0	3	20	144	2	0	11	15	176	5	1
2	7	17	1	7	7	4	49	1	0	14	3	81	10	1	10	5	113	5	1	3	21	145	2	0	11	16	177	10	0
2	8	18	1	8	7	5	50	1	5	14	4	82	10	1	10	6	114	5	1	3	22	146	1	0	11	17	178	5	1
3	0	19	2	0	7	6	51	1	1	14	5	83	15	2	10	7	115	5	1	3	23	147	1	0	11	18	179	5	15
3	1	20	2	0	7	7	52	2	0	14	6	84	10	1	11	8	116	5	1	3	24	148	1	0	11	19	180	30	1
3	2	21	1	0	7	8	53	10	1	14	7	85	10	1	11	9	117	5	1	3	25	149	2	0	11	20	181	20	1
3	3	22	1	0	7	9	54	1	1	0	3	86	1	0	11	10	118	5	0	3	26	150	1	0	11	21	182	20	1
3	4	23	1	0	7	10	55	1	1	0	4	87	1	1	11	11	119	30	1	3	27	151	1	0	11	22	183	3	5
3	5	24	2	0	7	11	56	10	1	0	5	88	1	0	11	12	120	20	1	3	28	152	3	0	8	1	184	5	1
3	6	25	1	0	7	12	57	3	0	1	7	89	5	0	11	13	121	20	1	3	29	153	1	0	9	3	185	2	1
3	7	26	1	0	7	13	58	1	1	1	8	90	5	0	12	1	122	3	7	3	30	154	1	0	13	2	186	10	1
3	8	27	3	0	7	14	59	1	1	1	9	91	5	0	9	2	123	2	1	3	31	155	1	0	14	9	187	20	0
3	9	28	1	0	7	15	60	10	1	2	9	92	3	0	13	1	124	10	2	3	32	156	1	0	14	10	188	2	1
3	10	29	1	1	8	0	61	5	6	2	10	93	3	0	14	8	125	1	0	3	33	157	1	0	14	11	189	1	2
3	11	30	1	1	9	0	62	2	0	2	11	94	1	0	0	6	126	1	0	3	34	158	1	0					
3	12	31	1	0	10	0	63	5	0	2	12	95	1	3	0	7	127	1	0	4	4	159	3	1					

Table C.14 Task Model

Index (R_i)	Expected Time to Complete Optimised Schedules (Weeks) - Datum Case									
	1	2	3	4	5	6	7	8	9	10
0	46.8	38.4	47.2	35.8	53.8	45.2	46.0	40.2	51.4	39.2
1	63.6	57.6	57.0	68.6	54.0	53.4	49.8	57.8	64.6	57.8
2	55.0	42.6	37.2	60.2	46.0	31.2	27.8	46.0	24.0	34.0
3	56.8	31.6	36.6	53.8	45.4	50.2	35.4	49.0	49.4	28.2
4	30.4	48.0	53.6	41.4	44.2	54.6	39.8	31.0	46.4	55.4
5	47.6	43.6	31.0	41.6	47.6	48.0	47.0	37.6	35.0	40.0
6	33.4	35.2	44.0	66.8	28.2	23.4	35.0	43.8	63.4	48.8
7	18.0	30.0	33.2	39.4	23.4	21.8	22.8	20.6	28.8	16.0
8	31.6	51.0	40.8	20.0	49.6	30.4	45.2	20.0	35.2	56.6
Total Cost (Units)	**224936**	**223208**	**230024**	**258592**	**227256**	**203672**	**197944**	**206088**	**237616**	**226200**
Total Time (Weeks)	**66.4**	**58.6**	**64.8**	**70.6**	**65.0**	**61.2**	**58.2**	**64.8**	**67.6**	**63.2**

Table C.15 Datum Case: Time and Cost associated with each Schedule

T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}
0	0	1	6	0.5	2.0	3	32	1	7	0.3	3.3	10	64	5	4	0.8	6.3	2	96	1	3	0.9	1.1	0	128	1	3	0.5	2.0	5	160	3	3	0.5	6.0
0	1	1	8	0.5	2.0	3	33	1	7	0.3	3.3	10	65	5	3	0.8	6.3	3	97	3	4	0.9	3.3	1	129	5	8	0.1	50.0	6	161	2	4	0.7	2.9
0	2	1	6	0.5	2.0	3	34	2	4	0.9	2.2	10	66	5	3	0.8	6.3	3	98	2	1	0.1	20.0	1	130	5	4	1.0	5.0	7	162	1	2	0.2	5.0
1	3	5	8	0.1	50.0	3	35	1	7	0.3	3.3	11	67	10	1	0.9	11.1	3	99	1	4	0.9	1.1	1	131	5	8	0.1	50.0	7	163	1	4	0.7	1.4
1	4	5	3	0.9	5.6	4	36	3	3	0.1	30.0	11	68	5	1	0.9	5.6	4	100	3	4	0.8	3.8	1	132	5	6	0.1	50.0	7	164	1	7	0.3	3.3
1	5	5	3	0.9	5.6	4	37	2	7	0.3	6.7	11	69	5	5	1.0	5.0	5	101	3	4	0.7	4.3	1	133	5	6	0.1	50.0	7	165	1	6	0.5	2.0
1	6	5	4	1.0	5.0	4	38	1	1	0.5	2.0	11	70	5	1	0.9	5.6	6	102	2	2	0.5	4.0	1	134	2	4	1.0	2.0	7	166	1	3	0.7	1.4
1	7	5	4	1.0	5.0	5	39	3	6	0.3	10.0	11	71	5	5	1.0	5.0	7	103	2	1	0.2	10.0	10	135	5	0	0.1	50.0	7	167	2	6	0.5	4.0
1	8	2	2	0.1	20.0	5	40	5	3	0.5	10.0	11	72	30	5	1.0	30.0	7	104	10	3	0.7	14.3	10	136	5	3	0.8	6.3	7	168	10	3	0.7	14.3
1	9	2	1	0.1	20.0	5	41	1	2	0.5	2.0	11	73	20	5	1.0	20.0	7	105	1	3	0.7	1.4	2	137	3	3	0.9	3.3	7	169	1	3	0.7	1.4
2	10	3	4	0.9	3.3	6	42	2	7	0.2	10.0	11	74	20	5	1.0	20.0	7	106	1	0	0.2	5.0	2	138	3	3	0.9	3.3	7	170	10	4	0.7	14.3
2	11	3	4	0.9	3.3	6	43	2	6	0.2	10.0	12	75	3	6	0.9	3.3	7	107	10	4	0.7	14.3	2	139	1	1	0.1	10.0	7	171	3	0	0.2	15.0
2	12	1	4	0.9	1.1	6	44	1	3	0.3	3.3	9	76	2	4	0.8	2.5	7	108	3	4	0.7	4.3	2	140	1	4	0.9	1.1	7	172	1	7	0.3	3.3
2	13	1	3	0.9	1.1	7	45	1	7	0.3	3.3	13	77	10	4	0.8	12.5	7	109	1	4	0.7	1.4	2	141	1	4	0.9	1.1	7	173	1	1	0.2	5.0
2	14	1	3	0.9	1.1	7	46	1	1	0.2	5.0	14	78	20	0	0.6	33.3	7	110	1	1	0.2	5.0	2	142	1	3	0.9	1.1	7	174	10	3	0.7	14.3
2	15	1	4	0.9	1.1	7	47	1	7	0.3	3.3	14	79	2	6	0.9	2.2	7	111	10	7	0.3	33.3	2	143	1	4	0.9	1.1	11	175	10	1	0.9	11.1
2	16	1	3	0.9	1.1	7	48	1	7	0.3	3.3	14	80	10	2	0.7	14.3	10	112	5	3	0.8	6.3	3	144	2	4	0.9	2.2	11	176	5	1	0.9	5.6
2	17	1	1	0.1	10.0	7	49	1	4	0.7	1.4	14	81	10	4	0.2	50.0	10	113	5	3	0.8	6.3	3	145	2	7	0.3	6.7	11	177	10	1	0.9	11.1
2	18	1	1	0.1	10.0	7	50	1	4	0.7	1.4	14	82	10	6	0.9	11.1	10	114	5	3	0.8	6.3	3	146	1	4	0.9	1.1	11	178	5	1	0.9	5.6
3	19	2	7	0.3	6.7	7	51	1	6	0.5	2.0	14	83	15	6	0.9	16.7	10	115	5	0	0.1	50.0	3	147	1	7	0.3	3.3	11	179	5	5	1.0	5.0
3	20	2	4	0.9	2.2	7	52	2	2	0.2	10.0	14	84	10	2	0.7	14.3	11	116	5	1	0.9	5.6	3	148	1	4	0.9	1.1	11	180	30	1	0.9	33.3
3	21	1	3	0.9	1.1	7	53	10	4	0.7	14.3	14	85	10	4	0.2	50.0	11	117	5	1	0.9	5.6	3	149	2	3	0.9	2.2	11	181	20	5	1.0	20.0
3	22	1	3	0.9	1.1	7	54	1	4	0.7	1.4	0	86	1	8	0.5	2.0	11	118	5	1	0.9	5.6	3	150	1	3	0.9	1.1	11	182	20	1	0.9	22.2
3	23	1	7	0.3	3.3	7	55	1	3	0.7	1.4	0	87	1	3	0.5	2.0	11	119	30	5	1.0	30.0	3	151	1	1	0.1	10.0	11	183	3	1	0.9	3.3
3	24	2	3	0.9	2.2	7	56	10	7	0.3	33.3	0	88	1	4	0.7	1.4	11	120	20	1	0.9	22.2	3	152	3	7	0.3	10.0	8	184	5	2	0.7	7.1
3	25	1	1	0.1	1.1	7	57	3	6	0.5	6.0	1	89	5	8	0.1	50.0	11	121	20	5	1.0	20.0	3	153	1	4	0.9	1.1	9	185	2	4	0.8	2.5
3	26	1	1	0.1	10.0	7	58	1	3	0.7	1.4	1	90	5	2	0.1	50.0	12	122	3	4	0.5	6.0	3	154	1	3	0.9	1.1	13	186	10	3	0.8	12.5
3	27	3	7	0.3	10.0	7	59	1	3	0.7	1.4	1	91	5	6	0.1	50.0	9	123	2	4	0.8	2.5	3	155	1	7	0.3	3.3	14	187	20	0	0.6	33.3
3	28	1	7	0.3	10.0	7	60	10	2	0.2	50.0	2	92	3	3	0.9	3.3	13	124	10	4	0.8	12.5	3	156	1	3	0.9	1.1	14	188	2	4	0.2	10.0
3	29	1	3	0.9	3.3	8	61	5	2	0.7	7.1	2	93	3	4	0.9	3.3	14	125	1	4	0.2	5.0	3	157	1	3	0.9	1.1	14	189	1	1	0.1	10.0
3	30	1	7	0.3	1.1	9	62	2	2	0.8	2.5	2	94	1	3	0.9	1.1	0	126	1	2	0.7	1.4	3	158	1	3	0.9	1.1						
3	31	1	7	0.3	3.3	10	63	5	4	0.8	6.3	2	95	1	3	0.9	1.1	0	127	1	3	0.5	2.0	4	159	3	7	0.3	10.0						

Table C.16 Assessment of Datum Case *(3rd Schedule)*

T_I	ΣT_{ED}	R_{FE}			n_R			$\Sigma T_{ED} / \Sigma R_{FE}$
		Available	Used	Deployment (%)	Available	Used	Deployment (%)	
0	17	4.1	2.9	70.7	7	6	71.4	5.9
1	468	2.3	2.3	100.0	6	5	100.0	203.5
2	63	1.9	1.9	100.0	3	3	100.0	33.2
3	141	2.2	2.2	100.0	4	4	100.0	64.1
4	52	2.5	1.7	68.0	5	3	80.0	30.6
5	32	2.5	1.8	72.0	5	4	80.0	17.8
6	30	2.7	1.9	70.4	7	4	71.4	15.8
7	313	2.8	2.8	100.0	7	7	100.0	111.8
8	14	3.2	0.7	21.9	6	1	16.7	20.0
9	10	3.1	1.6	51.6	4	2	50.0	6.3
10	150	1.7	1.7	100.0	3	3	100.0	88.2
11	308	1.9	1.9	100.0	2	2	100.0	162.1
12	9	3.1	1.4	45.2	5	2	40.0	6.3
13	37.5	2.0	1.6	80.0	6	3	33.3	23.4
14	250	2.7	2.5	92.6	6	5	83.3	100.0

Table C.17 Summary of Assessment of Datum Case *(3rd Schedule)*

Case		Optimised Schedules					
		1	2	3	4	5	Mean
1.1	Total Cost (Units)	209888	184074	287800	224344	220792	225380
	Total Time (Weeks)	66.0	62.2	71.6	63.6	59.2	64.52
1.2	Total Cost (Units)	242518	241840	218936	233952	215064	230462
	Total Time (Weeks)	66.2	67.2	58.8	61.4	59.2	62.56
1.3	Total Cost (Units)	243352	251408	216216	241688	271192	239183
	Total Time (Weeks)	59.0	61.0	64.4	58.4	67.2	60.58
1.4	Total Cost (Units)	224640	199888	217600	233344	253440	225782
	Total Time (Weeks)	65.0	63.4	55.4	65.0	71.0	63.96
1.5	Total Cost (Units)	208064	219552	261904	241088	228352	231792
	Total Time (Weeks)	58.8	58.4	65.2	63.2	61.4	61.40
1.6	Total Cost (Units)	230096	247696	235864	229264	219232	232430
	Total Time (Weeks)	64.0	63.4	60.2	57.4	57.6	60.52
1.7	Total Cost (Units)	237576	248712	244920	237048	232960	240243
	Total Time (Weeks)	61.0	63.6	58.8	64.4	62.8	62.12

Table C.18 Cases 1.1 - 1.7: Time and Cost associated with each Schedule

T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}
0	0	1	8	0.5	2.0	3	32	1	3	0.9	1.1	10	64	5	4	0.8	6.3	2	96	1	3	0.9	1.1	0	128	1	0	0.3	3.3	5	160	3	6	0.3	10.0
0	1	1	4	0.1	1.0	3	33	1	7	0.3	3.3	10	65	5	4	0.8	6.3	3	97	3	1	0.1	30.	1	129	5	1	0.1	50.0	6	161	2	1	0.5	4.0
0	2	1	0	0.7	1.4	3	34	2	7	0.3	6.7	10	66	5	3	0.8	6.3	3	98	2	1	0.1	20.0	1	130	5	2	0.1	50.0	7	162	1	1	0.2	5.0
1	3	5	6	0.3	16.7	3	35	1	3	0.9	1.1	11	67	10	5	1.0	10.0	3	99	1	3	0.9	1.1	1	131	5	4	1.0	5.0	7	163	1	10	1.0	1.0
1	4	5	4	1.0	5.0	4	36	3	1	0.5	6.0	11	68	5	5	1.0	5.0	4	100	3	2	0.8	3.8	1	132	5	6	0.1	50.0	7	164	1	2	0.2	5.0
1	5	5	4	1.0	5.0	4	37	2	1	0.5	4.0	11	69	5	5	1.0	5.0	5	101	3	1	0.5	6.0	1	133	5	8	0.1	50.0	7	165	1	1	0.2	5.0
1	6	5	4	1.0	5.0	4	38	1	7	0.3	3.3	11	70	5	5	1.0	5.0	6	102	2	7	0.2	10.0	1	134	2	6	0.1	20.0	7	166	1	3	0.7	1.4
1	7	5	4	1.0	5.0	5	39	3	4	0.7	4.3	11	71	5	5	1.0	5.0	7	103	2	6	0.5	4.0	10	135	5	0	0.1	50.0	7	167	2	2	0.2	10.0
1	8	2	8	0.1	20.0	5	40	5	6	0.3	16.7	11	72	30	5	1.0	30.0	7	104	10	2	0.2	50.0	10	136	5	3	0.8	6.3	7	168	10	4	0.7	14.3
1	9	2	8	0.1	20.0	5	41	1	1	0.5	2.0	11	73	20	5	1.0	20.0	7	105	1	7	0.3	3.3	2	137	3	4	0.9	3.3	7	169	1	4	0.7	1.4
2	10	3	3	0.9	3.3	6	42	2	3	0.2	10.0	11	74	20	1	0.9	22.2	7	106	1	3	0.7	1.4	2	138	3	4	0.9	3.3	7	170	10	7	0.3	33.3
2	11	3	4	0.9	3.3	6	43	2	3	0.3	6.7	12	75	3	4	0.5	6.0	7	107	10	0	0.2	50.0	2	139	1	3	0.9	1.1	7	171	3	3	0.7	4.3
2	12	1	4	0.9	1.1	6	44	1	6	0.2	5.0	9	76	2	6	0.9	2.2	7	108	3	3	0.7	4.3	2	140	1	4	0.9	1.1	7	172	1	1	0.2	5.0
2	13	1	1	0.1	10.0	7	45	1	1	0.2	5.0	13	77	10	4	0.8	12.5	7	109	1	4	0.7	1.4	2	141	1	4	0.9	1.1	7	173	1	1	0.2	5.0
2	14	1	3	0.9	1.1	7	46	1	10	1.0	1.0	14	78	20	0	0.6	33.3	7	110	1	3	0.7	1.4	2	142	1	4	0.9	1.1	7	174	10	6	0.5	20.0
2	15	1	3	0.9	1.1	7	47	1	7	0.3	3.3	14	79	2	0	0.6	3.3	7	111	10	6	0.5	20.0	2	143	1	3	0.9	1.1	11	175	10	5	1.0	10.0
2	16	1	3	0.9	1.1	7	48	1	0	0.2	5.0	14	80	10	4	0.2	50.0	10	112	5	4	0.8	6.3	3	144	2	7	0.3	6.7	11	176	5	1	0.9	5.6
2	17	1	3	0.9	1.1	7	49	1	10	0.1	1.0	14	81	10	2	0.7	14.3	10	113	5	4	0.8	6.3	3	145	2	3	0.9	2.2	11	177	10	1	0.9	11.1
2	18	1	4	0.9	1.1	7	50	1	1	0.2	5.0	14	82	10	0	0.6	16.7	10	114	5	4	0.8	6.3	3	146	1	4	0.9	1.1	11	178	5	9	1.0	5.0
3	19	2	4	0.9	2.2	7	51	1	4	0.7	1.4	14	83	15	0	0.6	25	10	115	5	3	0.8	6.3	3	147	1	7	0.3	3.3	11	179	5	1	0.9	5.6
3	20	2	3	0.9	2.2	7	52	2	0	0.2	10.0	14	84	10	4	0.2	50	11	116	5	9	1.0	5.0	3	148	1	4	0.9	1.1	11	180	30	5	1.0	30.0
3	21	1	4	0.9	1.1	7	53	10	3	0.7	14.3	14	85	10	0	0.6	16.7	11	117	5	5	1.0	5.0	3	149	2	7	0.3	6.7	11	181	20	5	1.0	20.0
3	22	1	4	0.9	1.1	7	54	1	3	0.7	1.4	0	86	1	8	0.5	2.0	11	118	5	5	1.0	5.0	3	150	1	1	0.1	10.0	11	182	20	5	1.0	20.0
3	23	1	3	0.9	1.1	7	55	1	6	0.5	2.0	0	87	1	0	0.3	3.3	11	119	30	5	1.0	30.0	3	151	1	4	0.9	1.1	11	183	3	5	1.0	3.0
3	24	2	4	0.9	2.2	7	56	10	2	0.2	50.0	0	88	1	6	0.5	2.0	11	120	20	5	1.0	20.0	3	152	3	4	0.9	3.3	8	184	5	3	0.5	10.0
3	25	1	1	0.1	10.0	7	57	3	3	0.7	4.3	1	89	5	8	0.1	50.0	11	121	20	9	1.0	20.0	3	153	1	4	0.9	1.1	9	185	2	6	0.9	2.2
3	26	1	3	0.9	1.1	7	58	1	10	0.1	1.0	1	90	5	2	0.1	50.0	12	122	3	3	0.5	6.0	3	154	1	4	0.9	1.1	13	186	10	3	0.8	12.5
3	27	3	4	0.9	3.3	7	59	1	7	0.3	3.3	1	91	5	2	0.1	50.0	9	123	2	4	0.8	2.5	3	155	1	4	0.9	1.1	14	187	20	3	0.2	100.0
3	28	1	3	0.9	1.1	7	60	10	3	0.7	14.3	2	92	3	3	0.9	3.3	13	124	10	4	0.8	12.5	3	156	1	4	0.9	1.1	14	188	2	2	0.7	2.86
3	29	1	4	0.9	1.1	8	61	5	4	0.7	7.1	2	93	3	1	0.1	30.0	14	125	1	6	0.9	1.1	3	157	1	4	0.9	1.1	14	189	1	2	0.7	1.43
3	30	1	7	0.3	3.3	9	62	2	4	0.8	2.5	2	94	1	4	0.9	1.1	0	126	1	1	0.9	1.1	3	158	1	4	0.9	1.1						
3	31	1	7	0.3	3.3	10	63	5	0	0.1	50.0	2	95	1	4	0.9	1.1	0	127	1	6	0.5	2.0	4	159	3	7	0.3	10.0						

Table C.19 Assessment of Case 1.6 *(3rd Schedule)*

T_I	ΣT_{ED}	R_{FE}			n_R			$\Sigma T_{ED} / \Sigma R_{FE}$
		Available	Used	Deployment (%)	Available	Used	Deployment (%)	
0	18	4.1	2.6	63.4	7	5	71.4	6.9
1	452	2.3	1.4	60.9	6	5	83.3	322.9
2	72	1.9	1.9	100.0	3	3	100.0	37.9
3	139	2.2	2.2	100.0	4	4	100.0	63.2
4	27	2.5	1.6	64.0	5	3	60.0	16.9
5	39	2.5	1.5	60.0	5	3	60.0	26.0
6	36	2.7	1.2	44.4	7	4	57.1	30.0
7	369	3.8	3.6	94.7	8	7	87.5	102.5
8	17	3.2	1.2	37.5	6	2	33.3	14.2
9	9	3.1	1.7	54.8	4	2	50.0	5.3
10	150	1.7	1.7	100.0	3	3	100.0	88.2
11	297	2.9	2.9	100.0	3	3	100.0	102.4
12	12	3.1	1.0	32.3	5	2	40.0	12.0
13	38	2.0	1.6	80.0	6	2	33.3	23.8
14	315	2.7	2.6	96.3	6	5	83.3	121.2

Table C.20 Summary of Assessment of Case 1.6 *(3rd Schedule)*

Case		Optimised Schedules					
		1	2	3	4	5	Mean
2.1	Total Cost (Units)	133944	135160	134688	135472	134368	134726
	Total Time (Weeks)	41.4	41.0	37.4	37.0	39.4	39.24
2.2	Total Cost (Units)	126968	123272	120072	125368	124848	124106
	Total Time (Weeks)	36.2	36.0	36.0	36.2	35.6	36.00
2.3	Total Cost (Units)	116128	117888	124528	115872	116872	118258
	Total Time (Weeks)	37.4	38.6	38.4	38.4	37.8	38.12
2.4	Total Cost (Units)	115528	122432	116792	116208	114912	117174
	Total Time (Weeks)	39.2	38.0	37.6	37.0	37.4	37.84
2.5	Total Cost (Units)	110928	119088	104744	112976	99480	109443
	Total Time (Weeks)	45.2	45.6	45.4	45.6	45.6	45.48
2.6	Total Cost (Units)	105648	109456	104392	115168	101720	107277
	Total Time (Weeks)	45.2	45.2	45.2	45.0	45.4	45.2

Table C.21 Cases 2.1 - 2.6: Time and Cost associated with each Schedule

T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}
0	0	1	4	0.7	1.4	3	32	1	7	0.3	3.3	10	64	5	3	0.8	6.3	2	96	1	3	0.9	1.1	0	128	1	6	0.5	2.0	5	160	3	2	0.5	6.0
0	1	1	3	0.5	2.0	3	33	1	7	0.3	3.3	10	65	5	3	0.8	6.3	3	97	3	7	0.3	10.0	1	129	5	3	0.9	5.6	6	161	2	1	0.5	4.0
0	2	1	4	0.7	1.4	3	34	2	7	0.3	6.7	10	66	5	4	0.8	6.3	3	98	2	4	0.9	2.2	1	130	5	4	1.0	5.0	7	162	1	4	0.7	1.4
1	3	5	3	0.9	5.6	3	35	1	3	0.9	1.1	11	67	10	1	0.9	11.1	3	99	1	3	0.9	1.1	1	131	5	4	1.0	5.0	7	163	1	4	0.7	1.4
1	4	5	4	1.0	5.0	4	36	3	2	0.8	3.8	11	68	5	5	1.0	5.0	4	100	3	7	0.3	10.0	1	132	5	3	0.9	5.6	7	164	1	3	0.7	1.4
1	5	5	3	0.9	5.6	4	37	2	1	0.5	4.0	11	69	5	5	1.0	5.0	5	101	3	4	0.7	4.3	1	133	5	3	0.9	5.6	7	165	1	6	0.5	2.0
1	6	5	4	1.0	5.0	4	38	1	4	0.8	1.3	11	70	5	1	0.9	5.6	6	102	2	2	0.5	4.0	1	134	2	4	1.0	2.0	7	166	1	6	0.5	2.0
1	7	5	4	1.0	5.0	5	39	3	4	0.7	4.3	11	71	5	5	1.0	5.0	7	103	2	3	0.7	2.9	10	135	5	4	0.8	6.3	7	167	2	6	0.5	4.0
1	8	2	4	1.0	2.0	5	40	5	2	0.5	10.0	11	72	30	5	1.0	30.0	7	104	10	4	0.7	14.3	10	136	5	4	0.8	6.3	7	168	10	3	0.7	14.3
1	9	2	4	1.0	2.0	5	41	1	3	0.5	2.0	11	73	20	5	1.0	20.0	7	105	1	7	0.3	3.3	2	137	3	3	0.9	3.3	7	169	1	3	0.7	1.4
2	10	3	4	0.9	3.3	6	42	2	1	0.5	4.0	11	74	20	5	1.0	20.0	7	106	1	3	0.7	1.4	2	138	3	3	0.9	3.3	7	170	10	4	0.7	14.3
2	11	3	3	0.9	3.3	6	43	2	2	0.5	4.0	12	75	3	2	0.7	4.3	7	107	10	6	0.5	20.0	2	139	1	4	0.9	1.1	7	171	3	6	0.5	6.0
2	12	1	3	0.9	1.1	6	44	1	1	0.5	2.0	9	76	2	6	0.9	2.2	7	108	3	6	0.5	6.0	2	140	1	4	0.9	1.1	7	172	1	3	0.7	1.4
2	13	1	3	0.9	1.1	7	45	1	4	0.7	1.4	13	77	10	3	0.8	12.5	7	109	1	3	0.7	1.4	2	141	1	3	0.9	1.1	7	173	1	4	0.7	1.4
2	14	1	3	0.9	1.1	7	46	1	6	0.5	2.0	14	78	20	6	0.9	22.2	7	110	1	7	0.3	3.3	2	142	1	4	0.9	1.1	7	174	10	7	0.3	33.3
2	15	1	3	0.9	1.1	7	47	1	3	0.1	10.0	14	79	2	2	0.7	2.9	7	111	10	3	0.7	14.3	2	143	1	4	0.9	1.1	11	175	10	5	1.0	10.0
2	16	1	4	0.9	1.1	7	48	1	3	0.7	1.4	14	80	10	6	0.9	11.1	10	112	5	4	0.8	6.3	3	144	2	4	0.9	2.2	11	176	5	5	1.0	5.0
2	17	1	4	0.9	1.1	7	49	1	4	0.7	1.4	14	81	10	6	0.9	11.1	10	113	5	4	0.8	6.3	3	145	2	3	0.9	2.2	11	177	10	5	1.0	10.0
2	18	1	3	0.9	1.1	7	50	1	6	0.5	2.0	14	82	10	2	0.7	14.3	10	114	5	4	0.8	6.3	3	146	1	3	0.9	1.1	11	178	5	1	0.9	5.6
3	19	2	3	0.9	2.2	7	51	1	7	0.3	3.3	14	83	15	2	0.7	21.4	10	115	5	3	0.8	6.3	3	147	1	4	0.9	1.1	11	179	5	5	1.0	5.0
3	20	2	3	0.9	2.2	7	52	2	3	0.7	2.9	14	84	10	6	0.9	11.1	11	116	5	5	1.0	5.0	3	148	1	4	0.9	1.1	11	180	30	5	1.0	30.0
3	21	1	4	0.9	1.1	7	53	10	7	0.3	33.3	14	85	10	2	0.7	14.3	11	117	5	5	1.0	5.0	3	149	2	7	0.3	6.7	11	181	20	1	0.9	22.2
3	22	1	4	0.9	1.1	7	54	1	7	0.3	3.3	0	86	1	2	0.7	1.3	11	118	5	5	1.0	5.0	3	150	1	3	0.9	1.1	11	182	20	1	0.9	22.2
3	23	1	4	0.9	1.1	7	55	1	6	0.5	2.0	0	87	1	2	0.7	1.3	11	119	30	1	0.9	33.3	3	151	1	3	0.9	1.1	11	183	3	1	0.9	3.3
3	24	2	3	0.9	2.2	7	56	10	6	0.5	20.0	0	88	1	3	0.5	2.0	11	120	20	1	0.9	22.2	3	152	3	4	0.9	3.3	8	184	5	6	0.8	6.3
3	25	1	4	0.9	1.1	7	57	3	7	0.3	10.0	1	89	5	3	0.9	5.6	11	121	20	1	0.9	22.2	3	153	1	7	0.3	3.3	9	185	2	6	0.9	2.2
3	26	1	4	0.9	1.1	7	58	1	3	0.7	1.4	1	90	5	4	1.0	5.0	12	122	3	6	0.9	3.3	3	154	1	7	0.3	3.3	13	186	10	3	0.8	12.5
3	27	3	7	0.3	10.0	7	59	1	7	0.3	3.3	1	91	5	4	1.0	5.0	9	123	2	6	0.9	2.2	3	155	1	7	0.3	3.3	14	187	20	2	0.7	28.6
3	28	1	4	0.9	1.1	7	60	10	6	0.5	20.0	2	92	3	4	0.9	3.3	13	124	10	3	0.8	12.5	3	156	1	3	0.9	1.1	14	188	2	2	0.7	2.86
3	29	1	7	0.3	3.3	8	61	5	6	0.8	6.3	2	93	3	3	0.9	3.3	14	125	1	2	0.7	1.4	3	157	1	3	0.9	1.1	14	189	1	2	0.7	1.43
3	30	1	4	0.9	1.1	9	62	2	2	0.8	2.5	2	94	1	4	0.9	1.1	0	126	1	8	0.5	2.0	3	158	1	3	0.9	1.1						
3	31	1	3	0.9	1.1	10	63	5	3	0.8	6.3	2	95	1	3	0.9	1.1	0	127	1	3	0.5	2.0	4	159	3	2	0.8	3.8						

Table C.22 Assessment of Case 2.2 *(2nd Schedule)*

T_I	ΣT_{ED}	R_{FE}			n_R			$\Sigma T_{ED} / \Sigma R_{FE}$
		Available	Used	Deployment (%)	Available	Used	Deployment (%)	
0	16	4.1	2.4	58.5	7	5	71.4	6.7
1	74	1.9	1.9	100.0	2	2	100.0	38.9
2	37	1.8	1.8	100.0	2	2	100.0	20.6
3	90	2.1	2.1	100.0	3	3	100.0	42.9
4	23	2.4	2.4	100.0	4	4	100.0	9.6
5	27	2.5	1.7	68.0	5	3	60.0	15.9
6	18	2.3	1.0	43.5	5	2	40.0	18.0
7	269	2.2	2.2	100.0	4	4	100.0	122.3
8	13	3.1	0.8	25.8	5	1	20.0	16.3
9	9	3.1	1.7	54.8	4	2	50.0	5.3
10	63	1.6	1.6	100.0	2	2	100.0	39.4
11	308	1.9	1.9	100.0	2	2	100.0	162.1
12	8	3.1	1.6	51.6	5	2	40.0	5.0
13	38	1.6	0.8	50.0	2	1	50.0	47.5
14	143	2.2	1.6	72.7	3	2	66.7	89.4

Table C.23 Summary of Assessment of Case 2.2 *(2nd Schedule)*

Case		Optimised Schedules					
		1	2	3	4	5	Mean
3.1	Cost (Units)	130816	133720	130960	131744	134984	132445
	Time (Weeks)	33.8	34.4	34.6	34.6	33.6	34.2
3.2	Cost (Units)	119720	115456	114816	118984	116424	117080
	Time (Weeks)	34.0	33.4	34.0	35.0	33.4	34.0
3.3	Cost (Units)	133824	131768	120168	128768	125312	127968
	Time (Weeks)	31.4	32.0	30.6	31.2	31.8	31.4
3.4	Cost (Units)	132464	125824	129864	132344	130344	130168
	Time (Weeks)	34.8	33.0	34.0	32.6	34.0	33.68
3.5	Cost (Units)	114152	117784	120896	116624	120112	117914
	Time (Weeks)	32.0	32.4	32.4	32.6	33.4	32.56
3.6	Cost (Units)	119824	124552	116992	119400	129080	121970
	Time (Weeks)	29.8	30.0	31.2	30.6	31.0	30.52

Table C.24 Cases 3.1 - 3.6: Time and Cost associated with each Schedule

T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}	T_I	T_G	T_{DD}	R_I	R_{FE}	T_{ED}
0	0	1	1	0.9	1.1	3	32	1	7	0.3	3.3	10	64	5	3	0.8	6.3	2	96	1	4	0.9	1.1	0	128	1	2	0.7	1.4	5	160	3	4	0.7	4.3
0	1	1	3	0.5	2.0	3	33	1	3	0.9	1.1	10	65	5	3	0.8	6.3	3	97	3	4	0.9	3.3	1	129	5	4	1.0	5.0	6	161	2	8	0.3	6.7
0	2	1	1	0.9	1.1	3	34	2	7	0.3	6.7	10	66	5	3	0.8	6.3	3	98	2	3	0.9	2.2	1	130	5	4	1.0	5.0	7	162	1	3	0.7	1.4
1	3	5	4	1.0	5.0	3	35	1	3	0.9	1.1	11	67	10	0	1.0	10.0	3	99	1	3	0.9	1.1	1	131	5	3	0.9	5.6	7	163	1	6	0.5	2.0
1	4	5	3	0.9	5.6	4	36	3	2	0.8	3.8	11	68	5	1	0.9	5.6	4	100	3	2	0.8	3.8	1	132	5	3	0.9	5.6	7	164	1	3	0.7	1.4
1	5	5	4	1.0	5.0	4	37	2	4	0.8	2.5	11	69	5	1	0.9	5.6	5	101	3	1	0.5	6.0	1	133	5	3	0.9	5.6	7	165	1	3	0.7	1.4
1	6	5	4	1.0	5.0	4	38	1	4	0.8	1.3	11	70	5	5	1.0	5.0	6	102	2	2	0.5	4.0	1	134	2	4	1.0	2.0	7	166	1	8	1.0	1.0
1	7	5	3	0.9	5.6	5	39	3	1	0.5	6.0	11	71	5	1	0.9	5.6	7	103	2	8	1.0	2.0	10	135	5	4	0.8	6.3	7	167	2	7	0.3	6.7
1	8	2	4	1.0	2.0	5	40	5	3	0.5	10.0	11	72	30	0	1.0	30.0	7	104	10	7	0.3	33.3	10	136	5	4	0.8	6.3	7	168	10	8	1.0	10.0
1	9	2	3	0.9	2.2	5	41	1	1	0.5	2.0	11	73	20	8	1.0	20.0	7	105	1	6	0.5	2.0	2	137	3	4	0.9	3.3	7	169	1	7	0.3	3.3
2	10	3	3	0.9	3.3	6	42	2	8	0.3	6.7	11	74	20	5	1.0	20.0	7	106	1	7	0.3	3.3	2	138	3	4	0.9	3.3	7	170	10	8	1.0	10.0
2	11	3	3	0.9	3.3	6	43	2	2	0.5	4.0	12	75	3	2	0.7	4.3	7	107	10	8	1.0	10.0	2	139	1	4	0.9	1.1	7	171	3	0	1.0	3.0
2	12	1	4	0.9	1.1	6	44	1	1	0.5	2.0	9	76	2	2	0.8	2.5	7	108	3	4	0.7	4.3	2	140	1	4	0.9	1.1	7	172	1	0	1.0	1.0
2	13	1	4	0.9	1.1	7	45	1	7	0.3	3.3	13	77	10	3	0.8	12.5	7	109	1	8	1.0	1.0	2	141	1	3	0.9	1.1	7	173	1	6	0.5	2.0
2	14	1	4	0.9	1.1	7	46	1	4	0.7	1.4	14	78	20	2	0.7	28.6	7	110	1	6	0.5	2.0	2	142	1	4	0.9	1.1	7	174	10	6	0.5	20.0
2	15	1	3	0.9	1.1	7	47	1	6	0.5	2.0	14	79	2	0	0.6	3.3	7	111	10	6	0.5	20.0	2	143	1	4	0.9	1.1	11	175	10	5	1.0	10.0
2	16	1	3	0.9	1.1	7	48	1	4	0.7	1.4	14	80	10	6	0.9	11.1	10	112	5	3	0.8	6.3	3	144	2	4	0.9	2.2	11	176	5	8	1.0	5.0
2	17	1	4	0.9	1.1	7	49	1	3	0.7	1.4	14	81	10	6	0.9	11.1	10	113	5	4	0.8	6.3	3	145	2	3	0.9	2.2	11	177	10	8	1.0	10.0
2	18	1	3	0.9	1.1	7	50	1	4	0.7	1.4	14	82	10	6	0.9	11.1	10	114	5	4	0.8	6.3	3	146	1	3	0.9	1.1	11	178	5	0	1.0	5.0
3	19	2	3	0.9	2.2	7	51	1	8	1.0	1.0	14	83	15	0	0.6	25.0	10	115	5	3	0.8	6.3	3	147	1	7	0.3	3.3	11	179	5	0	1.0	5.0
3	20	2	7	0.3	6.7	7	52	2	8	1.0	2.0	14	84	10	6	0.9	11.1	11	116	5	1	0.9	5.6	3	148	1	7	0.3	3.3	11	180	30	0	1.0	30.0
3	21	1	7	0.3	3.3	7	53	10	8	1.0	10.0	14	85	10	6	0.9	11.1	11	117	5	0	1.0	5.0	3	149	2	4	0.9	2.2	11	181	20	5	1.0	20.0
3	22	1	3	0.9	1.1	7	54	1	0	0.2	5.0	0	86	1	2	0.7	1.4	11	118	5	0	1.0	5.0	3	150	1	3	0.9	1.1	11	182	20	1	0.9	22.2
3	23	1	4	0.9	1.1	7	55	1	3	0.7	1.4	0	87	1	8	0.5	2.0	11	119	30	5	1.0	30.0	3	151	1	3	0.9	1.1	11	183	3	5	0.1	3.0
3	24	2	4	0.9	2.2	7	56	10	7	0.3	33.3	0	88	1	2	0.7	1.4	11	120	20	8	1.0	20.0	3	152	3	3	0.9	3.3	8	184	5	2	0.7	7.1
3	25	1	4	0.9	1.1	7	57	3	4	0.7	4.3	1	89	5	4	1.0	5.0	11	121	20	1	0.9	22.2	3	153	1	3	0.9	1.1	9	185	2	6	0.9	2.2
3	26	1	3	0.9	1.1	7	58	1	6	0.5	2.0	1	90	5	4	1.0	5.0	12	122	3	2	0.7	4.3	3	154	1	7	0.3	3.3	13	186	10	3	0.8	12.5
3	27	3	4	0.9	3.3	7	59	1	4	0.7	1.4	1	91	5	4	1.0	5.0	9	123	2	2	0.8	2.5	3	155	1	3	0.9	1.1	14	187	20	6	0.9	22.2
3	28	1	4	0.9	1.1	7	60	10	8	0.1	10.0	2	92	3	4	0.9	3.3	13	124	10	4	0.8	12.5	3	156	1	4	0.9	1.1	14	188	2	0	0.6	3.3
3	29	1	7	0.3	3.3	8	61	5	4	0.7	7.1	2	93	3	4	0.9	3.3	14	125	1	0	0.6	1.7	3	157	1	4	0.9	1.1	14	189	1	0	0.6	1.7
3	30	1	7	0.3	3.3	9	62	2	4	0.8	2.5	2	94	1	3	0.9	1.1	0	126	1	2	0.7	1.4	3	158	1	3	0.9	1.1						
3	31	1	7	0.3	3.3	10	63	5	3	0.8	6.3	2	95	1	3	0.9	1.1	0	127	1	6	0.5	2.0	4	159	3	7	0.3	10.0						

Table C.25 Assessment of Case 3.6 *(4th Schedule)*

T_I	ΣT_{ED}	R_{FE}			n_R			$\Sigma T_{ED} / \Sigma R_{FE}$
		Available	Used	Deployment (%)	Available	Used	Deployment (%)	
0	14	4.1	3.1	75.6	7	5	71.4	4.5
1	74	1.9	1.9	100.0	2	2	100.0	38.9
2	37	1.8	1.8	100.0	2	2	100.0	20.6
3	81	2.1	2.1	100.0	3	3	100.0	38.6
4	21	2.4	1.9	79.2	4	3	75.0	11.1
5	28	2.5	1.7	68.0	5	3	60.0	16.5
6	23	2.3	1.3	56.5	5	3	60.0	17.7
7	223	4.2	4.2	100.0	6	6	100.0	53.1
8	14	3.1	1.4	45.2	5	2	40.0	10.0
9	10	3.1	2.5	80.6	4	3	75.0	4.0
10	63	1.6	1.6	100.0	2	2	100.0	39.4
11	300	3.9	3.9	100.0	4	4	100.0	76.9
12	9	3.1	0.7	22.6	5	1	20.0	12.9
13	38	1.6	1.6	100.0	2	2	100.0	23.8
14	141	2.2	2.2	100.0	3	3	100.0	64.1

Table C.26 Summary of Assessment of Case 3.6 *(4th Schedule)*

Resource Index (R_I)	Goal Index (T_I)														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	0.3	0	0	0	0	0	0	1.0	0.4	0	X	1.0	0.5	X	0.6
1	0.9	X	X	X	0.5	0.5	0.5	X	X	0	0	0.9	0	X	X
2	0.7	X	0	0	0.8	0.5	0.5	X	0.7	0.8	0	0	0.7	X	0.7
3	0.5	0.9	0.9	0.9	X	0.5	0.3	0.7	0.5	0.6	0.8	0	0.5	0.8	X
4	0.7	1.0	0.9	0.9	0.8	0.7	0.7	0.7	0.7	0.8	0.8	0	0.5	0.8	X
5	0	0	0	0	0	0	0	0	0	0	0	1.0	0	0	0
6	0.5	X	0	0	0	0.3	X	0.5	0.8	0.9	0	0	0.9	X	0.9
7	0	0	0	0.3	0.3	0	X	0.3	0	0	0	0	0	0	0
8	0.5	X	0	0	0	0	0.3	1.0	0	0	0	1.0	0	0	0

Table C.27 Proposed Resource Model

In Table C.27, heavily shaded cells represent the goals, with associated tasks that the respective resource can undertake. Lightly shaded cells indicate where a resource's forecasted efficiency has been developed. Cell entries of zero signify that the resource cannot undertake associated tasks of the goal. Cells marked with a cross indicate resources formerly assigned R_{FE}=0.1 or 0.2, however are now considered to be zero indicating that the resources are no longer considered to undertake tasks associated with the goal.

Appendix D

Correspondence from Industry

As a result of carrying out three practical case studies from engineering industry, each of the companies involved provided feedback in the form of correspondence. This appendix contains the letters received from those three companies:

- Siemens Power Generation Limited
- Armstrong Technology Associates
- domnick hunter limited

SIEMENS

Mr.G.Coates
Engineering Design Centre
University of Newcastle upon Tyne
Newcastle upon Tyne.
NE1 7RU

Name	Dr.J.Grant
Department	Engineering
Division	Siemens Power Generation Ltd
Telephone	0191 275 2077
Fax	0191 265 2532
Email	john.grant@spgl.siemens.co.uk
Your Ref	
Our Ref	
Date	15 March 01

Dear Graham,

Re: Siemens Power Generation Limited Case Study

Thank you for your presentation on Friday 23 February in which you described and demonstrated the application of your 'real-time' co-ordination methodology. It was useful to have done this by applying your software system to the case study provided by Siemens Power Generation Limited. As a result of our meeting, I thought it would be helpful to make the following comments.

Our initial discussion regarding the 'real-time' operational co-ordination methodology implemented within your software system proved to be interesting and informative. I found your explanations, of how management issues encountered within an unpredictable environment could be addressed, such that a process could be continuously conducted in an optimised manner, to be well thought out and comprehensive. By addressing these and many other important issues faced in design management, your research offers a valuable contribution.

With specific regard to your software system, I acknowledge that you have used the simulation tools provided by Siemens Power Generation Limited as used by our engineers in the design of turbine blades. Traditionally, the simulation tools are executed sequentially by the designer using a single computer. While there are obvious benefits of automating the process involving the use of simulation tools on a network of machines, I appreciate that it is the underlying real-time operational design co-ordination methodology and the work in setting up the architecture for this that is of key importance. Enabling the turbine blade design process to be continuously co-ordinated in real time, while being responsive to changes in the environment such that the process is performed in an optimised way, is a considerable achievement of your research.

Whilst your methodology has been proven in the context of this particular case study, it would be of interest to apply your research to other case studies to demonstrate the scope and applicability of your research. In addition, I would be personally interested in the application of your research to a project, which involves human resources and the complexities of multi-disciplinary design activity.

Siemens Power Generation Ltd

C.A. Parsons Works
Shields Road
Heaton
Newcastle upon Tyne
NE6 2YL

Tel: 0191 276 1188
Fax: 0191 276 0276

I would like to congratulate you on the development of your methodology and its implementation within a software system. I believe the principles involved provide an improvement to current approaches aimed at managing/co-ordinating and engineering design. Finally, I would like to express my appreciation for the efforts of you and your colleagues at the Newcastle Engineering Design Centre in successfully applying academic research to industrial problems. Academic/industrial collaboration of this nature is extremely useful and encouraged by Siemens Power Generation Limited.

Yours sincerely,

V Bolton

pp Professor John Grant.

ARMSTRONG
TECHNOLOGY

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Engineering Design Centre
University of Newcastle upon Tyne
NE1 7RU

Attention : Mr. G. Coates

Your Ref. :
Our Ref. : G01/UON/2659/GCM

Dear Graham

12 February 2001

RE: Industrial Case Study

Further to your visit to Armstrong Technology Associates on 30 January 2001, during which we discussed the results of the case study provided by the Company, I would like to offer the following feedback.

We would like to acknowledge that the design programme information we provided reflected the actual programme, as it was delivered in practice.

The findings of the case study are in agreement with the final allocation of resources as implemented in practice. The case study identified, at the outset of the design programme, the specific areas within our organisation in which it would have been beneficial to allocate additional skilled personnel. This finding corroborates with our decision to allocate two additional electrical engineers to the design programme. However, this decision was determined during the design programme rather than at the outset as would have been indicated had we applied your methodology. Thus, the findings suggest that the methodology applied is an effective feature of engineering management.

There is scope for further application of your methodology. It would be useful to apply your methodology to a multi-project environment in which design is usually carried out, since the management of resources in these situations proves immensely difficult. Such an application would present companies such as ours with a powerful approach to design management/ coordination. It is also suggested that the hierarchical nature of the design tasks should be more rigorously modelled such that the methodology would be able to further identify more specific improvements in terms of resources, e.g. differentiating between concept/embodiment/detail design.

While these comments are made on the basis of a single case study, I would like to applaud the fundamental research, which you have carried out at the Engineering Design Centre. The methods

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employed are practical and of considerable value, and would improve the management of future design programmes.

Yours sincerely,

Graeme Mackie
Technical Director

cc. Prof W Hills

domnick hunter

INDUSTRIAL DIVISION

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Tel: (44) 0191 402 9000
Fax: (44) 0191 482 6296

Mr. Graham Coates
Engineering Design Centre
Armstrong Building
University of Newcastle upon Tyne
Newcastle upon Tyne NE1 7RU

Dear Graham,

Re: domnick hunter limited Case Study

Thank you for your visit to domnick hunter on 29th May 2001. Following your presentation of the work you have carried out on the case study, I would like to offer some remarks.

The aspect of engineering management in which you have conducted your work is fundamental to the effective operation of a research and development department such as that within domnick hunter limited. Your work offers an advanced methodology to modelling and managing the engineers within our R&D department. In addition, your work provides a very useful technique for assessing our personnel requirements prior to starting the design development phase involving our multi-disciplinary, multi-skilled design team.

With respect to your findings, I was interested to find that your advice of establishing the most appropriate way of modelling people's capabilities prior to developing them, as opposed to the traditional project management technique of adding extra personnel, was the best way of reducing the duration of the design development phase. This serves to emphasise the non-trivial nature of and the complexity involved in the management of the design development phase. Specific to the case study, your results indicate that the appropriate modelling and development of the capabilities of existing engineers could result in approximate reductions of 52% and 45% in time and cost respectively. Figures of this order need to be realised in order for companies, such as domnick hunter limited, to be successful in the future.

Finally, I would like to take this opportunity to express my thanks to you for delivering your methodology, which allows us to assess our resources prior to the start of a project. We feel the research you have done is extremely useful to us and provides us with a new technique of managing our technical personnel. Further, the generic nature of your methodology should make it applicable elsewhere within our company as well as within our supplier chain companies who are increasingly becoming key members of our new product development programmes.

Yours sincerely,

Professor Rob Fielding
Divisional Director – Technology

pure innovation

Appendix E

List of Publications

Journal Papers

Coates, G., Duffy, A.H.B., Hills, W. and Whitfield, R.I., "A Generic Coordination Approach Applied to a Manufacturing Environment", Journal of Materials Processing Technology, Vol. 107/1, Issue 3, pp 404-411, November 2000.

Coates, G., Whitfield, R.I., Duffy, A.H.B. and Hills, W., "Coordination Approaches & Systems - Part II: An Operational Perspective", Journal of Research in Engineering Design, Vol. 12, No. 2, pp 73-89, October 2000.

Coates, G., Ritchey, I., Duffy, A.H.B., Hills, W. and Whitfield, R.I., "Integrated Engineering Environment for Large Complex Products", The International Journal of Concurrent Engineering: Research & Applications, Vol. 8, No. 3, pp 171-182, September 2000.

Whitfield, R.I., Coates, G., Duffy, A.H.B. and Hills, W., "Coordination Approaches & Systems - Part I: A Strategic Perspective", Journal of Research in Engineering Design, Vol.12, No. 1, pp 48-60, July 2000.

Whitfield, R.I., Wright, P.N.H., Coates, G. and Hills, W., "A Robust Methodology Suitable for Application to One-off Products", Journal of Engineering Design, Vol. 9, No. 4, pp 373-387, 1998.

Journal Paper (Submitted)

Whitfield, R.I., Duffy, A.H.B., Coates, G. and Hills, W., "Efficient Process Optimisation", submitted in May 2001 to the International Journal of Concurrent Engineering: Research and Applications.

Conference Papers

Whitfield, R.I., Coates, G., Duffy, A.H.B. and Hills, W., "A System for Coordinating Concurrent Engineering", In Proceedings of the 13th International Conference on Engineering Design (ICED '01), Glasgow, United Kingdom, 21-23 August 2001.

Coates, G., Duffy, A.H.B., Hills, W. and Whitfield, R.I., "Enabling Concurrent Engineering through Design Coordination", In Proceedings of the 6th ISPE International Conference on Concurrent Engineering: Research & Applications (CE '99), pp 189-198, Bath, United Kingdom, 1-3 September 1999.

Coates, G., Duffy, A.H.B., Whitfield, R.I. and Hills, W., "A Methodology for Design Coordination in a Distributed Computing Environment", In Proceedings of the 12th International Conference on Engineering Design (ICED '99), Vol.2, pp 673-678, Munich, Germany, 24-26 August 1999.

Whitfield, R.I., Coates, G. and Hills, W., "Multi-Objective Concept Exploration Within the Made-To-Order Sector", In Proceedings of the 12th International Conference on Engineering Design (ICED '99), Vol. 2, pp 739-744, Munich, Germany, 24-26 August 1999.

Whitfield, R.I., Hills, W. and Coates, G., "The Application of Multi-Objective Robust Design

Methods in Ship Design", In Proceedings of the 10th International Conference on Computer Applications in Ship Building, Cambridge, United States, 7-11 June 1999.

Coates, G., Duffy, A.H.B., Whitfield, R.I. and Hills, W., "A Generic Coordination Methodology Applied to a Manufacturing Environment", In Proceedings of the 15th International Conference on Computer Aided Production Engineering (CAPE '99), pp 701-708, Durham, United Kingdom, 19-21 April 1999.

Workshop Paper

Whitfield, R.I., Coates, G., Duffy, A.H.B. and Hills, W., "A Multi-Agent Based System to Enable Strategic and Operational Design Coordination", Workshop on Developing Intelligent Support for Collaboration in Design in Artificial Intelligence in Design (AID '00), Worcester, United States, 25 June 2000.

Papers Contributed to a Book (To be published)

Coates, G., Whitfield, R.I., Duffy, A.H.B. and Hills, W., "Operational Coordination Approaches and Systems", (Approx. 9 pages), Design Co-ordination Theory and Practice.

Whitfield, R.I., Coates, G., Duffy, A.H.B. and Hills, W., "Strategic Coordination Approaches and Systems", (Approx. 10 pages), Design Co-ordination Theory and Practice.

Coates, G., Whitfield, R.I., Duffy, A.H.B. and Hills, W., "Operational Agent-Based Design Coordination", (Approx. 9 pages), Design Co-ordination Theory and Practice.

Whitfield, R.I., Coates, G., Duffy, A.H.B. and Hills, W., "A Coordination System for the Management of the Engineering Design Process", (Approx. 10 pages), Design Co-ordination Theory and Practice.

Coates, G., "An Introduction to Agents, Multi-Agent Systems and Coordination", (Approx. 7 pages), Design Co-ordination Theory and Practice.