A heuristic integrated planning decision support model for large multiple capital projects

by

Stephanus Johannes Coetzee

Dissertation presented for the degree of

Doctor of Philosophy (Industrial Engineering)

at the University of Stellenbosch, South Africa

Promoter : Prof. N.D. du Preez

November 1999

"The fear of the Lord is the beginning of knowledge"

Proverbs 1 verse 7

Acknowledgements

I am thankful to all the people and organisations that have helped and supported me towards the completion of my dissertation. In particular I would like to extend my gratitude to:

- Professor ND du Preez of the Department of Industrial Engineering at the University of Stellenbosch, my promoter, for his continuous academic support and motivation;
- Professor D Cattrysse of the Catholic University of Leuven, Belgium, for his specialist input as co-promoter;
- Professor G Geldenhuys of the Department of Applied Mathematics, University of Stellenbosch, for his advice regarding the initial problem formulation;
- Dr W van Wijck of the Department of Industrial Engineering, University of Stellenbosch, for his valuable contribution towards the final document;
- Dr AJ Buys of ARMSCOR's Planning Department for his support, and
- Ms TA Eberlanz of ARMSCOR's Language Services for the language editing of the dissertation.

Declaration

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and has not previously been submitted, in its entirety or in part, for a degree at any university.

Terms of reference

During 1995, the author started to investigate a complex planning problem, namely how to schedule capital projects, subject to monetary constraints, down to phase level and how to obtain the necessary input from various levels of role players from different organisations in order to find a solution to the problem and eventually also ascertaining the impact of a chosen schedule on certain factors. In mid-1996 the problem was presented to senior and top management of the Armaments Corporation of South Africa. It was decided that research should continue to find a methodology for solving this kind of problem. The aim was to complete the research within a three-year period so that it could be proposed as a solution while the transformation of the Department of Defence was under way.

The project proposal was also presented to the research evaluation committee of the Department of Industrial Engineering at the University of Stellenbosch. It was accepted as a PhD project within the Department of Industrial Engineering.

Samevatting

Langtermynbeplanning van groot kapitaalprojekte waarvan die fondse deur 'n sentrale instansie (bv. die regering) voorsien word, benodig insette vanaf strategiese vlak asook van projekbestuurders op die taktiese vlak om te verseker dat beplanningsbehoeftes alle vlakke van bestuur insluit.

Hierdie insette word deur middel van 'n heuristiese kapitaalbeplannings- en besluitnemingsondersteuningsmodel verwerk sodat resultate wat aan die meeste van die gegewe beperkings voldoen, finansiële en ander impakte aan al die rolspelers tydens die uitvoering van die kapitaalprojekproses uitwys. Hierdeur word ingeligte projek- en beleggingsbesluite gemaak.

Op strategiese vlak word begrotings, behoeftes en prioriteite van projekte aangespreek terwyl daar op taktiese vlak skedules en kontantvloeivooruitskattings vir projekte en subprojekte bereken word. Hiermee word 'n gekose skedule geformuleer. Die impak van die gekose skedule op menslike hulpbronne en verskeie ingenieursfunksies word geëvalueer waarna sensitiwiteitsanalises gedoen word.

Na die afhandeling van sensitiwiteitsanalises kan 'n geskikte naby-optimale makroskedule deur die besluitnemers op strategiese vlak aanvaar word. Hierna word finale resultate aan besluitnemers en uitvoerders op taktiese vlak beskikbaar gestel. Insig in die hoëvlakmannekragbehoefte en die langtermyn-kontantvloeibehoefte kan met behulp van die geskeduleerde groot kapitaalprojekte en geprosesseerde inligting afgelei word sodat strategiese besluite geneem kan word.

Vanweë die kompleksiteit van die model wat uit die baie moontlike kombinasies spruit, word 'n heuristiese benadering voorgestel om die beplanning van kapitaalprojekte te doen. Die impak op verskeie faktore, soos byvoorbeeld die impak op menslike bronne, word op grond van die skeduleresultate bereken. Enige verandering wat op grond van die impakanalise nodig mag wees, kan met behulp van die programresultate en deur middel van onderhandelinge tussen die rolspelers aangebring word.

Synopsis

In order to do proper long-term planning for major capital projects which are funded collectively by a central body (e.g. the government), input is required from strategic level as well as from project managers at tactical level to ensure that planning requirements are included from all levels of management.

This input is processed by means of a heuristic capital planning and decision support model so that the results, which comply with most of the given constraints, can indicate financial and other impacts on all role players during the execution of the capital project. Through this, good decisions can be made with regard to the projects and investments.

At strategic level, budgets, requirements and priorities of the various projects are taken into consideration, while at tactical level, schedules, project and subproject cash flow predictions are calculated. With this a chosen schedule can be formulated. The impact of the chosen schedule on human resources and various engineering functions can be evaluated, after which sensitivity analyses are conducted.

After the completion of sensitivity analyses, decision makers at strategic level can accept an appropriate near optimal macro schedule. Hereafter the final results are made available to decision makers and executors at tactical level. Insight into long-term cash flow requirements can be derived from the available information. All the major capital projects can be scheduled and the requirements in terms of high-level manpower can be determined so that strategic decisions can be made.

Owing to the complexity of the model, which results from the many possible combinations that may occur, a heuristic approach is proposed for doing the capital planning. The impact on various factors, for example the impact on human resources, is determined from the schedule results. Any changes that might be necessitated by the schedule results can be negotiated with the role players, based on the output of the programme.

Table of contents

List of tables

List of figures

Nomenclature and abbreviations

Nomenclature

b = constant

$B_{i\tau}$ = beginning of sector $\tau \in \{1,2,3,4\}$ for project Pi with priority i

C_{ij} = supplier country of subproject j of project Pi with priority i where $C_{ij} \in$ {supplier countries}

$d_{i\tau}$ = the difference between the maximum and minimum duration of sector τ of project Pi with priority i

D_i = the sum of the differences $d_{i\tau}$ for project Pi with priority i

${}_dHR^{uvw}{}_k$ = default human resource requirement of phase k for impact parameter u and specific impact v for human resource type w

${}_dr^{uv}{}_{ijk}$ = default average real rand intensity per month for impact number u and specific impact v for phase k of subproject j of project Pi with priority i

${}_dR^{uv}{}_k$ = default rand value of phase k for impact parameter u and specific impact v

${}_dT^{uv}{}_k$ = default duration of phase k for impact parameter u and specific impact v

$E_{i\tau}$ = end of sectors $\tau \in \{1,2,3,4\}$

${}_eR^n{}_{im}$ = existing nominal rands for project Pi with priority i during month m

${}_eR^n{}_m$ = existing total nominal rands during month m

$ete_{ij\tau}$ = end of search ending time of subproject j of project Pi with priority i in sector τ

$ets_{ij\tau}$ = end of search starting time of subproject j of project Pi with priority i in sector τ

$f^r{}_{it}$ = real value of cash flow profile for project Pi with priority i at time t

f_t = function in time t

G_y = budget growth factor per annum

h = index of month during which project is active where $h = ts^0$ to $ts^0 + Tav_i - 1$

H = constant

$HR^{uvw}{}_{ijkm}$ = predicted human resource requirement for impact parameter u and specific impact v for human resource type w per month and for phase k for subproject j for project Pi with priority i at month m

$HR^{uvw}{}_m$ = predicted human resource requirement for impact parameter u and specific impact v for human resource type w per month m

i = index of projects where i represents the priority of the project

I = average intensity of cash flow over a specified time

I^r_i = R^r_i / T_i

= uniform intensity in real rands per time unit of total supply per project Pi with priority i

I^r_{it} = $R^r_{i\tau} / T_{it}$

= real uniform intensity per sector per time unit where τ=2,3,4 and t = $B_{i\tau}$, ..., $E_{i\tau}$

If_i = Rf_i / T_i

= uniform intensity in real rands per time unit of foreign supply per project

Il^r_i = Rl^r_i / Tav_i

= uniform intensity in real rands per time unit of local supply per project

$I\Gamma^n_m$ = average budget intensity per month in nominal rands = $\Gamma^n_y / 12$

j = subproject index of project Pi with priority i

k = phase index of subproject j of project Pi with priority i

m = index for time units in months

m_e = expected duration in months when actual monthly cash flow is equivalent to the average monthly cash flow over a duration of twelve months

no = number of movements during pseudo operations

${}_nR^n_{i\,m}$ = new nominal rands for project Pi with priority i during month m

${}_{n-}R^n_m$ = the new total monthly nominal cash flow reduced with the project's existing monthly cash flow

${}_{n+}R^n_m$ = the new total monthly nominal cash flow increased with the project's new monthly cash flow

${}_nts_i$ = the new starting time of project Pi with priority i after pseudo operations

${}_n\Gamma^{ni}_m$ = new nominal monthly budget available for project Pi with priority i

M^r_{ijk} = real money value of phase k of subproject j of project Pi with priority i in any foreign currency

N_m = number of months

N_y = number of years

O^1_i = pseudo project operation for project Pi with priority i during optimisation iteration 1

$O^{\rho L}_i$ = operation shift left for project Pi with priority i

$O^{\rho R}_i$ = operation shift right for project Pi with priority i

$O^{\nu L}_{i}$	=	operation shrink left for project Pi with priority i
$O^{\nu R}_{i}$	=	operation shrink right for project Pi with priority i
$O^{\lambda L}_{i}$	=	operation stretch left for project Pi with priority i
$O^{\lambda R}_{i}$	=	operation stretch right for project Pi with priority i
p	=	constant
P	=	number of projects under consideration
P_i	=	project number of priority i
q	=	constant
r	=	interest rate monthly compounded
R^r	=	$\sum R^r_i$
	=	real rand value of total supply for all projects
R^r_i	=	$\sum R^r_{ij}$, j = 1, ..., S_i where S_i = number of subprojects per project Pi with priority i
	=	real rand value per project Pi with priority i
$R^r_{ij\tau}$	=	real value of subproject j of project Pi with priority i in sector τ
$R^r_{ijk\tau}$	=	real value of phase k of subproject j of project Pi with priority i in sector τ
R^r_{ik}	=	$\sum R^r_{ijk}$, k = 1, ... , 9
	=	real rand value of total supply per subproject j per project Pi with priority i
R^r_{ijk}	=	Rl^r_{ijk} or Rf^r_{ijk}
	=	real rand value of total supply per phase k per subproject j per project Pi with priority i
$R^r_{i\tau}$	=	$\sum R^r_{ijk}$, where k is sector τ phases and j = 1, ..., S_i
Rf^r	=	$\sum Rf^r_i$
	=	real rand value of foreign supply for all projects
Rf^r_i	=	$\sum Rf^r_{ij}$, j = 1, ..., S_i where S_i = number of subprojects per project Pi with priority i
	=	real rand value of foreign supply per project Pi with priority i
Rf^r_{ij}	=	$\sum Rf^r_{ijk}$, k = 1, ... , 9
	=	real rand value of foreign supply per subproject j per project Pi with priority i
Rf^r_{ijk}	=	$M^r_{ijk} * X_{ijy}$ with y = 0
	=	real rand value of foreign supply per phase k per subproject j per project Pi with priority i

R^{fn}_{im}	=	final pseudo nominal cash flow of project Pi with priority i during month m
Rl^{r}	=	$\sum Rl^{r}_{i}$
	=	real rand value of local supply for all projects
Rl^{r}_{i}	=	$\sum Rl^{r}_{ij}$, $j = 1, ..., S_i$ where S_i = number of subprojects per project Pi with priority i
	=	real rand value of local supply per project Pi with priority i
Rl^{r}_{ij}	=	$\sum Rl^{r}_{ijk}$, $k = 1, ..., 9$
	=	real rand value of local supply per subproject j per project Pi with priority i
Rl^{r}_{ijk}	=	M^{r}_{ijk}
	=	real rand value of local supply per phase k per subproject j per project Pi with priority i
R_{m}	=	monthly cash flow
R^{n}_{ih}	=	nominal cash flow of project Pi with priority i during month h
R^{sn}_{im}	=	subproject s monthly cash flow per project Pi with priority i at month m
$R^{sn}_{im\tau}$	=	subproject s monthly cash flow per project Pi with priority i in sector τ at month m
$R^{sn}_{ijm\tau}$	=	subproject s monthly cash flow per subproject j per project Pi with priority i in sector τ at month m
r^{uv}_{ijk}	=	average real rand intensity per month for impact number u and specific impact v for phase k of subproject j of project Pi with priority i
R^{uv}_{ijk}	=	real value allocated to impact parameter u and specific impact v due to phase k of subproject j of project Pi with priority i
$R^{\phi n}_{im\tau}$	=	phase ϕ monthly cash flow per project Pi with priority i in sector τ at month m
$R^{\phi n}_{ijm\tau}$	=	phase ϕ monthly cash flow per subproject j of project Pi with priority i in sector τ at month m
$R^{\phi n}_{ijkm\tau}$	=	phase ϕ monthly cash flow per phase k of subproject j of project Pi with priority i in sector τ at month m
R^{*n}_{m}	=	optimal nominal cash flow over planning horizon per month m
S_i	=	number of subprojects per priority i
$ste_{ij\tau}$	=	start of search ending time of subproject j of project Pi with priority i in sector τ
$sts_{ij\tau}$	=	start of search starting time of subproject j of project Pi with priority i in sector τ
t	=	time units

$\bar{t}$	=	duration of any project
te_i	=	ending time of project Pi with priority i
te_{ijk}	=	starting time of phase k of subproject j of project Pi with priority i
$te_{i\tau}$	=	ending time of project Pi with priority i in sector τ
$te_{ij\tau}$	=	ending time of subproject j of project Pi with priority i in sector τ
te^r_p	=	required or constraint completion date of project p
te_z^n	=	new ending time of project z violating a scheduling rule
te^*_i	=	pseudo optimised ending time of project Pi with priority i
$te^*_{ij\tau}$	=	optimised ending time of subproject j of project Pi with priority i in sector τ
te^*_{ijk}	=	optimised ending time of phase k of subproject j of project Pi with priority i
ts_i	=	starting time of project Pi with priority i
ts_{ijk}	=	starting time of phase k of subproject j of project Pi with priority i
$ts_{i\tau}$	=	starting time of project Pi with priority i in sector τ
$ts_{ij\tau}$	=	starting time of subproject j of project Pi with priority i in sector τ
ts_z	=	starting time of project z violating a scheduling rule
ts_z^n	=	new starting time of project z violating a scheduling rule
ts^*_i	=	pseudo optimised starting time of project Pi with priority i
$ts^*_{ij\tau}$	=	optimised starting time of subproject j of project Pi with priority i in sector τ
ts^*_{ijk}	=	optimised starting time of phase k of subproject j of project Pi with priority i
T	=	total time of all projects $= \sum T^0_i$
T_i	=	duration of project Pi with priority i where $Tmin_i \leq T_i \leq Tmax_i$
T^*_i	=	pseudo optimised duration of project Pi with priority i
$T^*_{ij\tau}$	=	optimised duration of subproject j of project Pi with priority i in sector τ
$T^*_{ijk\tau}$	=	optimised duration of phase k of subproject j of project Pi with priority i in sector τ
T^0_i	=	initial pseudo project duration for project Pi with priority i
Tav_i	=	$\sum Tav_{i\tau}$, $\tau = 1, ..., 4$
	=	average completion time for project Pi with priority i
$Tav_{i\tau}$	=	integer $((Tmax_{i\tau} + Tmin_{i\tau})/2)$
	=	average duration per sector τ for project Pi with priority i
$T_{i\tau}$	=	duration time per sector τ for project Pi with priority i
$Tmax_i$	=	$\sum Tmax_{i\tau}$, $\tau = 1, ..., 4$

$Tmax_{i\tau}$	=	$\max\{Tmax_{ij\tau}\}, j = 1, ..., S_i$
$Tmax_{ij\tau}$	=	$\sum \delta Tmax_{ijk}$, where k is sector τ phases and $j = 1, ..., S_i$
$Tmin_i$	=	$\sum Tmin_{i\tau}, \tau = 1, ..., 4$
$Tmin_{i\tau}$	=	$\max\{Tmin_{ij\tau}\}, j = 1, ..., S_i$
$Tmin_{ij\tau}$	=	$\sum \delta Tmin_{ijk}$, where k is sector τ phases and $j = 1, ..., S_i$
u	=	number of impact parameter
v	=	specific impact
V_{ij}	=	$V_{ij}(C_{ij})$
	=	foreign or local currency for subproject j of project Pi with priority i of supplier country C_{ij} where $V_{ij} \in$ {currency of countries}
V_u	=	number of specific impacts on impact parameter u
W	=	weighted annual escalation
w^a_{ijm}	=	actual escalation factor for subproject j of project Pi with priority i at month m
Wf_{iy}	=	annual weighted foreign escalation for project Pi with priority i at year y
w_{im}	=	monthly escalation factor for project Pi with priority i at month m
W_{iy}	=	total weighted annual escalation for project Pi with priority i at year y
Wl_{iy}	=	annual weighted local escalation for project Pi with priority i at year y
X_{ijy}	=	$X_{ij}(V_{ij}(C_{ij}), y)$
	=	exchange rate for subproject j of project Pi with priority i for valuta $V_{ij}(C_{ij})$ of supplier country C_{ij} at year y (local rand per foreign currency)
X_{ij0}	=	$X_{ij}(V_{ij}(C_{ij}), y)$ where y=0
y	=	index of year
Y	=	total number of years under consideration
$_{+}R^{\phi r}_{ijkm}$	=	real value additional cost at phase level for all m
α	=	profile constant
α_i	=	profile constant for project Pi with priority i
$\alpha_{ij\tau}$	=	profile constant for subproject j of project Pi with priority i in sector τ
$\alpha_{ijk\tau}$	=	profile constant for phase k of subproject j of project Pi with priority i in sector τ
β	=	profile constant
β_i	=	profile constant for project Pi with priority i
$\beta_{ij\tau}$	=	profile constant for subproject j of project Pi with priority i in sector τ
$\beta_{ijk\tau}$	=	profile constant for phase k of subproject j of project Pi with priority i in sector τ

γ = profile constant

γ_i = profile constant for project Pi with priority i

$\gamma_{ij\tau}$ = profile constant for subproject j of project Pi with priority i in sector τ

$\gamma_{ijk\tau}$ = profile constant for phase k of subproject j of project Pi with priority i in sector τ

Γ^r_y = the annual budget in real rands

Γ^n_y = the annual budget in nominal rands

Γ^n_m = the monthly budget in nominal rands

$\delta Tmax_{ijk}$ = maximum completion time of phase k of subproject j of project Pi with priority i

$\delta Tmin_{ijk}$ = minimum completion time of phase k of subproject j of project Pi with priority i

δTav_{ijk} = average completion time of phase k of subproject j of project Pi with priority i

Δt^0 = the increase in time of iteration 0

η = a monthly cash flow fraction of the average monthly cash flow

η_g = Gompertz eta value

η_i = cash flow fraction of project Pi with priority i

η^*_i = best fit fraction for project Pi with priority i

$\theta e_{i\tau}$ = ending slope of cash flow profile of project Pi with priority i in sector τ

$\theta e_{ij\tau}$ = ending slope of cash flow profile of subproject j of project Pi with priority i in sector τ

θe_{ijk} = ending slope of cash flow profile of phase k of subproject j of project Pi with priority i

$\theta s_{i\tau}$ = starting slope of cash flow profile of project Pi with priority i in sector τ

$\theta s_{ij\tau}$ = starting slope of cash flow profile of subproject j of project Pi with priority i in sector τ

θs_{ijk} = starting slope of cash flow profile of phase k of subproject j of project Pi with priority i

λ = number of time units to stretch during pseudo operations

λ^R_i = number of right stretch units of project Pi with priority i during pseudo operations

λ^L_i = number of right stretch units of project Pi with priority i during pseudo operations

$\mu_{ij}(C_{ij}, y)$ = inflation rate for subproject j of project Pi with priority i for supplier country C_{ij} at year y

ν = number of time units to shrink during pseudo operations

ν^R_i = number of right shrink units of project Pi with priority i during pseudo operations

$\nu^L{}_i$	=	number of left shrink units of project Pi with priority i during pseudo operations
π_y	=	the annual compound rate at which the budget is growing (percentage)
ρ	=	number of time units to shift during pseudo operations
$\rho^R{}_i$	=	number of right shift units of project Pi with priority i during pseudo operations
$\rho^L{}_i$	=	number of left shift units of project Pi with priority i during pseudo operations
σ_i	=	cash flow eta profile number for project Pi with priority i where $\sigma_i \in \{1,2,3,4,5\}$
$\sigma^*{}_i$	=	best fit profile for project Pi with priority i
τ	=	project scheduling sector where $\tau \in \{1,2,3,4\}$
ϕ_{ij}	=	number of phases per subproject j per project priority i
$\chi^{uv}{}_{ijk}$	=	fraction allocated to impact parameter u and specific impact v due to phase k of subproject j of project Pi with priority i
Ω^0	=	sum of squares for deviation
	=	$\sum_m(\Gamma^n{}_m - \sum_i R^n{}_{im})^2$ for pseudo optimisation iteration 0 which is based on the initial macro schedule
$\Omega^{\rho L1}{}_i$	=	sum of squares for deviation after left shift pseudo operation of project Pi with priority i during optimising iteration 1
$\Omega^{\rho R1}{}_i$	=	sum of squares for deviation after right shift pseudo operation of project Pi with priority i during optimising iteration 1
$\Omega^{\nu L1}{}_i$	=	sum of squares for deviation after left shrink pseudo operation of project Pi with priority i during optimising iteration 1
$\Omega^{\nu R1}{}_i$	=	sum of squares for deviation after right shrink pseudo operation of project Pi with priority i during optimising iteration 1
$\Omega^{\lambda L1}{}_i$	=	sum of squares for deviation after left stretch pseudo operation of project Pi with priority i during optimising iteration 1
$\Omega^{\lambda R1}{}_i$	=	sum of squares for deviation after right stretch pseudo operation of project Pi with priority i during optimising iteration 1
$\Omega^{*1}{}_i$	=	the selected pseudo operation for project Pi with priority i during optimisation iteration 1

Abbreviations

ABL	allocated baseline
ADM	advanced development model
AMD	Aeronautics, Maritime and Defence Industries
AP	acquisition plan
ARMSCOR	The Armaments Corporation of South Africa Ltd
AS	acquisition study
CDR	critical design review
DefSec	Defence Secretariat
DoD	Department of Defence
DP	development plan
DS	development study
EDM	engineering development model
FBL	functional baseline
LCBA	local constrained based analysis
MBL	manufacturing model
MOD	Ministry of Defence
NP	non-deterministic polynomial
P	polynomial
PM	programme management/manager
PBL	product baseline
PPM	pre-production model
QA	quality assurance
R&D	research and development
SADIA	South African Defence Industry Association
SANDF	The South African National Defence Force
SDR	system design review
SRBL	statement of requirements baseline
SS	system study
TT&E	technical test and evaluation
USD	United States dollar
XDM	experimental development model

1. Introduction

1.1 General description

The scheduling of large multiple capital projects subject to a number of constraints, such as priorities and budgets, and factors such as inflation rates and changes in exchange rates, is one of the most complex problems to solve. At top management level decisions must be made which will both fit in with the overall strategic plan and result in a feasible solution set. This research was prompted by this complex problem, with a view to finding a solution that could improve the existing situation with regard to project budgeting, planning and execution.

1.2 Importance of the research

At strategic level decision makers must make critical decisions regarding long-term requirements which must be met, while at tactical level the required data is prepared to assist decision makers at strategic level. It is of the utmost importance to integrate these two levels and the input from other possible role players so that sound strategic decisions can be made, based on an impact analysis. Huge amounts of money, many people and a number of organisations are involved. The better this problem can be defined and formulated, the better the solution that can be obtained to enable the decision makers at strategic level to make substantiated decisions.

1.3 Research overview

The structure of the dissertation is discussed below:

Chapter 1 gives a general introduction to the problem and describes the relationship between the strategic and tactical levels of the decision-making process. The importance of the research lies in the fact that huge amounts of money and many people from a number of organisations are involved in the process. It is necessary to integrate processes in order to make better decisions with regard to capital planning. The contribution of this research is in the area of solving problems where strategic decisions are taken, the main contribution being the establishment of a system that can operate at both strategic and tactical levels, thus assisting the decision-making process by providing answers to many questions.

Chapter 2 describes the current situation with regard to the problem and gives a description of the problem. Although the environment in which the research takes place could be identified as the capital expenditure at national, provincial and local government levels, only the Department of Defence is taken as frame of reference. A brief description is given of the different role players, namely the Secretary for Defence, the South African National Defence Force, the Armaments Corporation of South Africa, and the South African defence industry. The major problem is how to schedule large capital projects with time and budgetary constraints and to determine the impact of the schedule on various factors.

Chapter 3 gives a summary of the relevant literature. Preliminary definitions are given in order to fully explain the remaining part of the chapter. Firstly the research problem is classified. Although various classes of problems are described in the literature, a new class of research problem is proposed. Secondly, solving methods are investigated. Two types of solutions are described, namely exact (non-heuristic) and heuristic approaches. Based on the literature, a heuristic approach is then chosen to solve the research problem.

Chapter 4 describes relevant theory and assumptions which support the development of a solution to the research problem. The research problem is split into a macro and micro level. The macro level provides information such as budgets, inflation rates, exchange rates, nominal and real cash flows, and cash flow targets. Annual cash flows are converted to monthly cash flows within a financial year. Different cash flow profiles of the budget are simulated and manipulated for every year. Project data are provided at the micro level. Each project can be simulated with a specific cash flow profile. Projects are broken down into subprojects and each subproject into phases.

Phases are grouped within sectors which best describe the typical process in a specific sector. Phase data are established, such as the value of the phase, minimum and maximum time to complete the phase, classification whether the phase will be contracted to a local or foreign organisation, and type of foreign currency, in order to be able to arrive at a solution for the research problem. Impact information is described and an impact analysis based on a final schedule is presented.

Chapter 5 describes the mathematical formulation of the research problem and the integration of all factors to present a near optimal solution. It starts by converting detailed project data into pseudo project data, which is necessary to initially schedule all projects subject to constraints such as budgets and priorities. The initial pseudo schedule is then 'freely' optimised, resulting in a final pseudo free schedule. If completion date constraints are activated, a constrained optimising follows the final pseudo free schedule, resulting in a final pseudo constrained schedule. With a final pseudo schedule available, free or constrained, detailed optimising per project takes place, thus presenting a final detailed schedule. Final starting and finishing dates and predicted nominal cash flow profiles are presented per project. The nominal cash flows per project, which are available at phase level, are de-escalated to determine the required real cash flows of a phase and thus for all projects and for the total acquisition. Once the required real cash flows have been calculated, a sensitivity analysis can be conducted in order to so choose a schedule where all possible impacts are acceptable to the decision maker.

Chapter 6 presents a case study using a number of selected projects. Various combinations of the model were run and the results are presented in the relevant appendices.

Chapter 7 sets out the conclusions and recommendations for further research.

Chapter 8 briefly describes the software model that was used to demonstrate the practical solution to the problem.

1.4 Contribution

The problem defined in this project is not a unique problem but it could be identified as a very special one. A unique solution has been developed and illustrated and takes into consideration many levels and factors. This indicates a complex system environment. The inputs and outputs are integrated so that it can be seen as a single model that provides alternatives as solutions to the research problem. The methods described in this dissertation can in future play a significant role in developing knowledge on how to solve similar complex problems. Not only has a theoretical solution been developed, but also a practical solution which makes use of a computer software (prototype) package, which was evaluated by means of a case study.

Lessons learned from this research are placed into two categories, namely theoretical and practical aspects. On the theoretical side, a decision support model has been developed that integrates a number of mathematical formulae into a system which eventually processes an enormous amount of raw data into a userfriendly managerial tool. The practical side has shown that planning, which is necessary for decision-making at higher levels, becomes a time-consuming exercise if computers are not used. The speed with which different scenarios can be developed and evaluated, allows the users to better asses the impact of their decisions. By doing so, an in-depth insight may be developed in order to fully understand the problem.

1.5 Achievements

The following achievements can be mentioned:

- Strategic and tactical levels of management have been integrated.
- A feasible solution for a complex problem has been proposed.
- The proposed solution is substantiated by a practical case study.

2. Current situation and description of problem

2.1 Background

The South African environment

Three levels of government can be identified in the Republic of South Africa, namely national, provincial and municipal, which may also be referred to as the first, second and third level of government. Each level has a capital budget, for example major weapon systems for the Department of Defence at national level, the supply of houses at provincial level, and the establishment of infrastructure at municipal level. Parastatals are seen to be at national level.

The availability and allocation of funds to operate on these three levels of government is one of the crucial factors that will determine whether an entity within this environment will be able to meet the requirements for personnel and operating expenditure, and capital outlay. A percentage of a total budget will be allocated to a capital budget. The question that arises is which projects should be tackled and when? What would be the actual money requirements per project and in what time should it be completed? What will the capital budget look like in future? What would happen in the event of sudden changes, such as drastic cuts or increases in the budget?

National level

The Department of Defence (DoD) is taken as example of a department at national level. Since 1989, the South African Department of Defence has experienced a rapid and drastic decline in its allocated defence budget, with serious consequences for both the sharp-end capabilities of the SA Defence Force and the sustainability of a broad spectrum of local defence industries. Major acquisition programmes have either had to be terminated or cut to a level of affordability or absolute minimum requirement. Rationalisation resulted both in ARMSCOR (the Armaments Corporation of South Africa Ltd) and the defence industry and many highly skilled personnel left the defence industry.

In 1992, Denel (Pty) Ltd was separated from ARMSCOR and was established as a fully state-owned company, taking most of ARMSCOR's subsidiaries with it.

Moreover, the Angolan war had come to an end, thus removing the major drive for a large defence budget and leaving the SA Defence Force with surplus personnel and defence equipment.

After the April 1994 elections, which brought a new government of national unity to power, new policies and controlling bodies came into operation, also in the defence environment. The SA Defence Force changed its name to the SA National Defence Force (SANDF) and a Defence Secretariat (DefSec) was established.

New requirements were identified by the industry, one of which was to establish a body to deal with government and other institutions on behalf of the SA defence industry. For this purpose, the South African Defence Industry Association (SADIA) was formed. Later, this organisation changed its name to Aeronautics, Maritime and Defence (AMD) Industries.

The 1996 Defence Review, which was an open debate on defence issues such as the force design and defence industry, brought many important issues to the minds of the decision makers. One such important issue was the call for efficient and effective communication and co-operation between the various role players to ensure cost-effective acquisition of major weapon systems that would satisfy the requirements of the SANDF.

It is clear that without a well-coordinated and integrated effort, it will be very difficult to assess the impact on the Department resulting from dynamic changes in the environment, including parameters such as budget, cash flow requirements, industry capability, and many others.

Provincial level

The Gauteng Province may be taken as an example. After the April 1994 elections, one of the major priorities of all the provinces was to build an enormous number of houses. Certain living areas were given a higher priority than other areas for the construction of houses. In certain cases some kind of an infrastructure already existed, which allowed the province to proceed immediately with the construction of houses. In other cases it was necessary to establish the full infrastructure prior to any construction. This in its own is a difficult task to fulfill.

Municipal level (or local government)

The City Council of Pretoria may be taken as an example. The engineering departments are grouped under either civil or electrical. Under civil engineering, divisions are identified as Design, Water, Sewerage, Traffic and Roads.

CAPITAL BUDGET PER ANNUM					
Levels of Government		Year 1	Year 2	Year 3	Year N
National Level (Level 1)	Department 1 Department N				
	Subtotal				
Provincial Level (Level 2)	Province 1 Province N				
	Subtotal				
Municipal Level (Level 3)	Municipal 1 Municipal N				
	Subtotal				
Total budget per annum					

Figure 2.1 : An example of capital budget per annum for the three levels of Government.

Each and every division has a capital budget within which certain projects must be completed at specified dates. If less money is available, fewer projects can be undertaken. The question is when to start with which project?

Generic problem

Taking the three levels of government into account, it is clear that the summation of all capital projects results in massive amounts of money being spent on capital alone on an annual basis. Dynamic changes in budget allocations not only have an impact on all three levels of government, but could also have a detrimental effect on the manufacturing and construction sectors of the industry. It is therefore necessary to look for a generic model that will be suitable at any government level and that can be used as a decision support tool in order to do proper long-term planning of capital projects. The three levels of government indicates the wide spectrum of application of a decision support tool.

In order to focus on a specific environment, the **Department of Defence** will be taken as a source of information for this research.

2.2 Description of problem

Introduction

The aim of this section is to explain who the role players are in the South African Department of Defence, with specific reference to the acquisition of major capital projects. Five role players are identified, namely the Minister of Defence, the Defence Secretariat, the South African National Defence Force, the Armaments Corporation of South Africa and the South African defence related industries.

Role and functions

Minister of Defence

The ultimate political authority and responsibility for the acquisition of major weapon systems rest with the Minister of Defence.

The Minister of Defence is responsible for the total function of the Department of Defence and is also the interface with other parliamentarians and political groups. He oversees the Defence Secretariat as the policy maker and budgeting control body, the SANDF as the body to defend South Africa's sovereignty and its resources, and ARMSCOR as the acquisition agency for defence armaments for the SANDF.

Defence Secretariat

The Defence Secretariat is responsible for ensuring that all acquisition activities are executed within national objectives, policies and constraints. The Defence Secretariat is furthermore primarily responsible for high-level programming and budgeting and for the annual control and auditing of defence expenditure.

The Secretary for Defence reports to the Minister and interacts with ARMSCOR, the SANDF and the industry as regards marketing and export services.

The South African National Defence Force (SANDF)

The SANDF is responsible for determining the armaments requirements as derived from and substantiated against the approved force structure and in accordance with policies, programmes and budgets. During the execution of armament acquisition programmes, the SANDF is furthermore responsible for overall project management, and for ensuring that stated requirements are satisfied through the acquisition of optimised user systems, and for final acceptance of these systems against the stated needs.

The Chief of the SANDF reports to the Minister of Defence and is in control of the Arms of Service, i.e. the SA Army, the SA Air Force, the SA Navy and the SA Medical Services. The SANDF operates in close co-operation with the Defence Secretariat in the execution of its role and function and the spending of money. The SANDF also has an interface with ARMSCOR, in terms of acquisition, maintenance, stock sales, and research and development. Its interface with the industry entails giving technical advice on the requirements for defence systems.

The Armaments Corporation of South Africa (ARMSCOR)

ARMSCOR is responsible for the professional programme management and contracting of industry during the execution of armament acquisition programmes. During programme execution ARMSCOR ensures that technical, financial and legal integrity are in accordance with Ministry of Defence (MOD) requirements. ARMSCOR is also responsible for overseeing industrial development in order to support acquisition programmes.

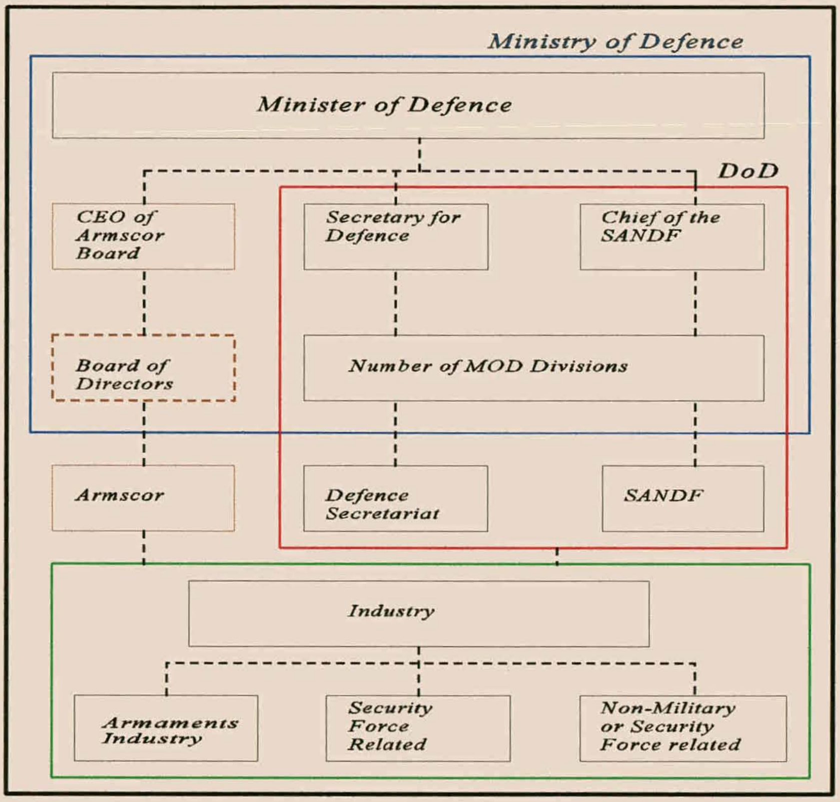
ARMSCOR's primary interfaces are with the SANDF as its main client, and with the local and foreign industry in the contracting process.

The South African defence related industries

The defence industry is contracted to do research, design, development, manufacture, testing, maintenance, support, and imports of armaments.

The marketing and export of armaments by the defence industry must be done in accordance with national policies as approved by the relevant State Departments.

The defence industry can be divided into two groups, namely the primary suppliers group and the subcontractors supplier group. The primary suppliers group comprises industries that have been accredited as suppliers with ARMSCOR and which have the necessary systems engineering and/or production capabilities and which can support complete systems or subsystems. The subcontractor supplier group mainly supplies the primary group with equipment that will be integrated into a larger system by the main contractor. The defence industry can be described as an engineering industry dealing with mechanical, aeronautical, electrical, electronic, chemical and other engineering disciplines.



Source : ARMSCOR

Figure 2.2 : The Defence environment.

Problem definition

Money as a resource has and will always determine the outcome of most decisions. One can specify systems to a high technological level but usually this level cannot be reached, primarily for money reasons and due to the unavailability of the required technologies and the temporary window of opportunity during which the required system should be developed and delivered.

If a country foresees a military threat in the near future and, depending on the kind of threat, decides that it must prepare to counter this threat by developing and producing weapon systems, money will be allocated to the defence budget so that the requirements can be met. This typical situation will possibly lead to a gradual or even steep incline in the defence budget. On the other hand, if no threat is anticipated in the near future, the defence budget will decline. Both these extremes will have an impact on the availability of the capital and operational budget for major weapon systems. Any planning model should, therefore, cover fluctuating budgets. See Figure 2.3.

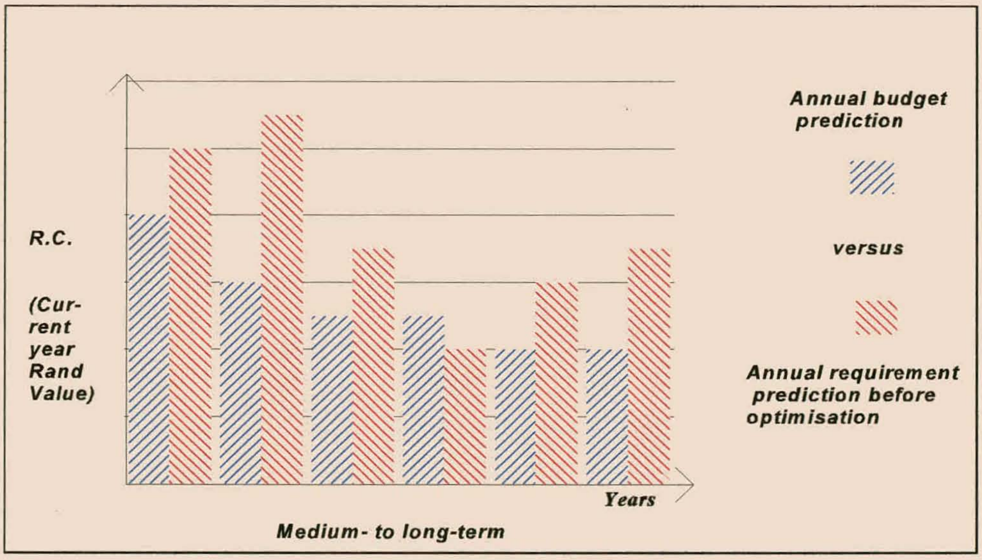


Figure 2.3 : Fluctuating budgets.

Irrespective of whether there is a threat or not, there will always be certain requirements, such as new, upgrading or replacement projects. As long as the priorities for the completion of these projects are known, these requirements must be met. It is then a question of when will it be acquired, at what cost, and will the total annual cost be equal to or less than the predicted annual budget? If there are sudden changes to any of the aforesaid, how quickly can a new schedule be generated?

A further important aspect is what human resources will be required to manage these projects? How will peak periods be managed? If future trends are not quantified in some way, will it be possible to have a strategic management process?

Finally, if it can be said that long-term planning information should be available for all parties who could be involved in the acquisition and supply of major weapon systems, what would be the necessary, sufficient and appropriate information to be used in tactical and operational planning? In this regard it would be an advantage to the defence industry to acquire long-term data, such as the number and value of projects planned for. This long-term information would be of help to industries to do proper human resources planning, as well as other planning based on the information.

As has been mentioned already, money plays an important role in every decision that is made, whether good or bad. If the information with regard to starting and finishing dates of projects is not known, how well can technologies required for a given project be planned for? Money could be wasted if the research and development (R&D) of the technology started too early. It could then rather have been allocated to other technologies where the need was much greater. How well can life-cycle costs be estimated and allocated to a specific annual expenditure if there is no long-term plan?

It is therefore clear that proper planning, with the emphasis on proper, is necessary in order to cut unnecessary costs and to assist all parties involved during the life cycle of a project, through all its phases, i.e. from the concept phase to the end of the operational phase. A scarce resource such as money, which is coupled to labour and time, must be utilized in the most cost-effective way.

Defence review

Sporadically the DoD goes through a process called the Defence Review in order to update the present and future defence situation and to determine requirements in terms of capital expenditure. By means of Project OPTIMUM, an operational research process, a force design and structure is proposed.

Long-term plans are drawn up by the Arms of Service which are synchronised at DoD level so that the requirements will not exceed the budget. Staff work is necessary in the medium and short-term in order to guide the project through its initial stages and phases.

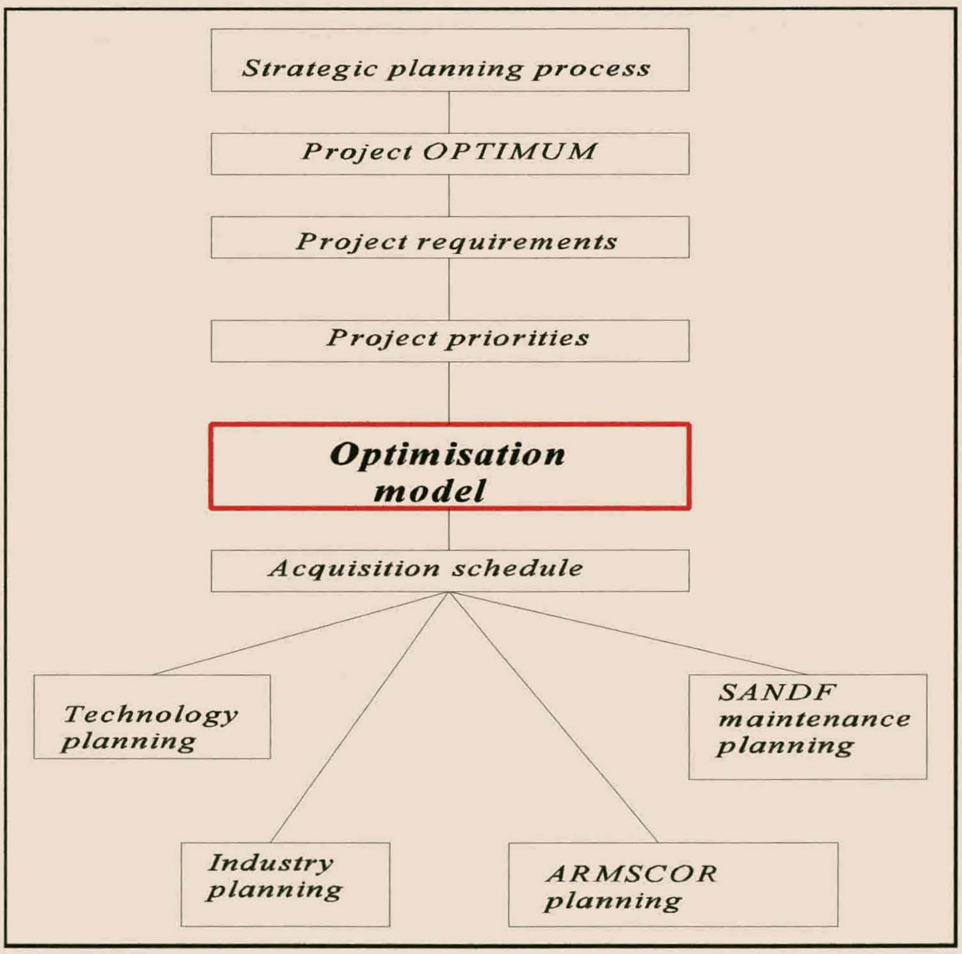


Figure 2.4 : The DoD strategic management process.

Once the staff work for these projects has been completed, financial authority can be obtained by ARMSCOR from the DoD for the execution of specific phases of the project or subproject.

Eventually contracts will be placed for all approved phases, which include phases such as concept, definition, development, production and maintenance. These contracts can be placed with local industries or foreign suppliers, depending on tender information or strategic issues.

Subproblems

The main problem, as pointed out in the foregoing, consists of many subproblems that must be solved. These include, *inter alia*:

* How can the overall situation be captured in a single model?
* How can the model incorporate all the data from all the role players at various levels?
* How can data be transformed into useful information?
* How can information be made available to the industry to ensure better long-term planning?
* How can the model provide alternative answers in the case of drastic changes?
* Can the model replace loose, unintegrated work with an integrated, automated system?
* Can the model help to save money, time and other resources?
* Can the model be a decision support model?
* Will the model be able to function at both strategic and tactical level?
* How will the current projects be incorporated?
* How will a varying budget be incorporated?
* How will a time unit of a month affect the model, instead of a time unit of one year?
* How will the time value of the rand be incorporated?
* How will the conventional phases, such as concept and definition, be re-phrased to suit for instance system integration and qualification as a separate phase so that it can be used in the model?

* What is the best way to determine an initial schedule before optimising?
* What is the best way to 'construct' a pseudo project?
* How will the actual cash flow per time unit be crashed to be as close as possible to the allocated budget per annum?
* In what way can the individual projects be amended without affecting the overall budget?
* What will a good cash flow profile be for a project?
* Under what circumstances should default values be determined?
* What are the rules to schedule the various subprojects of a project so that they fit into the main schedule of the system?
* How often and when should the model be run and updated within a financial year?
* What should the planning horizon be? (15, 20, 25, or 30 years)
* Once a long-term schedule has been determined, how many years of the beginning years should be seen as 'fixed'? (1, 2, 3 or 4 years)

These are but a few questions that need to be answered.

2.3 Conclusion

The framework within which this research takes place, is that of the Department of Defence, which is at national level. It is clear from the subproblems listed above that many issues will have to be addressed in order to arrive at a reasonable solution to a complex problem. This is seen as a challenge, however.

3. Literature

3.1 Introduction

The aim of this chapter is to present an overview of related literature. Preliminary definitions (§3.2) are given in order to understand the basics of the theory. The next step is to study similar or related literature in order to classify the research problem (§3.3). Once the research problem has been classified, possible methods of solving the problem are identified, namely exact methods or heuristics (§3.4). Finally, with the heuristic approach chosen, different heuristics, as well as non-heuristic approaches, are evaluated against the research problem in order to find further relevant information on the research problem (§3.5). This evaluation takes place in three steps, namely project scheduling heuristics in general, project scheduling non-heuristics with a money component and project scheduling heuristics with a money component. In conclusion, a summary of the literature survey is given (§3.6).

3.2 Preliminary definitions

It is necessary to present a number of definitions in order to be able to classify the research problem.

Resources

A number of researchers (Weglarz [101]1980 p160, Blaźewicz *et al* [6]1986 p2, Paterson *et al* [72]1990 p69, Boctor [9]1990 p3, Demeulemeester [23] 1992 p2, Drexl *et al* [29]1992 p307, Li *et al* [55]1992 p372, Boctor [10]1993 p2547, Sprecher [86]1993 p1, Özdamar *et al* [65]1995 p575) have classified resources as *renewable*, *non-renewable* or *doubly constrained.* Özdamar's classification of resources is as follows:

Renewable resources are constrained on a period-by-period basis. Labour as a renewable resource is used everyday but it is limited on a daily basis.

Non-renewable resources are constrained on a project basis. The total project budget becomes a non-renewable resource if the total consumption over the whole project duration is limited to a certain value.

Doubly constrained resources are simultaneously constrained on a period and project basis. Money as a resource constraint on a period-by-period basis as well as a resource constraint on the project as a whole, is seen as doubly constrained.

Preemptive vs non-preemptive resources

General definitions of preemptive and non-preemptive resources are given in the literature (e.g. Weglarz [101] 1980 p160, Blaźewicz *et al* [6] 1986 p2, Bock [8]1990 p387, Boctor [9] 1990 p4, Drexl [28] 1991 p1590, Demeulemeester *et al* [25]1992 p 1803, Boctor [10]1993 p 2547, Sprecher [86] 1993 p3). Weglarz' definitions are used , as follows:

A resource will be *preemptive* if it may be preempted, i.e. withdrawn from its current allocation, allotted to another process and then returned to the original allocated process whose performance may be continued without error.

Resource units which do not have the above property will be a *non-preemptive* resource.

Fixed, discrete, continuous and hybrid resource requirements

(Weglarz [101]1980 p161, Blaźewicz *et al* [6] 1986 p4)

The resource requirements of any activity concern numbers of resource units. *Fixed resource requirements* exist where the numbers of resource requirements are fixed. *Discrete resource* *requirements* exist where the numbers are elements of certain finite sets.

Discrete or fixed resource requirements are generally treated as renewable, e.g. machines, processors and manpower.

Continuous resource requirements exist where the numbers are arbitrary within certain intervals. Continuous resource requirements are treated as non-renewable, e.g. money or energy.

If a resource requirement simultaneously requires some resources in a discrete and others in a continuous way, the resource is identified as a *hybrid* resource requirement.

Splittable vs non-splittable activities

(Weglarz [101] 1980 p162)

A *splittable* activity can be arbitrarily interrupted at any moment unknown *a priori*. A *non-splittable* activity cannot be interrupted at all.

Dependent vs independent activities

(Weglarz [101] 1980 p162, Blaźewicz *et al* [6] 1986 p2)

No precedence constraints exist among *independent* activities. All other cases are defined as *dependent*.

Resource conflict

(Bey et al [5]1981 p39)

A *resource conflict* may be defined as a situation where two or more activities are competing for the same type of resource but the availability of that resource is insufficient for all activities.

Normal vs crash durations

(Hamacher *et al* [39] 1984 p166)

If two durations Tav_i and $Tmin_i$ exist for activity i such that $Tmin_i < Tav_i$, $Tmin_i$ and Tav_i are called the *crash* and *normal* durations for the activity. Durations for the project as a whole are analogous to durations for activities.

Slow duration

A *slow* duration $Tmax_i$ of activity i (or project as a whole) is defined where $Tmin_i \leq Tav_i \leq Tmax_i$.

Computational complexity

(Błażewicz *et al* [6]1986 p341 - 350)

An *algorithm* is any procedure solving a problem. In the case of an *optimisation problem*, it is possible to reach an *approximate (suboptimal) solution* that is feasible but does not extremise the objective function.

The *time complexity function* of the algorithm is a function that maps the number of elementary steps needed to solve the problem. This function will not be well defined unless the encoding scheme and computer model are precisely defined.

Both the encoding scheme and the computer model will have no influence on the distinction between *polynomial- and exponential-time algorithms*. A polynomial algorithm is one whose time complexity function is of the order p(k) where p is some polynomial and k is the input length of an *instance*. An instance is obtained by specifying values for all the problem parameters. Algorithms whose time complexity functions cannot be identified as polynomial, are called *exponential algorithms*.

Two classes of decision problems are identified, viz. *Class* **P** (P stands for polynomial) and *Class* **NP** (NP stand for non-deterministic polynomial). *Class* **P** consists of all decision problems that may be solved by the deterministic Turing computer machine in time bounded above by a polynomial in the input length. Class **NP** of a decision problem is defined as consisting of all decision problems that may be solved in polynomial time by a non-deterministic Turing computer. Historically, the name Turing was given to a computing device capable of solving yes-no problems.

Project makespan

(Patterson et al [72]1990 p 68)

The project's *makespan* is equivalent to its duration.

Activity modes

(Patterson et al [72]1990 p 69)

Alternative *modes* exist in which a project activity can be completed, each mode having a potentially different cost, resource requirement and duration.

Serial vs parallel heuristics

(Davis [16] 1973 p 300, Özdamar *et al* [65] 1995 p578)

A *serial heuristic* is where the activity priority is predetermined and remains fixed throughout the scheduling procedure. A *parallel heuristic* is where the activity priority is updated each time an activity is scheduled.

Project network diagrams

(Davis [46] 1973 p 297)

Two types of network diagrams are referred to. In an *activity-on-arrow* diagram, arrows denote activities and each activity originates and terminates in a unique pair of nodes called events. In an *activity-on-node* or *precedence* diagram, the role of arrows and nodes is changed. Nodes represent jobs and arrows indicate precedence.

Research problem

Throughout this dissertation the terminology *research problem* is used to identify the problem that must be solved by this research.

3.3 Problem classification

Introduction

A large number of different types of problems, each with specific characteristics, are described in the literature. It is necessary to review these different types in order to establish an information matrix of typical problems (see Table 3.1) and then to classify the research problem accordingly.

Fundamental classes

As far back as 1966, Davis [18,1966] did a survey of models where resources are allocated to *project networks*. Here follows a summary of the different types of problems.

Time-only scheduling problems

As the heading describes, time-only scheduling problems use only the time of an activity, with some precedence among the activities, to schedule the project in the shortest possible time. In this case no resources, whether constrained or unconstrained, are taken into consideration.

Problems with constrained and unconstrained resources

Three special cases of resource allocation are mentioned, namely *time/cost trade-off* in the case of unconstrained resources, *resource levelling* under resource allocation with resource constraints, and the *minimisation of project duration* under resource allocation with resource constraints.

In the case of *time/cost trade-off*, the cost of reducing project completion time is determined by allocating more resources to activities.

Once the final completion time of a project is fixed, an initial resource requirements diagram can be drawn. Usually this diagram shows a non-uniform resource loading. It is then necessary to *level* the resource diagram in order to have as close a uniform resource loading as possible.

Finally, with resource constraints, the *project completion time can be minimised.*

To summarise, Davis [18,1966] classified project network into two types, viz.

(a) time-only scheduling
(b) time scheduling and resource allocation, which can be divided into three classes, i.e.
  (i) unconstrained resources resulting in a time/cost trade-off
  (ii) constrained resources with resource levelling, and
  (iii) constrained resources with the minimisation of project duration.

Herroelen [40,1972] classified the latter three as follows:

(a) A *time/cost trade-off* problem, which consists of reducing project completion time by adding additional resources to certain activities, so that the execution of these activities may be accelerated.

(b) A *resource levelling* problem, i.e. when sufficient resources are available for the completion of the project but the resource usage is kept at a constant rate as far as possible.

(c) A *resource allocation* problem, i.e. when total resource usage is restricted to a given limit the objective may be to allocate the various resources to activities in such a way that project duration is minimised.

In 1973 Davis [16] published a second article which gave a historical review and categorisation of procedures for project scheduling under resource constraints. The three resource allocation problems as described by Davis [18,1966] and Herroelen [40,1972] are again confirmed, with the last of the three problems being classified as a *resource constrained project scheduling* problem.

The *resource constrained scheduling* problem is representative of a class of *combinatorial* problems which are characterised by a factorial growth in the amount of computation required to consider <u>all</u> possible solutions as problem size increases.

Another class of problem under the resource constraint types is the *time/resource trade-off* problem as studied by Talbot [88,1982]. Two variations of the resource constraint time/resource trade-off problem are finding a schedule of jobs that *minimises project completion time*, and determining a schedule of jobs that *minimises overall project cost.*

Demeulemeester [24, 1995] defines another class of problem, i.e. the *resource availability cost* problem. This is a problem of scarce time. If a time limit is put on the project duration, what are the least costs for required resources if resources are assumed to be available in unlimited amounts at a cost per unit of a resource type? This is close to the unconstrained resource time/cost trade-off problem where cost is minimised (Davis [18,1966], Davis [16,1973], Leachman [54, 1993] and Magott [58, 1993]).

Payment scheduling problem

A final class of problem identified is the *payment scheduling problem* as described by Icmeli *et al* [42, 1993]. Given a project described by a network, the payment scheduling problem involves identifying a schedule that maximises the present value of all transactions.

Icmeli *et al* classified project scheduling problems into three fundamental problems, namely:

(a) resource constrained project scheduling problem
(b) time/cost trade-off problem
(c) payment scheduling problem

Other possible classes of problems have also been identified, such as the *resource constrained time-resource trade-off* problem (Talbot [87, 1982]), the *resource availability cost* problem (Demeulemeester [24, 1995]), *resource constrained resource levelling* problem (Davis [18,1966], Herroelen [40,1972], Davis [16,1973], Weglarz [102,1981]), and the *time-only project scheduling* problem (Davis [18,1966], Davis [16,1973], Leachman [54,1993], Magott [58,1993]). It is furthermore evident that recent research (Icmeli *et al* [42, 1993]) in project scheduling has looked into bridging the gap between the three fundamental classes.

Hybrids of fundamental classes

Three hybrids of the fundamental classes of project scheduling are described [Icmeli *et al*], as follows:

Project scheduling with cash flow and resource restrictions

This is a combination of a net present value objective and a resource constraint project scheduling problem. Another definition is the maximisation of the net present value subject to precedence relations and resource restrictions.

Resource constrained time/cost trade-off project scheduling problem

This is equivalent to Talbot's [88, 1982] time/resource trade-off problem. Different modes can be applied to an activity which could result in different durations and resource requirements per activity. The objective could be either to minimise cost or to minimise duration. No cash flows or net present values are taken into account.

Time/cost trade-off project scheduling problem with discounted cash flows

Cash flows are known throughout the life cycle of a project. The objective function is to maximise the net present value of cash flows. Activity durations and a schedule of activity starting times are determined in order to reach the objective. Resource constraints are not taken into consideration.

Identification of type of class for research problem

Reviewing the literature with regard to the class of problem in mind, it is now possible to map through the possible classes in order to establish the typical class of the research problem.

A project is divided into a number of subprojects. Each subproject is divided into a number of phases. Each phase has a fixed money resource requirement in real terms, and a variable duration in which the phase can be completed. With each feasible duration a different monthly cash flow requirement profile exists, making it a multi-mode problem. Durations can vary between a minimum and a maximum duration. These limits are known as the crashing and slow durations respectively. An initial duration is the starting duration which is taken as the average between the crashing and slow durations and is known as the normal duration.

Owing to the existence of some kind of precedence between phases within a subproject, and between subprojects within a project, and between projects, projects are classified as dependent.

The computational complexity of the research problem is classified as class NP due to the hardness to solve for an exact solution. (See **Computational complexity** in paragraph 3.2, **Preliminary definitions.**)

The phases are considered to be non-splittable. In certain cases a subproject can be split between phases, making the subproject splittable.

The other resource available apart from time, is the budget for all projects, making it a single resource. Although the total budget is allocated on a monthly basis, it is not renewable. It can be seen as a kind of target renewable resource as reasonable deviations from money requirements below or above the target renewable resource could be negotiated.

A project's money requirement is fixed in real terms. An equal amount of money will be put aside as a budget resource for each project. This is a non-renewable resource because the total cost of the project in real terms is fixed unless the scope of work changes.

Once a project has started, it cannot be stopped unless top management makes that decision. It means that a project's money requirement, which has been put aside as a project budget resource, is non-preemptive. On the other hand, although undesirable, the total budget resource is preemptive.

Not only one project is scheduled, but a number of projects simultaneously, making it a multi-project scheduling problem.

Icmeli's [42,1993] descriptions of project scheduling problems will be used to identify the research problem according to a specific fundamental class or hybrid of fundamental classes.

The research problem is not a resource constraint project scheduling problem as the money value of cash flow is taken into consideration.

It is not a time/cost trade-off problem as the resource is not unconstrained. The minimising of cost will not work because the resource requirement (cost) is fixed in real terms. The minimising of duration will not be suitable because somewhere between the crashing and slow duration, a duration exists so that the overall objective of optimising the total requirement can be met.

It is not a payment scheduling problem because the net present value of all transactions is not maximised, nor minimised. This is even less applicable to a multi-project problem where the duration and the starting and finishing times of a phase, subproject and project are unknown.

It is not a resource constrained time/cost trade-off project scheduling problem where the value of money is not taken into consideration.

The remaining two hybrid classes are project scheduling with cash flows and resource restrictions and time/cost trade-off project scheduling problem with discounted cash flows. Both these problems determine the effect of net present value. The net present value takes into account the time value of money. Future cash flows are estimated and discounted against a required rate of return, also known as the cost of capital. This is not applicable to the research problem. Firstly, the research project is not dealt with from the viewpoint of a supplier or contractor dealing with both income and expenditure, and secondly, the cost of capital as a rate of return cannot be supplied by the Government. Thus, neither of these two hybrid classes of problems applies to the research problem, although they seem to be close to an application.

Research problem classification

In conclusion and with the previous information and definitions in mind, the research problem can be classified as follows:

An *NP multi-project scheduling problem with a single target renewable resource with time value of cash flow and budget restrictions, and precedence relations.*

Lastly, objectives to solve this problem must be identified according to the situation as it occurs in practice. A set of projects exists where all projects are listed according to predetermined priorities. It will be necessary to schedule a subset of projects, also according to the priority list, within an arbitrary chosen planning horizon. This scheduling will take place in time-corrected money terms. The **first objective** will then be to maximise the number of projects of the subset which can be scheduled within the planning horizon. Alternatively, the planning horizon (or overall makespan) may be minimised if a fixed number of projects are chosen to be scheduled. This first objective cannot be reached without a **second objective**, namely to minimise the deviations of the time-corrected value of project cash flows against the time-corrected value of an allocated budget.

These two objectives will ensure the scheduling of a number of projects resulting in a starting and finishing time for each project.

Classes

- *Fundamental classes*
  - *Time only scheduling (Davis 1966)*
  - *Payment scheduling problem (Icmeli et al* 1993)
  - Time scheduling and resource allocation (Davis 1966)
    - Unconstrained resources resulting in a time/cost trade-off problem (Davis 1966, Herroelen 1972, Icmeli et al 1993)
    - Constrained resources with resource levelling (Davis 1966, Herroellen 1972)
    - Constrained resources with minimisation of project duration (Davis 1966) also known as resource allocation (Herroelen 1972) and renamed as resource constrained project scheduling (Davis 1973)
      - Time/resource tade-off (Talbot 1982)
      - Resource availability cost (Demeulemeester 1995)
- *Hybrids of fundamental classes (Icmeli et al 1993)*
  - Project scheduling with cash flows and resource restrictions
  - Resource constraint time/cost trade-off project scheduling
  - Time/cost trade-off project scheduling problem with discounted cash flows
- *Research problem classification*
  - A multi-project scheduling problem with a single target renewable resource with time value of cash flow and budget restrictions, and with multiple objectives to solve the problem

Figure 3.1 : Summary matrix of problem classes.

3.4 Problem-solving approach

Introduction

Different approaches to solving these kinds of problems are discussed in the literature. The aim of this section is to identify the various solution approaches and to choose the approach that should be followed in solving the research problem.

Solution techniques

A number of solution techniques (Herroelen, [40, 1972]) have been used to solve specific problems generally for the resource constrained project scheduling problem. Five techniques are classified by Herroelen, namely integer programming, dynamic programming, implicit enumeration approach, bounded enumeration techniques, and heuristic programming.

Davis [16,1973] groups solution techniques into two major groups, viz. *heuristic* and *optimal* procedures. Integer and dynamic programming, implicit enumeration and bounded enumeration techniques can be regarded as optimal procedures which comprise exact mathematical solutions. Wiest [106,1967] describes a heuristic as a systematic method for solving problems based on rules of thumb and algorithms with their supporting theories. It is a method of reducing search in problem-solving in order to find a good and feasible, although not optimal, solution.

Heuristic approach

The heuristic approach will be examined, not specifically for the research problem, but for solution techniques in general.

In 1966 Davis [18] noted that available solution techniques to solve problems of class resource allocation under constraints were, for the most part, limited to heuristic procedures. He also mentioned that non-heuristic procedures were available for resource levelling problems, but that these procedures "*require very restrictive and, for the most part unrealistic, assumptions and/or are computationally prohibitive for large problems*." He stated further that the difficulty in formulating the problem mathematically could be the major reason why there were no generalised analytical solutions for the constrained resource type problems.

Wiest [106, 1967] noted that even modest sized projects had an enormous number of possible schedules and that optimal solutions for these kinds of problems were usually impossible to find. Analytical approaches such as linear programming were computationally impractical for many real problems. Other possible approaches such as heuristics had to be considered.

In 1968 Fendley [32] mentioned that analytical and iterative approaches to solve project scheduling problems of practical size had been unsuccessful and that the most successful approach in solving a scheduling problem was a heuristic approach.

In 1971 Davis [19] developed a form of bounded enumeration and established an algorithm for optimal project scheduling under multiple resource constraints. It was stated that integer linear programming formulations had existed for some years but that these proved to be both unreliable and computationally expensive in solving network scheduling problems of even very moderate size.

Two surveys of the resource constrained project scheduling problem class were conducted by Herroelen [40, 1972] and Davis [16,1973] within a year of each other. On the one hand Herroelen concluded that future research and development should be carried out on exact analytical methods and that some evaluation and objective ranking of the then available heuristic solutions would be useful. On the other hand, Davis observed that considerable progress had been made in the development of optimal procedures, but for smaller-sized problems. He continued by stating that no existing procedure could be demonstrated as a computational feasible solution for the type of large, complex projects that occurred in practice. He summarised by saying that heuristic scheduling rules giving "good" schedules had been the basis for all practical systems up to 1973 and that he had little reason to believe that the trend would change in future.

In 1975 one of the first comparisons between heuristic and optimal solutions in resource constrained project scheduling problems was made by Davis *et al* [20]. It was noted that due to the combinatorial nature of this type of problem, solution techniques of mathematical (or optimal) programming were only applicable to smaller-sized projects. Furthermore, "*because of this relative lack of success with optimisation procedures, major efforts in attacking the problem have been expended in developing heuristic procedures which produce 'good' feasible solutions.*"

In 1976 Thesen [90] presented another heuristic scheduling algorithm because "*unfortunately, at this time, optimal solutions can be found only for unrealistically small problems of marginal practical value.*" In the same year Cooper [14,1976] stated that a number of exact methods were available but that they were computationally impracticable for problems of a realistic size.

In 1981 Bey *et al* [5] recognised the importance and general acceptance of heuristic solution methods. It was noted that large commercial software packages that solve the resource constrained project scheduling problem used heuristic techniques. Three reasons for this phenomenon were given, namely (a) the difficulty of conceptualising the mathematical formulation of the problem, (b) the difficulty in solving some problems once formulated, and (c) the cost of an optimal solution for very large problems.

In 1986 Russell [81] reiterated what Davis *et al* [20] had stated in 1975, namely that the combinatorial nature of resource constrained project scheduling problems resulted in the development of many heuristic procedures.

In search for a solution to maximise the net present value of a project, Smith-Daniels *et al* [84, 1987] concluded that, given the computational size and limitations of certain mixed-integer programming codes, it would be necessary to use a heuristic approach to solve such problems. It was also mentioned that although research was being done into all areas of solution techniques to the problem, the development of heuristics should provide the most assistance to project managers in managing large projects.

In 1990 Khattab *et al* [46] stated that the basic problem in the area of project scheduling was to find a feasible schedule that minimises the project duration. However, project scheduling with resource constraints is NP-hard in obtaining an optimal solution, especially for large projects. Again a heuristic approach was followed, which proved to be computationally very efficient in obtaining consistently good solutions in reasonable computing time.

Boctor [9,1990] stated that as certain problem varieties were NP-hard and projects consisted of hundreds or thousands of activities, heuristics offered the only computationally feasible solution methods.

In 1993 Boctor [10] investigated the resource constrained project scheduling problem in a multi-mode case and found that the implicit enumeration technique presented by Talbot in 1992 could not be used to solve real-life large-scale problems. He confirmed the need for good heuristic methods.

In 1995 Ulusoy *et al* [96] found that multi-objective considerations were scarce in literature due to NP-hardness and that a solution to a problem with project duration and net present value criteria would hardly be possible. He therefore concentrated on heuristic approaches.

In one of the last surveys done on the resource constrained project scheduling problem, Özdamar *et al* [65,1995] mentions that because non-renewable resource constraints and discrete time-resource functions increase problem complexity, there is a need for developing decision rules and high-quality heuristics.

<u>To summarise the problem-solving approach</u>:

It is clear from the literature that two distinct areas of problem-solving techniques have been developed for resource constrained project scheduling type problems, namely:

(a) optimal or exact mathematical methods, and

(b) heuristics or rule of thumb methods.

It is further clear that heuristic approaches are used to find feasible solutions for very large and highly combinatorial problems and that optimal procedures are used for smaller problems where exact solutions are required.

As the research problem has been defined as Class NP to solve, large and complex, the rest of this research will be based on a **heuristic approach** and not on the different optimal methods.

3.5 Overview of literature on heuristic and certain non-heuristic approaches

Introduction

This section deals with the different approaches employed by research workers to find heuristic solutions to specific problems. Heuristics in general will be looked at first, non-heuristics with a discounted money component will be looked at next, and thereafter heuristics with a discounted component. The aim of this section is to find heuristics that can be applied to the research problem.

Project scheduling heuristics in general

One of the earliest efforts to schedule jobs of a project under resource constraints, was that of Wiest [105, 1964]. His aim was to schedule all the jobs, each with a fixed duration, subject to constraints of technological order and resource limitations, and with a view to minimising project length. According to Wiest, a critical sequence is determined by jobs having a zero slack. Slack is defined as the difference between the job's early starting and late starting times. Although certain jobs will be on the critical sequence, it could be an unfeasible solution where resource requirements exceed resource supply, with the result that completion times of these jobs would have to be extended in order to meet the resource constraints. This will in turn lead to an overall extension of the makespan. This method cannot be applied to the research problem because

(a) it is a single-mode problem, i.e. the duration of each job is fixed, whereas the research problem is a multimode problem with variable durations;

(b) it minimises the project's makespan, which is not necessarily optimal or near optimal for the research problem. The research problem is a multiproject problem and each project can be completed between a minimum and maximum duration. This means that the duration that should be used to present an optimal or near optimal solution is unknown. It may be any duration between the upper and lower duration limits.

One of the first efforts to schedule a multiproject problem was that of Fendley [32,1968]. He defined the problem with a systems approach as follows:

> **"A multiproject scheduling system consists of a series of procedures for the allocation of scarce resources to the activities at the appropriate point in time such that the projects are completed by their due dates (or as close to the due dates as possible)."**

This statement by Fendley does apply to the research problem. The concept of assigning due dates to incoming projects and then sequencing the activities of the projects towards meeting those due dates is a total system approach to the multiproject scheduling problem. The next point which is of importance, is the necessity of a priority decision rule to rank the waiting activities. Although it is stated that it is desirable to complete each project as economically as possible and that due dates should be assigned to enable economical operation, no methods have been described where the money aspect is taken into consideration. Nevertheless, the aspect of a priority decision rule to rank the waiting projects will be used in the problem solution.

In Fendley's case, only a single-mode analysis was done by simulating the activity duration by means of a beta distribution [Fendley, 32, p508]. Previous completion times obtained from a PERT analysis were used as the initial completion times of the projects under consideration. By adding resource constraints, these completion dates must be extended in order to meet the resource requirements, resulting in a same type of problem by minimising completion time. This is proven by the result of the experiment to find the best priority rule which can reduce project slippage, thus minimising the completion time. These objectives do not fit the research problem. The heuristic rule which was used was to minimise job slack.

Gonguet [35,1969] presents different procedures to schedule jobs. These procedures furnish a left-justified schedule, i.e. each job is scheduled as early as possible. One of the procedures which gives reasonably good results has as its objective to minimise project duration. It mechanistically schedules any job that is furthest from the end of the project and also allocates resources to this job. This approach will not suit the research problem as such as a mechanistic justified operation does not necessarily give an optimal or near optimal solution to the research problem. The author mentioned that none of the procedures tested really gave good results. The basic rule that was used, was to minimise late finishing time.

In 1975 Davis [17] compared a number of heuristic rules and found that only three give good results, namely minimum job slack, minimum late finish time, and the resource scheduling method (RSM). All three methods aim to minimise total duration. The RSM allocates resources to the activity that will contribute least towards an increase in project duration.

Woodworth [107,1975] presents one of the first heuristic algorithms for resource levelling in multiproject, multiresource scheduling. Although no aspects with regard to the time value of money are discussed, it is assumed that the most level resource profile would approach the minimum least-cost schedule, which is not necessarily true for the research problem. Two principles used by Woodworth could also be used in solving the research problem:

(a) the levelling methodology, where the principle of the sum-of-the-squares is used, and
(b) the left and right shift of activities.

Thesen [90,1976] describes a heuristic to solve a resource constrained scheduling problem. Although good results are claimed, the author suggests that further research will be necessary to improve the performance of the algorithm. Two of the assumptions in the problem setting differ from the research problem, namely

(a) each activity has a known duration, and
(b) each activity should have a constant resource level assignment.

Another aspect where the algorithm produces unwanted results for the research problem, is the question of an *urgency factor*. The urgency factor is used during run time to determine which activities should be scheduled first. This is in contrast with the research problem where priorities of projects in a multiproject environment are given prior to any optimisation and all activities within all projects have to follow this initial prioritising.

Cooper [14,1976] presents heuristic methods with a view to minimising the project duration. Once again, this objective does not necessarily give an optimal or near optimal solution to the research problem. The aspect that can contribute to solving the research problem, is the aspect of *priority rule*. The job with the maximum priority is selected for scheduling. Cooper investigated a total of twenty-six priority rules. About five of these have been found to be useful and one could be described as the best, namely the priority rule which has least float per successor. This means to schedule the activity that has the least float (spare time or leeway).

Patterson [68,1976] found that for minimising project makespan, two heuristics would be sufficient, viz. minimise total float and minimise late finish time. This approach, i.e. minimising project makespan, will not be used to find solutions for the research problem.

Kurtulus *et al* [51,1982] investigated a number of heuristic rules in order to find good rules to solve a multiproject resource constrained scheduling problem. Two aspects which do not concur with the research problem are the objective of minimising total project delay, in other words minimising project makespan, and the fact that all projects must start at the same point in time. This is an unrealistic constraint as projects in a multiproject environment should start at any point as long as they can meet the requirements subject to constraints. Kurtulus acknowledges that very little research has been published on rules developed for a multiproject problem.

Dumond *et al* [31,1988] presented one of the first papers which identified the dynamic scope of multiproject scheduling problems. The dynamic situation occurs when due dates have been assigned to projects and suddenly a number of new projects enter the arena, resulting in new due dates. Whether static or dynamic, Dumond minimises the project completion times. This approach will not solve the research problem.

Ulusoy *et al* [94,1989] considers non-preemptive scheduling of activities in a project network with the objective of minimising project duration under limited resource constraints. The method that was used minimises project makespan without considering any discounted money component, and will therefore not contribute to the solution of the research problem.

Bock *et al* [8,1990] investigates preemption heuristics for the multiproject scheduling problem. It is assumed that the research problem is a non-preemptive problem. Two performance measures are used, a *mean absolute lateness* and a *mean weighted lateness*.

A new heuristic to solve a scheduling problem with a single resource constraint was introduced by Khattab *et al* [46,1990]. Again it minimises project duration without taking into account any discounted money considerations. Other aspects that differ from the research problem is the fact that all activity durations are known and constant, and that only one project is considered.

Bell *et al* [3,1991] propose a new heuristic algorithm for making the required sequencing decisions so as to minimise the increase in project duration, subject to given resource and precedence constraints. This objective of minimising the increase in project duration is in conflict with the research problem. Increasing the project's duration could be acceptable for the research problem but would depend on the overall situation and not only on a single project.

Jaafari [45,1996] presents a time and priority allocation scheduling technique for projects. A point made by Jaafari is that single duration assignment to an activity is not realistic and that a more realistic approach would be to treat an activity duration as an unknown which fluctuates within a specified range. This aspect will be applied to the research problem.

The remaining part of this section identifies another way of using heuristics, namely in a tandem or multi-heuristic approach. This approach allows consecutive calculations with a number of heuristics in order to find a better solution for the problem. The possibility of using the tandem or multi-heuristic approach will be investigated during the problem solution phase of the research project.

> Boctor [9,1990] presented a paper in which hybrid or multi-heuristics are analysed in a minimising project delay problem. It was found that a combination of three heuristics had a relatively high probability of giving the best and even the optimum solution. Khattab *et al* [47,1991] presented a paper with the following objectives: to develop new priority rules, to propose a new heuristic procedure for single-resource constrained project scheduling while minimising the project duration, and to identify performance measures for comparing the new heuristic and priority rules. This paper confirmed previous statements that a combination of more heuristics gave better results. Another paper by Boctor [10,1993] described heuristics in solving non-preemptive resource constrained project scheduling problems in a multi-mode. Boctor identifies the problem of determining when each activity should begin and in which duration mode it should be used to minimise project duration. The research problem will benefit from the objective to find the starting (as well as finishing) time of activities subject to the duration mode of the activity. Boctor also introduces the term *heuristic tandems,* which is analogous to heuristic combinations as mentioned earlier. Another important aspect is that resource consumption is assumed

to be uniformly distributed. In the research problem, the resource consumption (money) may take any profile.

To summarise project scheduling heuristics in general:

This section of the literature study investigated heuristics in general. None of the heuristics as discussed in this section touched on the aspect of discounted money. This aspect will be evaluated in a later section under **Project scheduling heuristics with a money component**.

Not one of the heuristics discussed in this section can be used as a complete and effective solution to the research problem. Most of them minimised the project duration under resource constraints. Some of the principles will however be evaluated in order to assess the applicability to a solution, namely

(i) ranking the waiting projects by means of a priority decision rule,
(ii) left or right justified scheduling,
(iii) left or right shift of activities,
(iv) the levelling methodology where the principle of the sum-of-the squares is used, and
(v) the use of tandem or multi-heuristics.

Project scheduling non-heuristics with a money component

This section aims to look for possible contributions to the solution of the research problem. No non-heuristic in this case will be used as a complete and effective solution to the research problem. The next section will cover the aspect of project scheduling heuristics with a money component.

Russell [80,1970] presents linear and non-linear programming techniques to solve a maximising present value problem. This means that the tendency will exist to shift all the activities as close as possible to the start of a project. The research problem, however, is from a client's point of view where money is put aside and where the maximum number of projects should be completed within a long-term makespan with the best technological solutions. Although money is invested, no return on investment can be measured, apart from technological usage. Therefore, maximising present value is not applicable to the research problem. One aspect that can be investigated is the calculation of a cost per time unit of lengthening or shortening the duration of an activity. According to Russell, cash is treated like any other resource, except that if unused it can be carried over to the next time interval. This principle that cash can be carried over to the next time interval also applies to the research problem. Once activities have been scheduled, all costs are aggregated, producing a profile of costs incurred against time which, is also known as a *cumulative cost curve*. Russel's approach will further not be suitable for solving the research problem as fixed durations are allocated to activities. This is in conflict with the research problem where the duration of activities can range between a minimum and a maximum duration, irrespective of penalty or bonus clauses. Moreover, Russell uses one discount rate, which could be the internal rate of return of the organisation. This will be difficult to determine in the case of the research problem as different rates apply, such as the growth rate of the budget allocation, inflation rates and exchange rates.

Doersch *et al* [27, 1977] present a zero-one programming approach to solve a scheduling problem with a view to maximising its present value. As has been explained already, maximising the present value will not be suitable for solving the research problem. One aspect that can be investigated, however, is the application of a penalty (bonus) clause for late completion (early completion), although in the research problem a penalty or bonus clause will have a different meaning. As mentioned earlier, a range of durations will apply to activities. If the average duration of the activity is chosen as the mode in which it must be completed, a bonus clause could be linked to that choice, eventually converting into a penalty clause as the choice of completion moves closer to the extreme points, i.e. the minimum or maximum duration. If for instance the extreme maximum duration is chosen, the possibility of aging technology exists, thus resulting in a strict penalty clause. A penalty clause will also apply if an extreme minimum duration is chosen because the execution cost to complete the activity will increase significantly. For the research problem it is therefore necessary to define the minimum and maximum durations of an activity, which are not the extreme minimum and maximum durations, as reasonable and feasible durations. These will be durations that will not induce any penalty or bonus clauses.

Valadares-Tavares [99,1987] developed a dynamic programming model to simulate optimal resource profiles for programme scheduling by means of maximising net present value. In the model he defined a *programme* as interconnected *projects* where activities in normal use relate to an elementary job. In the case of a programme, activities are defined as *subprojects*. Although the objective function of maximising net present value conflicts with the research problem, the principle of a sequential relation between the projects within a programme will apply. In the case of the research problem phases will be completed sequentially but with the possibility of a time lag between the phases.

In Smith-Daniels *et al* [84,1987] it is maintained that "**the vast majority of methodologies presented in the literature have ignored the financial aspects of project management**". In conclusion Smith-Daniels point out that the development of heuristics should provide the most assistance to project managers in managing large projects. Their model once again maximises the net present value of cash flows over the course of the project, which is in conflict with the research problem.

Integer programming algorithms by Patterson *et al* [72,1990] and Yang [108,1993], a branch and bound procedure by Icmeli *et al* [43,1996], and a general purpose integer programme were introduced to solve problems where the objective is to maximise net present value. Again, the problem of maximising the net present value does not contribute to the solution of the research problem.

<u>To summarise project scheduling non-heuristics with a money component</u>:

A few articles cover the field of non-heuristic solving of problems with a money component. All of them maximise the net present value of the project. This can only apply to situations as described in the literature, namely where an organisation invests an amount of money at the beginning of the project (negative cash flow) and where net positive income is received in later stages of the project.

If only negative cash flows exist, as viewed by the client, minimising the net present value of the project will cause all the projects to start as late as possible, i.e. shifted towards the end of the planning horizon or total makespan. This is unacceptable for the research problem as all projects should be scheduled in such a way that the deviation of the cash flow around the allocated budget is a minimum. This aspect will be discussed further in the next section.

Aspects that will be investigated are:

- the lengthening or shortening of a duration of an activity, and
- that the cash flow is treated as a resource and if unused can be carried over to the next time interval.

Project scheduling heuristics with a money component

This section will look at heuristic solutions to project scheduling problems with a money component. The aim is to find contributions for solving the research problem.

Back in 1967 Wiest [106] developed a heuristic model for scheduling large projects with limited resources. The aim was to find a schedule of job starting times and resource assignments that satisfied the constraints and minimised schedule related project cost. The solution routine consists of a group of scheduling rules which determines the starting time of each job as well as the resources allocated to the job. The basic approach is to allocate available resources serially and period by period in the order of their starting times. Jobs are scheduled in such a way that the critical jobs will be scheduled first. One of the main reasons why this approach cannot be used to solve the research problem is that the time value of the cost equations is not taken into account. Furthermore, it is not shown how these costs fit in with an overall period-by-period budget.

Single duration for activities is used, which conflicts with the previously proposed use of a range of durations per activity (multi-mode).

The impact of the net present value criterion on project scheduling has been described by Bey *et al* [5,1981]. A very important factor mentioned, is from which viewpoint the scheduling should be done. If it is from the point of view of a supplier, scheduling to complete the project as soon as possible will be an advantage in order to maximise the net present value. On the other hand, if it is from the point of view of the client, scheduling to complete the project as late as possible could be an advantage. Neither of these two approaches can be used to solve the research problem. The single-mode operation chosen, i.e. one period of duration for an activity, is also not suitable for solving the research problem. Although it is claimed that the net present value criterion always yields a solution and that this criterion is regarded to be a superior rule and should be adopted for project scheduling, this cannot be true for the research problem for reasons already stated.

In 1986 Russell [81] compared a number of heuristics for scheduling projects with cash flows and resource restrictions. Apart from the fact that the objective was to maximise the net present value of the project, Russell proved that none of the heuristics tested performed best on all problems.

Smith-Daniels *et al* [83, 1987] show that by using a heuristic scheduling rule of *late-start* (right-shifted) instead of the previous attempts of *early-start* (left-shifted), a better result is obtained for a problem where the objective is to maximise the net present value subject to resource constraints. Although the objective of maximising net present value is not suitable for the research problem, both the right-shifted and left-shifted scheduling rules will be investigated.

Padman *et al* [67,1993] investigated eight heuristics in a resource constrained project scheduling problem with a view to maximising the net present value which is again not suitable for the research problem.

The Local Constrained Based Analysis (LCBA) of Özdamar and Ulusoy has been described in a number of articles [Ulusoy *et al*, 95, 1994], [Ulusoy *et al*, 96, 1995], [Ulusoy *et al*, 97, 1996], [Özdamar *et al*, 64, 1994]. Basically, three heuristic rules (minimum slack time, minimum late finish time and weighted resource utilisation and precedence (WRUP)) are used together with a decision process (LCBA) . It was further mentioned in the articles that the LCBA proves to be better than single heuristics in that the results show a lower percentage deviation from the optimum result. According to Ulusoy *et al* [96, 1995] the two objectives, namely minimising makespan and maximising net present value, contradict each other. The first one schedules the activities as early as possible while the latter schedules the activities as late as possible in order to postpone cash outflows. This statement is not true in all cases. If an activity has a small cash flow at the beginning and a large cash flow at the end, then surely to schedule this activity as early as possible would increase the net present value. Each activity should thus be considered individually to see whether it contributes to the optimising objective or not.

<u>To summarise project scheduling heuristics with a money component:</u>

There have been few articles on scheduling problems with a monetary objective under resource constraints. The objective of most, if not all of them, is to maximise the net present value. As mentioned before, this will cause all scheduling to start and end as early as possible. If from a clients point of view the net present value is minimised, then all scheduling will start and end as late as possible. Neither of these two objectives can apply to the research problem as the time-corrected values of the cash flows of a number of projects should be optimised around the allocated budget.

One aspect that will be investigated is the principle of right or left shifting of activities.

3.6 Summary of literature survey

The literature survey on the **problem-solving approach** has shown that two types of problem-solving techniques have been developed, namely exact mathematical and heuristic methods. A heuristic approach has been chosen to solve the research problem, which has been classified as a Class NP problem due to its size and combinatorial nature.

The survey on **heuristics in general** identified a number of principles that can be used to solve the research problem, for example the ranking of waiting projects by means of a priority decision rule, left or right justified scheduling, left or right shifting of activities, the levelling methodology where the principle of the sum-of-the squares is used, and finally, the use of multi-heuristics.

The survey on **project scheduling non-heuristics and heuristics with a money component** identified the current approach of many researchers to solve project scheduling with a money component. If the viewpoint is that of a supplier where money will be invested prior to any return on the investment, the objective that was used in all the literature cases studied was to maximise the net present value of all projects that had to be scheduled. If the viewpoint is that of a client where only negative (expenditure) cash flow exists, the objective was to minimise the net present value of the projects which had to be scheduled. In the first case the tendency will be to start and finish all projects or activities as early as possible, whereas in the latter case all projects or activities will be scheduled to end at the latest possible time and within the shortest duration.

This approach of either maximising or minimising the net present value is not acceptable as a possible solution for the research project. For the research project the starting and finishing times for each project of the subset of projects that has to be scheduled, are unknown and it will therefore be necessary to schedule all projects so that the accumulated time-corrected cash flow for all projects is close to that of the time-corrected allocated budget.

Additional aspects that will be used for the solution of the research problem are the lengthening or shortening of the duration of an activity, and that cash flow is treated as a resource and if unused can be carried over to the next time interval.

Although the South African Department of Defence was taken as reference in the development of a solution for the research problem, no specific literature was found during the literature survey that could relate to other defence environments.

Finally, the research problem is classed as follows:

The research problem is a class NP multiproject scheduling problem with a single target renewable resource with time value of cash flow and budget restrictions, and precedence relations, and will need multiple objectives to be solved, namely

(i) minimise the overall makespan in which a number of chosen projects must be scheduled, and

(ii) minimise the deviations of the time-corrected value of cash flows against the time-corrected value of the budget.

4. Support for problem solution

4.1 Introduction

This chapter describes theories and principles to support a solution for the research problem. The aim is to identify and to define the necessary parameters that will be used in later chapters to develop a mathematical solution.

Aspects covered are finances and economics that characterise the research problem, a breakdown of the project into conventional acquisition phases with certain amendments, and general information such as the size of the problem, the handling of existing and future projects, and also what information will be needed to determine the impact of a chosen schedule on various factors.

Primary functions are given, placing the development of the theory inside the required frame of reference.

The conclusions at the end of the chapter summarise some of the findings. All the above building blocks, when eventually integrated into a single model, will produce a system approach solution to the research problem.

In order to understand the theory development in the next chapter, it is necessary to define two problem levels, namely a **macro** and **micro** level. The macro level may be seen as a government department corporate (strategic) level, whereas the micro level is seen as the project (tactical) level. The practical execution of a project is seen as the operational level, which is not covered by this dissertation.

4.2 Finances and economics

Introduction

This section covers the finances and economics at macro level. Budget, inflation and exchange rates will be dealt with under economics while cash flows and project cash flow profiles will be dealt with under finances. Cash flows refer to the overall cash flow of all projects during the current financial year while the project cash flow profile refers to the predicted cash flow of an individual project.

Economics

Nominal *versus* real values (Samuelson, [82] 1995, p248)

In order to understand what is meant by nominal and real values in the research problem, the definition of nominal and real interest may be taken as example:

The nominal interest rate is the interest rate on money in terms of money, whereas the real interest rate is corrected for inflation. In the case of small values for inflation and interest rates, the real interest rate is calculated as the nominal interest rate minus the rate of inflation. The exact calculation of real interest rate is (1 + real interest rate) = (1 + nominal interest rate)/(1 + inflation rate) which results in real interest rate = (nominal interest rate - inflation rate)/(1 + inflation rate).

Both the terms *nominal* and *real* are used in the research problem. Annual plans are drafted in terms of real values, while it will be seen later on in this dissertation that the near optimal optimisation takes place in nominal values.

Budget

The Department of Defence is allocated an annual budget, according to which its salary, operational and capital expenditure must be planned. Final planning takes place in the year preceding the actual spending. Short term (following year 1), medium term (2 to 3 years) and long term (4 to up to 20 years) planning are based on the predicted annual budget. Budget over the years is presented in year 0 money terms, i.e. in real terms.

The budget under consideration in the research problem is that part of the capital budget which is allocated to acquire major weapon systems. The capital budget currently includes both capital for weapon systems and capital for computers, office furniture, etc. On an annual basis, this budget grows at a compound rate which is different to the local inflation rate. This growth can be seen as an additional allocation of funds by the Government to the Department of Defence within a current financial year. A financial year runs from 1 April to 31 March of the following year. It is important to note that the growth rate of the budget is not the same as the growth rate of the project's cost. If it were the same, it would not be a problem to optimise in real terms. The fact is, they are seldom the same. Furthermore, inflation rates applicable to a project may differ from other projects because different suppliers from different countries may be involved.

These differences in local and foreign inflation rates, the growth rate of the overall budget, and the fluctuations in the rates of exchange make it difficult to so schedule projects that the total summation of their respective cash flows will be close to that of the allocated budget.

Figure 4.1 briefly describes what happens during the capital planning process. If a long-term plan for major acquisition projects is established with real values of the budget and requirements, the requirement is more or less equal to the budget (top graph). However, as the growth rate of the budget differs from that of the requirements (currently it is less than the growth rate of the requirements), there will be a shortage of funds in the next year already, as can be seen in the middle graph. This shortage will continue to escalate until the end of, say, a twenty-year period. It will be explained in the following chapters how to optimise in nominal terms so that the adjusted requirement in real terms is less than the allocated budget in order to make provision for these escalating costs.

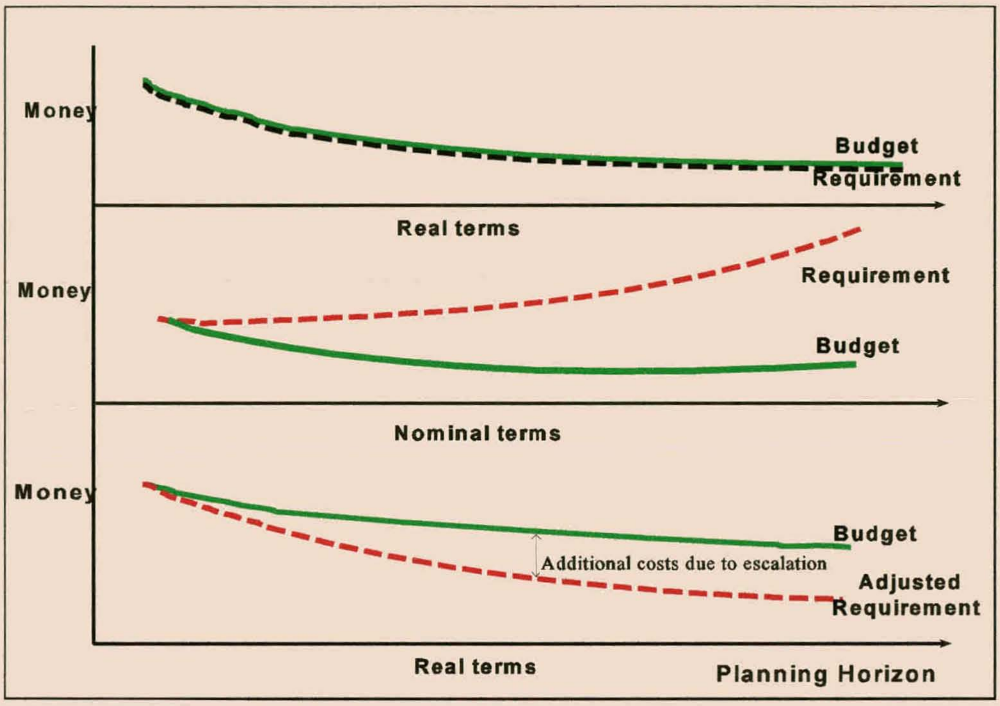


Figure 4.1 : Nominal *versus* real values of budget and requirement.

Cumulative budget

A cumulative budget can be either in nominal or in real terms and is defined as the summation of all annual budgets to the end of the planning horizon.

Cumulative cash flow

A cumulative cash flow can be either in nominal or in real terms and is defined as the summation of cash flows of all projects under consideration up to the end of the planning horizon. Cash flows are defined as the expected annual or monthly cash flows of all the projects. If the cumulative budget is presented in nominal terms, then the cumulative cash flow must be presented in nominal terms.

Cumulative cash flow target

The cumulative nominal budget up to the end of the planning horizon is regarded as a cumulative cash flow target. The objective will be to schedule existing and new projects in such a way that their cumulative cash flow is close to the cumulative cash flow target.

Inflation rates

Major weapon systems can be acquired from local or foreign suppliers. Each country has its own predicted annual inflation rate. These inflation rates play an important role in that project estimates can escalate annually depending on the inflation rate of the supplier country.

It is important to note that, due to differences in budget growth and project escalation due to inflation, planning should be done in nominal terms in order to find a near optimal solution between the budget and the estimated expenditure. This means that once a near optimal schedule is chosen, the cumulative cash flow will be close to the cumulative cash flow target, i.e. the budget.

Exchange rates

The exchange rates between the local supplier country and foreign supplier countries are of importance in solving the research problem. If changes in exchange rates are not taken into account, money shortages will occur, especially if the local country's currency weakens against that of foreign supplier countries over the years. In the same way a surplus in money will occur if the currency becomes stronger. In such a case more projects could have been scheduled for completion during the planning horizon, within the available budget.

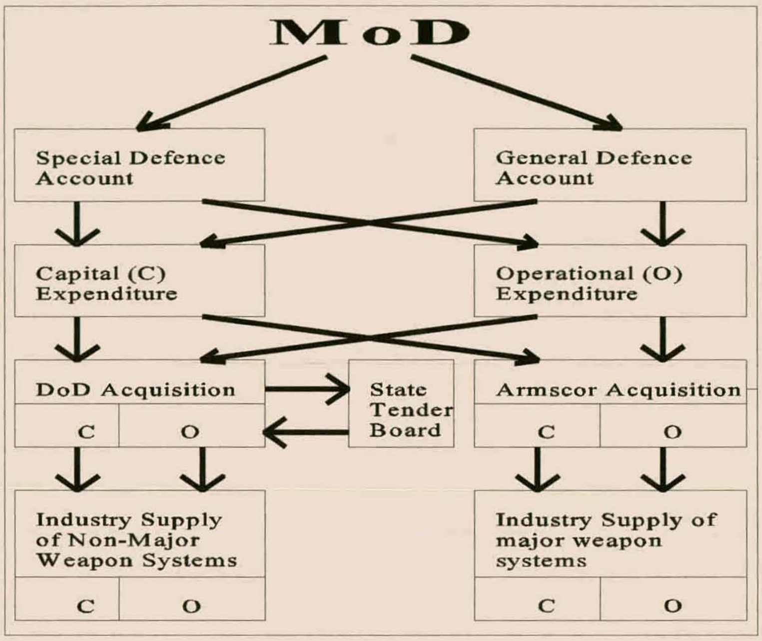


Figure 4.2: Defence accounts.

Finances

Accounts

Two financial accounts are used within the DoD, namely the Special Defence Account and the General Defence Account. Both capital and operational expenditure is funded out of these accounts. Two organisations function as tender boards, namely the State Tender Board and the ARMSCOR tender board. The State Tender Board is primarily used to acquire operational supplies while the ARMSCOR tender board is primarily there to acquire weapon systems. For the purpose of this research, the acquisition of major weapon systems through the ARMSCOR tender board will be the modus operandi. See Figure 4.2 for a layout of the two accounts.

Annual and monthly cash flows

Cash flow is considered to be the annual or monthly expenditure on major weapon systems. The total cash flow of all projects should be balanced with the budget allocated for capital expenditure on major weapon systems. The budget will be the target cash flow. In order to compare the budget and the expenditure, both should be presented in nominal terms.

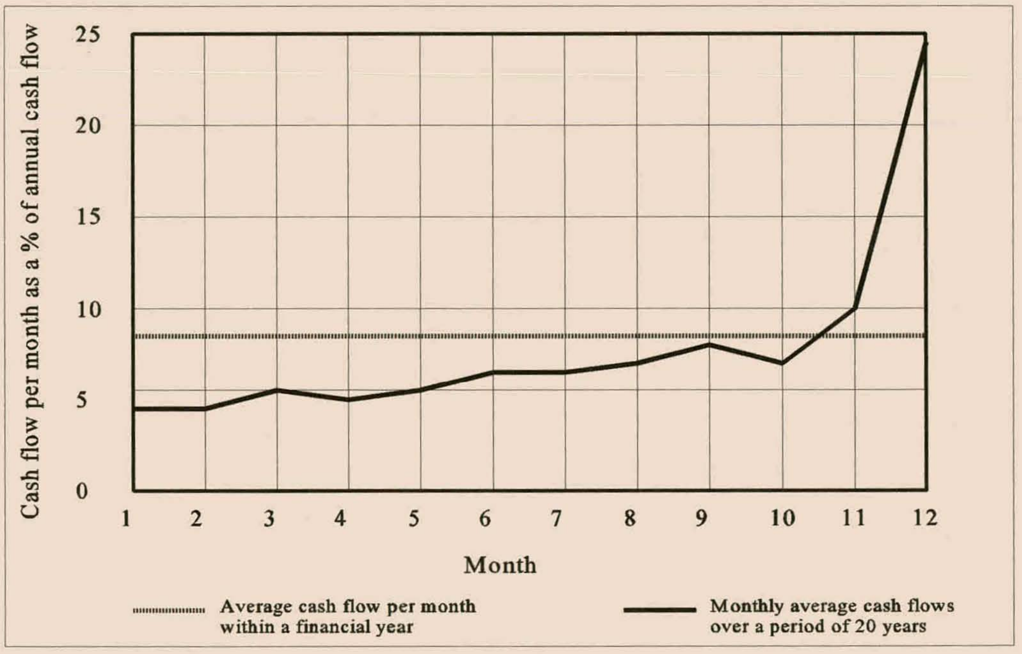


Figure 4.3 : Average monthly cash flows (%) within a financial year.

Within a financial year one could simulate the monthly budget based on the allocated nominal annual budget. Data gathered on the monthly cash flow profile over 20 years shows that initial expenditure is below that of the average monthly expenditure, while there is a sharp increase above the average monthly expenditure over the last few months. It can be seen from Figure 4.3 that the

Source : ARMSCOR

Financial year	Month											
	April	May	June	July	August	September	October	November	December	January	February	March
1977/78	0.6	2.2	4.8	3.6	7.2	8.0	8.8	10.0	9.4	11.6	14.7	19.1
1978/79	0.9	2.9	3.9	4.2	6.7	7.8	9.0	10.5	10.2	12.0	12.8	10.1
1979/80	1.1	1.8	3.6	4.1	5.2	6.3	7.4	8.4	9.1	10.1	20.5	22.4
1980/81	1.6	2.2	3.9	4.3	5.6	6.7	7.8	8.7	8.9	10.6	18.9	20.8
1981/82	1.8	2.4	4.0	4.7	5.1	5.7	7.3	9.4	8.2	14.6	17.5	19.3
1982/83	1.3	2.2	5.2	6.3	6.8	8.7	7.8	9.4	6.8	7.3	16.7	21.5
1983/84	3.5	5.0	7.6	5.3	6.7	8.7	7.2	9.4	8.5	4.9	8.9	24.3
1984/85	6.9	5.9	5.3	4.9	6.1	6.2	6.3	8.6	6.1	7.3	10.5	26.0
1985/86	3.0	4.6	10.7	6.4	7.4	6.3	3.5	6.7	12.8	7.5	8.2	22.6
1986/87	3.5	6.7	5.3	7.0	6.0	8.8	7.2	7.2	8.5	4.6	7.4	27.9
1987/88	2.7	5.6	4.7	5.6	4.4	4.8	8.2	7.2	6.2	5.3	8.2	37.1
1988/89	0.6	4.6	3.6	2.5	7.0	5.6	9.5	5.9	8.8	6.2	8.5	37.1
1989/90	5.6	6.9	7.0	7.3	5.4	6.2	4.7	5.5	6.3	5.2	6.1	33.7
1990/91	10.3	12.0	5.2	5.3	6.3	7.1	5.1	3.9	4.9	4.8	6.6	28.3
1991/92	0.0	12.3	9.7	8.8	5.3	7.4	6.3	4.8	6.0	4.9	6.2	28.3
1992/93	12.2	3.3	10.6	3.7	5.6	3.2	8.2	4.8	6.6	4.7	8.1	29.1
1993/94	16.0	5.9	5.4	4.0	4.5	6.0	5.2	6.1	8.2	8.4	7.6	22.7
1994/95	16.6	6.1	4.6	5.2	4.7	4.9	4.7	8.1	10.0	6.3	7.0	21.9
1995/96	8.1	3.6	4.9	5.1	6.6	6.7	6.3	5.0	11.6	4.7	8.3	29.0
1996/97	5.6	5.4	4.1	5.9	5.7	9.8	6.8	6.8	10.2	6.7	8.2	24.8
Average	4.8	4.8	5.4	5.0	5.6	6.4	6.5	7.0	8.0	7.0	10.0	24.5

Table 4.1 : Monthly percentage cash flow per annum from 1977/78 to 1996/97.

initial cash flow is about 50% to 60% of the average monthly cash flow and that the cash flow increases to high values at around the 10th to 12th months. This is a typical example of the "hockey stick" effect. Figure 4.3 is derived from Table 4.1. Note that the monthly percentages in a financial year add up to 100%. This could have negative or positive implications, depending on which side of the problem is viewed. If one could reason that the technological requirements will be met within a financial year, then, from the client's point of view, it would be good practice to delay payments until the last month of a financial year.

Should there be other reasons for not wanting to pay out huge amounts over the last few months of a financial year, then a more equal monthly cash flow distribution will be required.

These two viewpoints necessitate a formula that could simulate monthly cash flow within a financial year subject to certain input values. For this purpose a modified Gompertz curve is chosen.

Gompertz curve (Spiegel, M.R., [85],1972, page 218)

The modified Gompertz curve is represented by

$$R_m = p\, q^{b^m} \qquad \text{...(4.1)}$$

where R_m = monthly cash flow, which could be presented as a percentage of the total annual cash flow

p, q and b = constants

m = time unit in months.

The following parameters, which are known, may be defined as follows (see Figure 4.4):

I = average intensity, i.e. average monthly percentage cash flow, which is per definition 100% / 12 = 8.33 %

η_g = the fraction which the first monthly cash flow is below or above the average, with $-1 \leq \eta_g < 1$

m_e = the time in which it is expected that the curve (R_m) will be equal to the average intensity

It will eventually be shown that by changing η_g and m_e, the monthly percentage cash flow can be simulated in almost any required way, but based on the Gompertz curve.

Firstly, the constants p, q and b will be determined, assuming that the period over which the modified Gompertz curve will apply is 12 months. Another assumption is that the time axis will be in months and discrete.

If m = 1 then

$R_m = (1-\eta_g)\, I$

thus

$$pq^b = (1-\eta_g)\, I \qquad \text{...(4.2)}$$

If $m = m_e$ then

$R_m = I$

thus

$$p\, q^{b^{m_e}} = I \qquad \text{...(4.3)}$$

But over the 12-month period, the summation of the curve values is

$$\sum_{m=1}^{12} p\, q^{b^m} = 12\, I$$

$$p \sum_{m=1}^{12} q^{b^m} = 12\, I \qquad \text{...(4.4)}$$

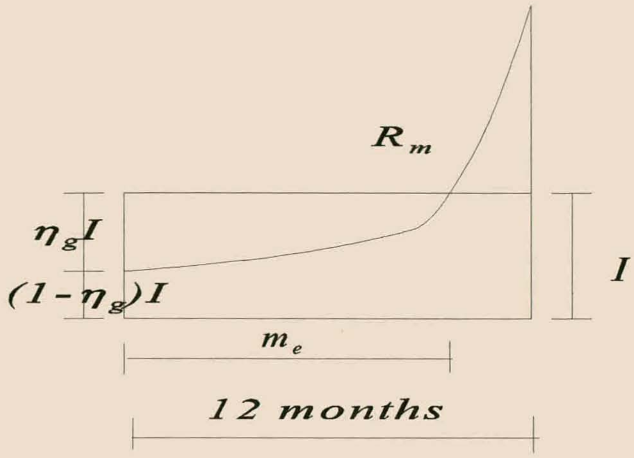


Figure 4.4: Gompertz application.

Thus, given three equations with three unknowns, solve the equations to determine constants p, q and b.

From 4.2

$$p = \frac{(1 - \eta_g)\, I}{q^{b}} \qquad \text{...(4.5)}$$

Substitute 4.5 in 4.3 and simplify

$$\frac{1}{(1 - \eta_g)} = q^{b^{m_e} - b} \qquad \text{...(4.6)}$$

Substitute 4.5 in 4.4 and simplify

$$\frac{12}{(1 - \eta_g)} = \sum_{m=1}^{12} q^{b^{m} - b} \qquad \text{...(4.7)}$$

From 4.6

$$q = \left[\frac{1}{(1 - \eta_g)}\right]^{\frac{1}{b^{m_e} - b}} \qquad ...(4.8)$$

Substitute 4.8 in 4.7 and simplify, resulting in

$$\frac{12}{(1-\eta_g)} = \sum_{m=1}^{12} \left[\frac{1}{(1-\eta_g)}\right]^{\frac{b^m - b}{b^{m_e} - b}} \qquad ...(4.9)$$

With $-1 \leq \eta_g < 1$, $\eta_g \in \mathbb{R}$ and

$b^{m_e} - b \neq 0$

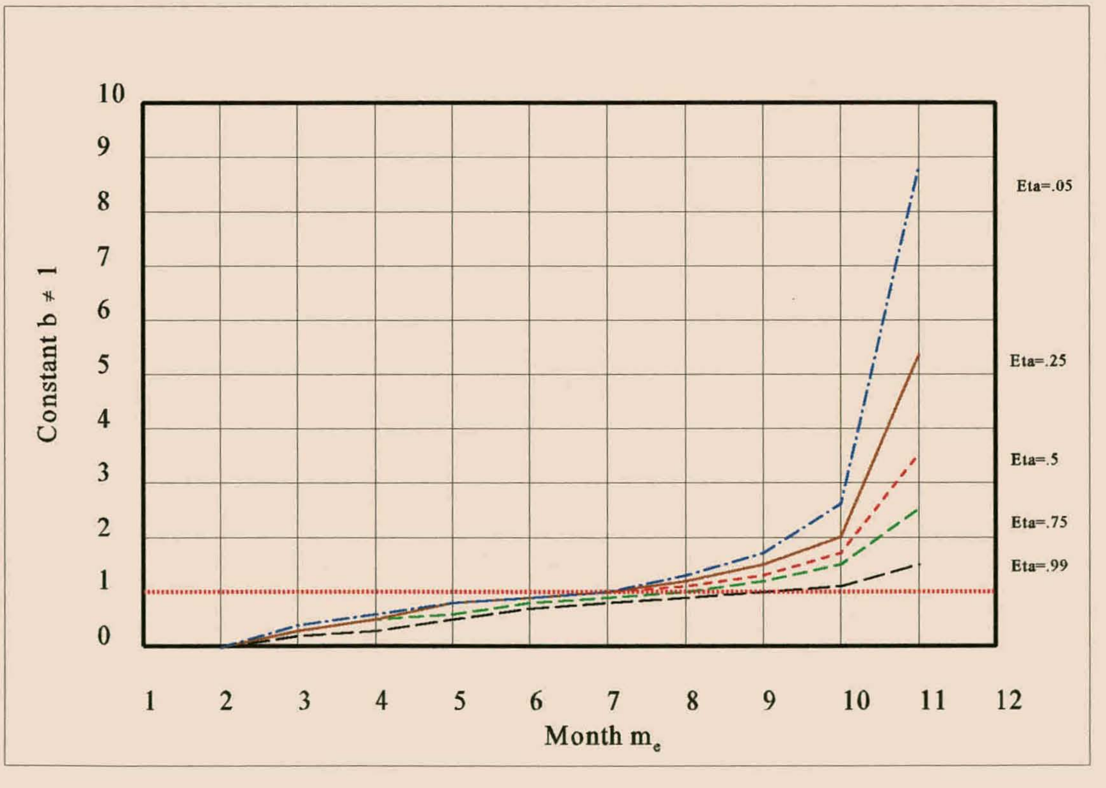


Figure 4.5: Behaviour of constant b of Gompertz formula.

requiring $b \neq 0$, $b \neq 1$, and $m_e \neq 1$. (See Appendix A for deduction.)

Equation 4.9 is solved with a numerical solution as it is difficult to solve it with an exact method. Figure 4.5 shows values for b depending on m_e and η_g, and which were calculated according to the algorithm in Appendix B.

Once b has been calculated, substitute in equation 4.8 to determine q. Substitute b and q in equation 4.5 to determine p. With all constants known, calculate the monthly percentage cash flow.

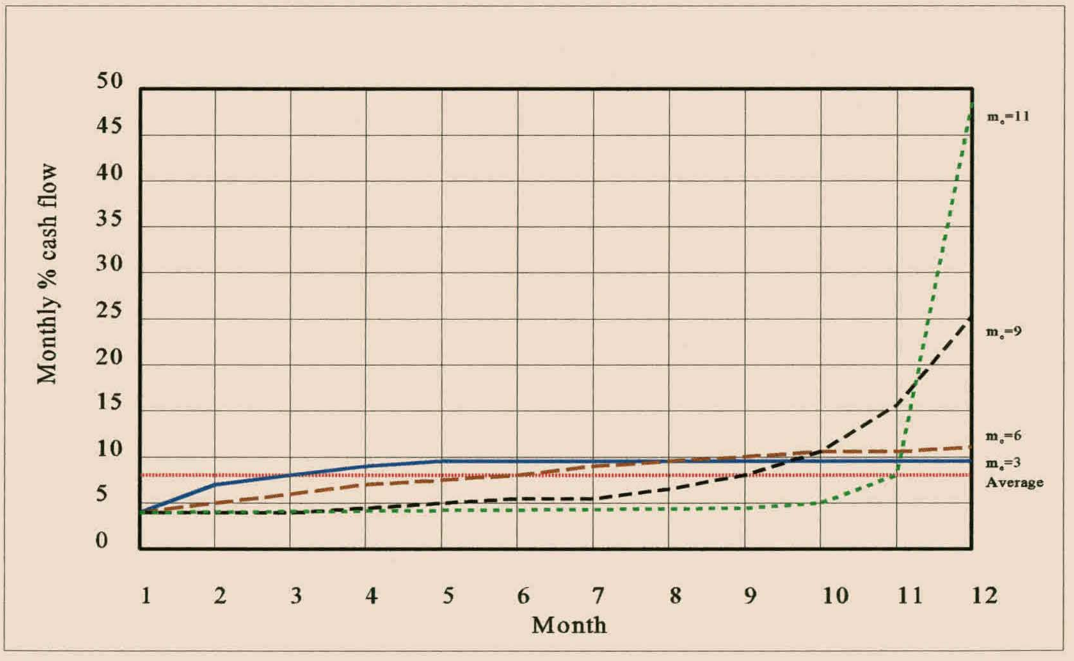


Figure 4.6 : Gompertz monthly % cash flows in different profiles with $\eta_g = .5$.

Figure 4.6 shows the monthly percentage cash flows within a financial year with $\eta_g = .5$ and $m_e \in \{3,6,9,11\}$. It is clear from Figure 4.6 that different monthly cash flows during a financial year can be simulated from the modified Gompertz curve.

The Gompertz modification can therefore be used to simulate the monthly cash flows within a financial year for a number of years. The simulation can be either a percentage or actual money terms. Each subsequent year may have different simulated monthly cash flow curves.

A hockey stick effect is found when $m_e = 11$ and when $\eta_g = .5$. Whenever $\eta_g \rightarrow 0$ and $m_e \rightarrow 0$, the hockey stick effect will be replaced by a more uniform monthly cash flow profile. Thus, by having a trade-off between m_e and η_g, different monthly cash flows can be simulated (see Figure 4.6). This is a valuable tool in that a required annual cash flow can be simulated and gradually be changed from, for example, an undesired hockey stick to a more acceptable, closer to uniform profile.

This tool can also be used to change the annual budget into a monthly budget. Projects can be scheduled in such a way that the summation of the cash flows of all projects can be close to the simulated monthly cash flow budget. See Figure 4.7 for an example where the in-year monthly simulated budget is shown, starting with a hockey stick and ending with a profile closer to a uniform cash flow.

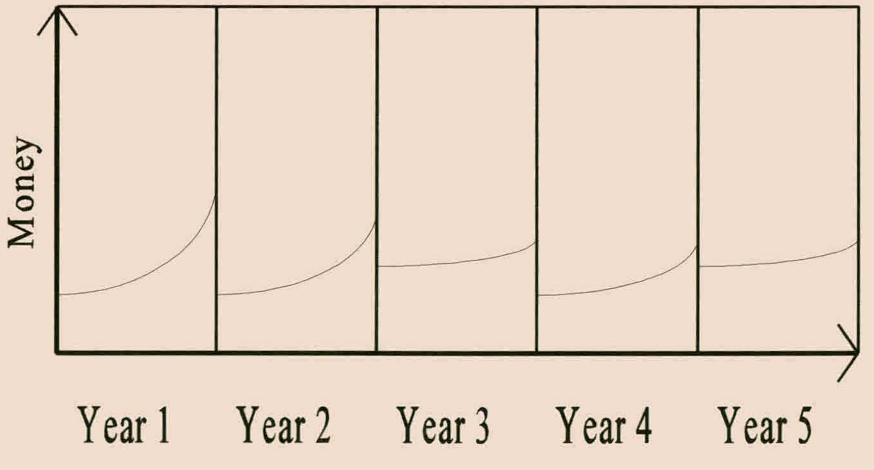


Figure 4.7 : Monthly budget presentation with Gompertz.

Project cash flow or eta(η) profiles

Introduction

The previous paragraph showed how the available budget can be simulated as a monthly budget over a number of years. This paragraph deals with the aspect of how to simulate the expenditure of a project as a cash flow profile and the aim is to develop standard cash flow profiles from which a specific profile can be allocated to a project.

Each project will have its own identified cash flow profile over a certain period. It will be very difficult to schedule individual projects if this profile is unknown. Different projects will each absorb a different amount of the budget at different times due to the different project cash flow profiles. The profile will simulate the project's cash flow in real money terms. It must be noted that the project cash flow profiles are not the same as the Gompertz cash flow profile for the available budget, which was described in the previous section.

The basic cash flow profile is the uniform cash flow profile, simulating a constant cash flow over the project's makespan. The uniform cash flow profile is determined by dividing the total real cash flow of the project by the normal duration of the project. The initial normal duration of a project is equivalent to the initial average duration of the project. It is further necessary to define the average cash flow of a project as the project's cash flow intensity.

The next cash flow profile to be defined is the straight line profile, which is determined from the formula of a parabola, i.e. $f_t = \alpha t^2 + \beta t + \gamma$ but with $\alpha = 0$ resulting in $f_t = \beta t + \gamma$ and with α, β and γ as constants which are determined from the boundary conditions.

Similar to the straight line profile, three other cash flow profiles are determined from $f_t = \alpha t^2 + \beta t + \gamma$, namely (i) a semi-parabolic curve with a zero slope at the end, (ii) a semi-parabolic profile with a zero slope at the beginning, and (iii) a parabolic curve with a zero slope at the middle of the project's makespan. (See Figure 4.8 for examples of the different profiles.)

Another factor which is needed in determining a cash flow profile of a project is the eta or η value, which is analogous to the η_g of the Gompertz curve for the budget simulation but not the same.

Eta (η) value

Eta or η is a factor used to define the intensity of cash flow at the beginning of each project. If $\eta = 0$, cash flow will follow the uniform distribution, while $\eta = 1$ describes a steep slope of intensity. A positive η defines a general positive slope while a negative η defines a general negative slope. This means that, irrespective of the cash flow profile that will be determined for a project, the uniform profile must be available.

Theory development of eta cash flow profiles

This paragraph gives a brief overview of the theory of how to determine the different cash flow profiles. The detailed development of the theory is shown in Appendix C.

The following steps apply:

Step 1: Assume a parabolic function $f_t = \alpha t^2 + \beta t + \gamma$ with α, β, and γ as constants. If a uniform profile must be simulated, $\alpha = \beta = 0$. If a straight line must be simulated, then $\alpha = 0$.

Step 2: Calculate the constants depending on the boundary conditions. A maximum of three equations will have to be determined in order to solve for these constants. Two of the required equations are determined from boundary conditions while the third one is determined due to the fact that the summation of discrete cash flow values for each time unit must be equal to the total amount of cash flow of the project. For this third equation a number of series must be established. (See Appendix C.)

Step 3: Once the three equations have been determined, they are solved for the constants, thus ending with a calculable cash flow function f_t. This is analogous to R_m, the simulated cash flow of the monthly budget, but not the same. Depending on the boundary conditions, different cash flow profiles can be determined.

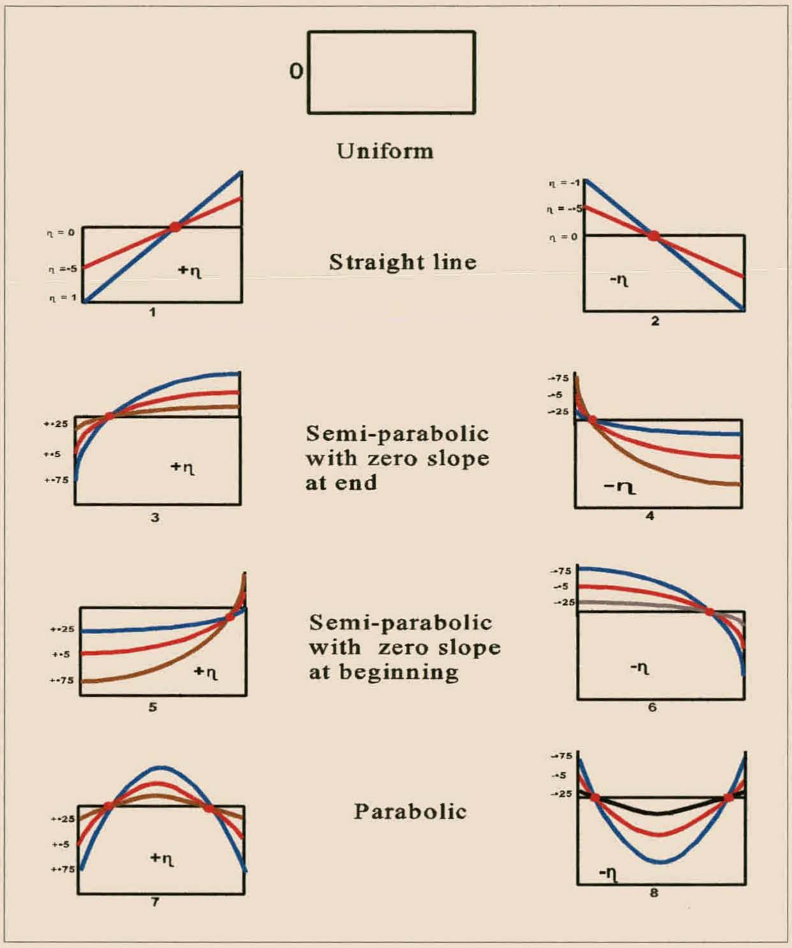


Figure 4.8: Summary of eta profiles (not cumulative).

Summary of eta cash flow profiles

Four additional cash flow profiles have been developed apart from the basic uniform profile. Eta can be either positive or negative. The bigger eta is, the steeper the average slope of the cash flow profile will be. These profiles will be used to simulate each project's cash flow profile, which in turn will be used to determine the overall cash flow per annum of all projects. See Figure 4.8 for a summary of all eta profiles with different positive and negative eta values. Note that a change in sign for eta from positive to negative results in a mirror image around the average intensity of a project.

Another aspect which is important is that the original cash flow profile is determined in real money terms. The next chapter will explain how the real cash flow profile will be converted into a nominal cash flow profile so that it can be used in determining a near optimal solution. This is an improvement on the uniform profile as discussed by Boctor [10,1993] in that other profiles have been introduced.

4.3 Project breakdown

Introduction

This and the following paragraphs cover the detail at micro level (i.e. at project level), requiring information from the project management level.

As before, the total acquisition is broken down into a number of projects. Each project, which is seen as the acquisition of a major weapon system, is divided into a number of major subprojects. Each subproject is acquired over a number of phases. These phases are executed in a sequential order. The maintenance phase is excluded from the research problem as it is not funded by capital funds. The aim of these last paragraphs is to define the necessary input which is required from the programme management level.

Summary of conventional acquisition phases (ARMSCOR document [2] 1994)

Introduction

The following paragraphs give a brief summary of the conventional phases currently being used during the acquisition process. The objective is to give a short overview before defining the phases for the research problem. The sequence in which these conventional acquisition phases will be executed is: concept, definition, development, industrialization and production phase.

Concept phase

Before the concept phase of a project at ARMSCOR's level can be started, the statement of requirements baseline (SRBL) should be completed and approved. This SRBL contains a memorandum of agreement between the role players and a preliminary acquisition plan.

A project study is undertaken to investigate all possible solutions in terms of the functional requirements. The purpose of the project study is to find the most effective solution to the requirement, to develop functional performance requirements, and to document this solution by means of an A-specification according to the relevant military standards.

A project study report is prepared by the client (user) of the proposed system and is a summary of the results of the project study.

The end of the concept phase is the approval of the functional baseline (FBL). The FBL document summarises the output from the project study and project study report.

Definition phase

This phase starts after the approval of the FBL. It entails a system study (SS) and includes a development study (DS), which is an analysis of how configuration items will be dealt with, which organisations will be involved, what the interfaces and integration needs will be, milestones, timescales and funds needed. The output of the DS is incorporated into a development plan (DP) prepared by the client.

Performance requirements are allocated and documented in a B-specification. A system design review (SDR) is carried out before B-specifications are finalised.

The end of the definition phase is marked by the approval of an allocated baseline (ABL). The ABL describes the requirements that must be met by the respective elements of the system during the development phase.

Development phase

The development phase starts when the ABL has been attained and approval has been given for the DP.

An acquisition study (AS) is undertaken to further define the selected product system as reflected in the A and B-specifications. This entails the development of the C (product), D (process) and E (material) specifications. Before the C, D and E-specifications are finalised, a critical design review (CDR) is conducted to ensure that the detail design for all configuration items complies with the specifications and integrate with each other.

During this phase the development models, i.e. the experimental development model (XDM), the advanced development model (ADM), and the engineering development model (EDM), are manufactured, tested and evaluated against the specifications and then modified where necessary. Technical test and evaluation (TT&E) results are prepared at product system level. The product is qualified in terms of form, fit and function.

Based on the AS, an acquisition plan (AP) is drawn up by the client, which is basically a summary of the AS. This plan covers, *inter alia*, the project management requirements, technical requirements, logistic requirements, financial requirements, and timescales. The development plan terminates when the product baseline (PBL) has been attained.

It is important to have experienced system engineers available during the concept, definition and development phases to specify the technical aspects of the project in order to allow proper costing by the programme management team. The programme management team comprises representatives from the SANDF, ARMSCOR and industry.

Industrialisation phase

The industrialisation phase starts when the PBL is approved. The objective of the industrialisation phase is to develop and qualify manufacturing processes. This includes the production line, process control and quality control. A number of pre-production models (PPMs) are built for the industrialisation, after which the manufacturing process is improved and documented. A preliminary operational test and evaluation is carried out on pre-production models and the product system is qualified against the A-specification and ultimately the SRBL.

The industrialisation phase terminates with the approval of the manufacturing baseline (MBL).

Manufacturing (production) phase

Once the MBL has been approved, manufacturing of the product system can begin.

Research problem phases

For the research problem certain phases are grouped together and other phases are added to the conventional phases in order to have more detailed information available to do an impact analysis. These phases are grouped into scheduling sectors, which may be described as follows:

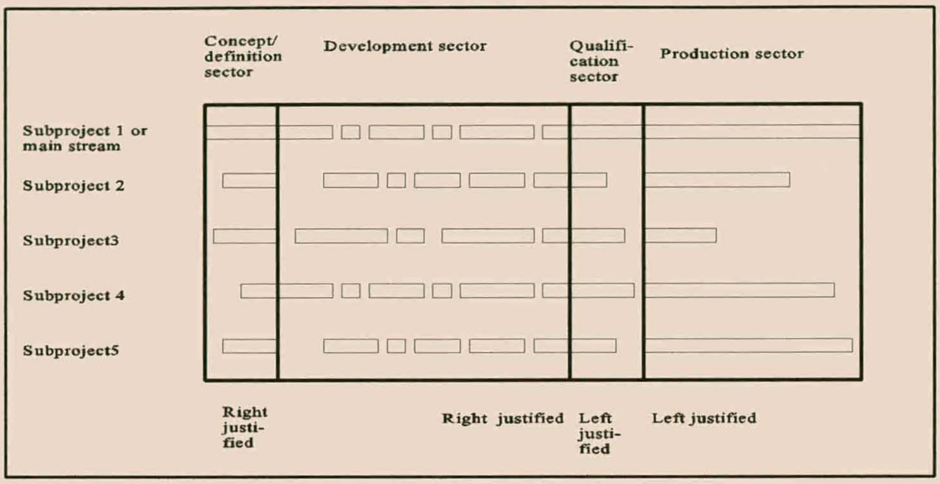


Figure 4.9 : Scheduling sectors.

Scheduling sectors (see Figure 4.9)

Four scheduling sectors have been identified for the research problem, each of which will be described and motivated in the following paragraphs.

<u>Concept/ definition - sector 1</u>

The concept and definition phases will be combined into one practical phase, namely the concept/definition phase, because of the low financial and time impact of the concept phase on its own. Usually these two phases also require the same type of human resources. The same work must still be done as described under the individual concept and definition phases.

<u>Development - sector 2</u>

The development sector is identical to that of the conventional development phase except that it is split between the various development models, with a phase to test and evaluate, and one to qualify the model or product. The qualification phase will form part of the next sector, namely the system test and evaluation and qualification sector 3. The phases of the development sector 2 are:

- *experimental development model (XDM) phase*
- *XDM test and evaluation (TE) phase*
- *advanced development model (ADM) phase*
- *ADM TE phase*
- *engineering development model (EDM) phase*
- *EDM TE phase.*

The abovementioned research problem phases will run consecutively, i.e. in series. In practice there could be an overlap of work when one phase is slowing down while the next phase is building up. For practical reasons therefore the individual phases of scheduling sector 2 should run consecutively. It will not be necessary to consider all phases in sector 2. Only phases that will apply to a specific subproject may be selected.

System test and evaluation (TE) and qualification (Q) - sector 3

This sector can only start once the development sector 2 has been completed and the products of the various subprojects have been qualified and are ready for integration into a complete system. Usually production is not allowed to continue unless the product system is qualified. Starting to prepare for industrialisation (or pre-production) without any approved financial backup poses a risk for the industry. Yet this risk could be worthwhile in order to ensure that certain production lines do not stop completely. It is for this reason that a certain amount of work under the conventional industrialisation phase will be carried out under the system test and evaluation and qualification sector 3 of the research problem. The next sector, namely the production sector, can be used to add certain parts of the pre-production work not covered under this sector.

Production - sector 4

This is the final sector and can only start once the qualification sector has been completed. It also means that all the test and evaluation and qualification phases of all subprojects must be completed.

Summary of scheduling sectors and phases

This is a slight deviation from the conventional description of phases, namely concept, definition, development, which includes ADM, ADM and EDM, and production. Test and evaluation have been defined for each of the XDM, ADM and EDM phases, as well as a final system test and evaluation and qualification phase.

The reason for including the test and evaluation phase is to be able to use this kind of information to eventually determine the impact of all test and evaluation on the testing facilities. Each and every subproject must have its own test and evaluation, and finally its qualification completed before all subprojects can be tested and evaluated as an integrated system, and then be qualified as a system ready for production.

The scheduling method will be introduced in the next chapter.

Phase technical information

Introduction

This information is necessary in order to build the model and to find a near optimal solution to the research problem. All the different parameters necessary to run the model are described in the next paragraphs.

The three most important parameters are phase money value, and a minimum and a maximum duration for the phase. These three parameters provide the optimisation model with the minimum of information in order to find a near optimal solution.

Money value

The money value of the phase represents an estimate of the total cost of the phase if the phase is completed in normal duration. The total estimated cost of the phase is assumed to be constant apart from escalation costs such as inflation and changes in exchange rates. The money value of the phase stays constant until such a time when the scope of the phase (project) has been changed formally and the cost is either reduced or increased. It is represented in either local or foreign currency and in real money terms.

Minimum duration

The minimum duration is the estimated minimum duration in months in which a phase will be completed, *without changing the cost estimate of the phase.*

Maximum duration

The maximum duration is the estimated maximum duration in months in which a phase will be completed, *without changing the estimate cost of the phase.*

Final duration

There is a final duration which is between the minimum and the maximum durations of the phase. Any final duration is a feasible duration as it is assumed that it does not affect the estimated cost of the phase.

Local and foreign contracts

Another aspect that is considered is whether a project (or phase) should be contracted to a local or a foreign organisation. A decision will be made whether the work of the subproject must be done locally or by a foreign supplier. Three important factors must be taken into consideration in this regard:

Inflation

When optimising in nominal money terms, inflation of the local supplier country or that of a foreign supplier country will have an impact on the nominal cost of the phase. Thus, by considering the inflation rate, it can be ascertained what each country's impact will be on the solution to the research problem due to inflation.

Currency

The phase value can be given either in local or in foreign currency. Any currency can be used and it is not necessary to use the currency of the supplier's country. A supplier could be a country such as Italy, but the currency could be in United States dollars (USD). When optimising in nominal terms, the differences due to weakening or strengthening of the local currency against the foreign currencies concerned are taken into account.

Import costs

Taxes and other duties are levied on imports and these can make up a high percentage of the total cost. These costs will have to be converted to local currency and in nominal terms. It is assumed that these costs form part of the phase estimated value previously described.

4.4 Size of the problem

The problem as a whole may consist of a very high number of calculations which have to be done to arrive at a feasible and near optimal solution. This paragraph substantiates the search for a heuristic solution to the research problem and describes the various levels of the solution which will be developed in the following chapters.

Total acquisition	Level 0
└Project	Level 1
└Subproject	Level 2
└**Phase** (within a scheduling sector)	Level 3
├Armscor function	Level 4
├Programme manager resources	Level 5
└Quality assurance resources	Level 5
├Organisation loading	Level 4
└Countertrade	Level 4

Figure 4.10 : The complexity of the environment.

Assume that there are 10 projects; each project has 3 subprojects (or subsystems) and each subproject has 3 phases in the development sector 2. Each phase can be completed in 3 modes, i.e. each phase has 3 possible durations in which the phase must be completed. Then the total number of possible combinations is $((3^3)^3)^{10} = 8.728E42$.

The real life problem is much bigger, however. With 100 projects, each with a maximum of 5 subprojects, each with a maximum of 9 phases, with the concept/definition phase seen as one phase, and, say, 5 possible durations each, the total number of combinations could rise to $((5)^9)^5)^{100}$, which is a very large number. This makes it very difficult to solve indeed.

This gives an idea of the size of a "three level" problem, i.e. if only phases, subprojects and projects are considered. It becomes much worse if a fourth or even fifth level is added, i.e. if two impact levels are added to the problem. Level 4 could be specific organisations associated with the phase, and level 5 could be personnel resources at a organisation. The number of combinations then will tend towards infinity.

4.5 Project priorities

The assumption is made that project priorities are seen as the order of precedence in which the production of the projects must be completed. In other words, a higher priority means production completion first and not start of project first. For future research, different meanings for project priorities could be investigated, for example that priority of one project over another project could be based on the starting time of the project as a whole or on the starting time of the production phase. See Figure 4.11 for priorities. It can be seen from Figure 4.11 that even if project 2 has a higher priority than project 3, project 3 could start before project 2. This is based on the assumption that completion of the production determines the priority rule.

Priorities are not determined dynamically by the research problem (Cooper, [14] 1976) but are given by higher authority. This research aims to determine the total impact of a set of priorities and then to negotiate a change in a set of priorities in order to get an impact that is more acceptable to all role players. Sensitivity analysis can be prepared in order to show different impact scenarios for different priorities.

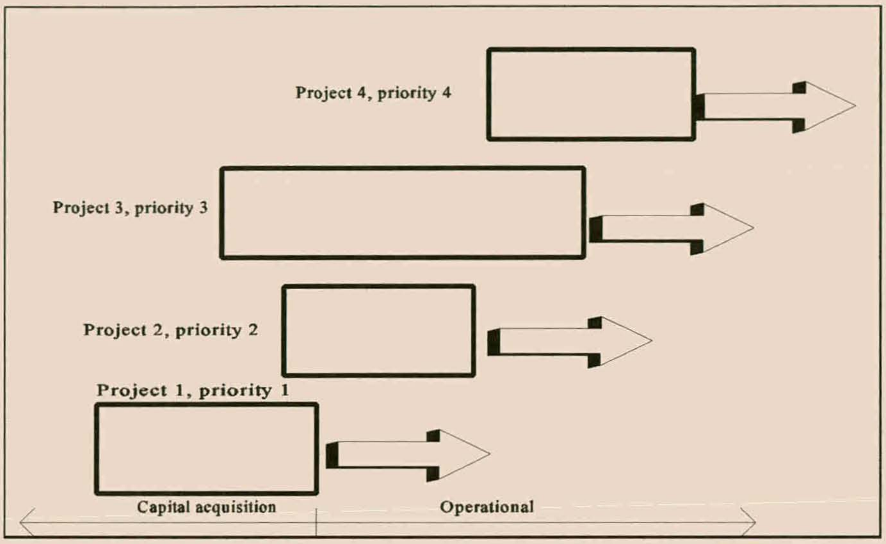


Figure 4.11 : Project priorities.

4.6 Existing versus future projects

Another aspect is what precedence existing projects have over future projects when considering the available budget that must be allocated to the various projects. Projects are seen as non-preemptive, i.e. once started it is desirable to complete them without any interruption or with the minimum of delay. Owing to this requirement, a certain amount of the annual budget must be made available to complete the scheduled phases of an existing project before allocating any amounts of the budget to future projects.

Existing projects are defined as those projects that have already started. The earliest start of the outstanding work of these projects must start at year one and will not be allowed to start in any other year but year one. This confirms the non-preemptive rule. Future projects are projects which have not yet started and which can be scheduled to start in any year.

4.7 Impact information

Introduction

This information is initially required in order to determine the impact on various aspects which will not form part of the process of finding a near optimal solution to the research problem. Impacts will only be determined once the near optimal schedule has been obtained. A sensitivity analysis will be conducted in order to simulate different scenarios and to show their impact on various parameters. Any changes to the initial data will be negotiated with the client in order to contain the various impacts within reasonable limits that will be acceptable to both the client and the major group of suppliers. The following paragraphs describe the various parameters on which an impact analysis will be based.

Engineering function

An engineering function is defined as an organisational function of an acquisition agency, structured to execute its part of the acquisition process on behalf of the Department of Defence. In general, acquisition will form the corporate function, dealing with the acquisition of major weapon systems and having specific functions that support the corporate function. Such functions are, for example, aircraft, vehicles, telecommunications, ships, radar, electronic warfare, etc. which are equivalent to the organisational divisions within a functional department, namely that of acquisition. Any number of engineering functions can be identified for the model with the view to evaluating the impact of an optimised schedule on these functions.

Local industry

Impact analysis on the local industry due to a near optimal schedule can be determined for every major organisation that forms part of the local defence industry. Organisations can be either a group of subsidiaries or individual business units, depending on the level of impact analysis.

Foreign countries

Only the foreign country which is envisaged to supply the Department of Defence with major weapon systems will be specified, and not individual organisations within that country. The reason is that foreign supplier countries do not form part of the local defence industry and therefore do not require an impact analysis.

Countertrade

Countertrade, or industrial participation, plays an important role. Countertrade can be subdivided into direct, indirect and commercial or non-military countertrade.

<u>Direct</u>

For all foreign contracts, direct countertrade implies foreign expenditure on local organisations for supplies directly into the project/subproject.

<u>Indirect</u>

Indirect countertrade implies foreign expenditure on local organisations for supplies not directly built into the project/subproject, or for supplies to other related projects/subprojects not originally ordered.

<u>Commercial</u>

This implies foreign expenditure on local suppliers but not for direct or indirect defence supplies.

It is important to identify the direct and indirect countertrade part of a contract as this provides additional knowledge of the impact on, for example, the local industry.

Human resources defaults

Functional

It is necessary to determine the human resources impact for programme managers (PM) and quality assurance (QA) officials for each engineering function. As previously defined, a function is also related to a division within the acquisition agency. Other areas of human resources impact in the industry can be determined, for example the relative number of system engineers or artisans required within an organisation. The impact on the industry's human resources will not be dealt with in this dissertation. See Figure 4.12 for examples of impact on ARMSCOR.

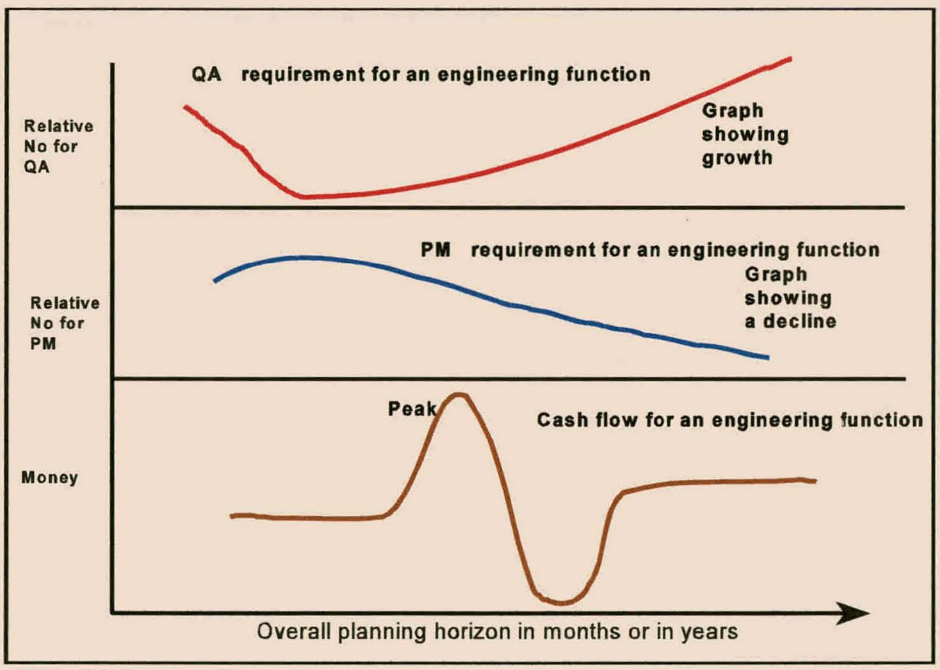


Figure 4.12 : Examples of impact on ARMSCOR.

In order to determine a human resources impact, default values are determined of the human resources required per phase and per function or organisation. These default values could be changed as changes occur any time during the execution of projects within a division. At least one update per annum will be necessary in order to allow for the effect of the local inflation rate on the default values each year.

Table 4.2 shows an example of a default table. These values can be calibrated until the model provides a reasonable human resources schedule. The first line of the table shows the average value of each identified phase in the acquisition process. This average amount is an amount given by a division as a sort of expected average value of all projects currently handled by the division. The division further estimates the average duration of each phase for all the projects managed by the division, which is shown in the second line of the table. The third line is determined by dividing the average amount of a phase by the average duration (in months) of the same phase. The fourth and fifth lines are also provided by the division and show the expected number of human resources required per month in terms of programme management and quality assurance.

When any phase is scheduled, the money value (cash flow profile) and the duration in which the phase will be completed will be known. The relative number of personnel necessary to complete the phase can be determined by making use of the default table of a function. The impact analysis with regard to the human resources requirement will for instance show the monthly human resources requirement for the overall planning horizon. Extreme human resources requirements will be identified from the results. Negotiations will take place between the client and other role players in order to change initial data so as to improve the human resources situation if it is not acceptable to the role players. (Refer to Figure 4.12.)

Every division must have its own default values because each division is dealing with a specific project in a unique divisional culture. The default cannot be generalised for the whole of ARMSCOR. Each and every division has a certain way in which its work is executed.

Default amounts in millions of money units:	Concept/ Definition	XDM	XDM T&E	ADM	ADM T&E	EDM	EDM T&E	System quali-fication	Prod-uction
Average amount of phase	2,000	15,000	1,500	20,000	3,000	30,000	5,000	3,000	60,000
Average months per phase	8	16	8	8	12	14	9	12	24
Average amount per month per phase	0,250	0,938	0,188	2,500	0,250	2,143	0,556	0,250	2,500
Average PM per month	0,5	1,3	0,9	1,1	0,8	1,5	1,3	0,8	1,8
Average QA per month	0,3	1,1	0,7	1,0	0,5	1,2	1,0	0,3	2,0

Table 4.2 : An example of default values for a function.

Example : From Table 4.2 it can be seen that for the concept/definition phase, the average default amount per month is 2 million money units over a period of 8 months. This gives an average amount of .25 million money units per month for the concept/definition phase. If, for example, a specific project with a total amount of 4 million money units for its concept/definition phase is analysed, and it is expected that the duration of the phase is 6 months, a pro rata calculation can be done in order to determine the human resources requirement for a division for the project (or projects) selected. The average amount of money for the selected project which will be spent per month equals 4 million money units divided by 6 months, giving an average of .667 million money units per month. The default value for the PM requirement is .5 for every .25 million money units to be spent per month on the phase. Thus, for an amount of .667 million units per month, the PM requirements for the selected project will be .5x.667/.25, which is equal to 1,334. Similar, the requirements for QA will be .3*.667/.25, which is equal to 0,8. These human resources requirement figures will be identified as relative figures for human resource requirements.

4.8 Primary assumptions

In order to understand the frame of reference that will be used for the development of a solution to the research problem, it is necessary to summarise the primary assumptions that have been made:

- Only major capital projects which are contracted through ARMSCOR are considered.
- Acquisition phases up to the completion of the production phase are taken into account.
- Project priorities are known and are established by top management.

4.9 Conclusions

Chapter 4 provides the basis for the development of a theory to solve the research problem. Macro parameters, namely inflation and exchange rates, have been introduced. The minimum data needed at project level have been defined. Parameters necessary to run a full impact analysis have been discussed. The next chapter will describe the mathematical formulation of a solution to the research problem.

5. Mathematical formulation of the problem and integration

5.1 Introduction

This chapter deals with the integration of the various aspects in finding a solution to the research problem and is described in five modules, namely Module 1: initial macro scheduling, Module 2: final macro free scheduling, Module 3: final macro constrained scheduling, Module 4: final micro scheduling, and Module 5: impact analysis. The aim is to integrate the various building blocks into a single functional system. The last paragraph of this chapter is a summary of the mathematical formulation of the problem and its integration in general.

The work that has been described in Chapter 4, **Support for the problem solution**, must be seen as an essential part of the overall solution and specifically this chapter. Although the summary of the problem solution is given at the end of this chapter, it is necessary to present the summary in this introductory paragraph in order to understand the detail of each module as described throughout this chapter. A flow chart is provided at the end of this dissertation to show the process that is described in Chapters 4 and 5.

Steps 1 and 2 below have been explained in **Chapter 4** (Section 4.2, Finances and economics) and are thus not repeated in this chapter in detail.

Step 1: Convert the available budget in real terms into a nominal budget by taking the annual growth of the available budget into account.

Step 2: Convert the annual nominal budget into a monthly budget by making use of the modified Gompertz formula.

The following steps are all explained in **Chapter 5**:

Step 3: Establish a pseudo project (**Module 1, Part 1**) from data obtained from all phases of all subprojects within a project and for all projects. The data per phase which is necessary to determine a pseudo project are the phase value in real terms and the minimum and maximum duration in which a phase can be completed. Determine the minimum and maximum duration for each pseudo project. The initial duration of a pseudo project is calculated as the average between the minimum and maximum duration of the project. Determine four scheduling sectors, namely concept/definition, development, qualification and production sectors. Each sector will have a minimum and a maximum duration. The summation of the minimum and maximum durations of the four sectors is equal to the minimum and maximum duration of the pseudo project. Find the best fit cash flow profile for the pseudo project based on the data as obtained from the phase information. At the end of step 3 the following information is known, namely the pseudo project cash flow profile in real terms, which in total is equivalent to the total project cost, and a duration for the pseudo project, which is between a minimum and a maximum duration of the pseudo project. What is not known, are the starting and finishing dates of the pseudo project.

Step 4: The next step is to calculate a weighted annual escalation factor (**Module 1, Part 2**) for each pseudo project. The inflation rates and changes in exchange rates for each subproject of a project are taken into account in determining the weighted annual escalation factor for a pseudo project.

Step 5 : According to the project priorities, schedule the pseudo projects (**Module 1, Part 3**) into an initial pseudo schedule by 'packing' a selected number of projects into the shortest possible time so that the cumulative nominal value of all the projects at a specific time is less than or equal to the cumulative nominal budget at that time. Real cash flows of pseudo projects are then converted into cash flows in nominal terms by taking into account a weighted escalation factor applicable to that pseudo project.

Step 6 : Determine a 'free' optimising schedule (**Module 2, Part 1 and Part 2**) by minimising the overall deviation of the nominal cash flow of all pseudo projects from the nominal budget over the final planning horizon. This is done by means of six pseudo scheduling operations, or heuristics, namely left and right shift, left and right shrink, and left and right stretch, depending on the scheduling constraints to which the pseudo project is subjected. The result of this step is a 'free' optimised pseudo schedule with a duration, starting and finishing dates, and cash flow profile in nominal terms for each pseudo project.

Step 7 : This step is optional, depending on the requirements of the operator. If expected dates for the completion of pseudo projects have been entered into the model as constraints, and these constraints have been activated, then from a 'free' optimised schedule determine a 'constrained' optimised schedule (**Module 3, Part 1 and Part 2**) by minimising the overall deviation of the nominal cash flow of all pseudo projects from the nominal budget over the final planning horizon, but subject to completion date constraints. The result is a final 'constrained' schedule with cash flow profiles, starting and finishing dates, and durations of each pseudo project.

Step 8 : Once a final pseudo schedule (whether free or constrained) has been determined, a detailed project optimisation (**Module 4, Part 1, Part 2 and Part 3**) can be conducted. Firstly, the subprojects are so optimised that the deviation from the cash flows of all subprojects of the project's required cash flow profile as obtained in the final pseudo schedule is a minimum. Secondly, the phases within a sector are so optimised that the deviation from the phase cash flow for the subproject's cash flow is a minimum.

In both the above cases, nominal values of each subproject are determined with actual inflation rates and changes in exchange rates. This, in other words, is not a weighted escalation, but an actual escalation of each subproject within a project. .

Step 9 : Once all the projects have been optimised, the actual predicted nominal cash flows must be converted to real value predicted cash flows (**Module 4, Part 3**). There are two conversions, namely the de-escalation of the final nominal cash flow to a **required real cash flow**, and a conversion to the **original real values**. The de-escalation to required real cash flows is calculated with the annual growth rate of the budget, while the de-escalation to original real values is based on the actual inflation rates and changes in exchange rates. The difference between the required real cash flow and the original real cash flow is the additional cost that must be planned for due to inflation and changes in exchange rates. The result of step 9 is a schedule of all phases with starting and finishing dates, and a predicted required real cash flow profile. This schedule is the **near optimal schedule** based on the input data of the model and the allocated budget.

Step 10 : Based on the final starting and finishing times of each phase and the corresponding required real cash flow of each phase, calculate various impacts (**Module 5**) such as required real cash flows of groups of selected projects, required real cash flows of specific local organisations, cash flows of specific engineering functions or divisions, and the corresponding human resources requirement of the functions for the planning horizon.

5.2 Module 1 : Initial macro scheduling

Introduction

This module deals with the initial macro scheduling of all projects. This is necessary because the starting and finishing times of all the projects are not known at this stage. The aim is to prepare pseudo projects and to schedule them subject to the macro economy and other scheduling constraints. Once all the pseudo projects have been initially scheduled, the final macro free (Module 2) and/or final macro constrained (Module 3) scheduling may commence.

Module 1 is covered by three parts, namely Part 1, Pseudo project scheduling, Part 2, Macro economy preparation, and Part 3, Initial pseudo project scheduling.

Part 1: Pseudo project preparation

Introduction

This part converts the raw project data into a pseudo project. A project with a maximum of 5 subprojects and 9 phases is converted into a single pseudo project with a single cash flow η-profile and a minimum and maximum duration.

Definitions

The following definitions are necessary in order to understand the development of the macro pseudo scheduling process:

$P =$ total number of projects

$i =$ index of projects where i represents the priority of the project. Priorities are given and in practice supplied by e.g. top management

$P_i =$ project number of priority i

$j =$ index of subprojects

$S_i =$ number of subprojects of project P_i with priority i

$k =$ index of phase

$\phi_{ij} =$ number of phases of subproject j of project P_i with priority i

$y =$ index of year

$N_y =$ number of years

$m =$ index of month

$N_m =$ number of months

$M^r_{ijk} =$ real money value of phase k of subproject j of project P_i with priority i in any currency

$\delta Tmin_{ijk} =$ minimum duration of phase k of subproject j of project P_i with priority i

$\delta Tmax_{ijk} =$ maximum duration of phase k of subproject j of project P_i with priority i

$C_{ij} =$ supplier country of subproject j of project P_i with priority i and $C_{ij} \in$ {supplier countries}

$V_{ij} = V_{ij}(C_{ij})$

= foreign or local currency of subproject j of project P_i with priority i of supplier country C_{ij} and $V_{ij} \in$ {currency of countries}

$X_{ijy} = X_{ij}(V_{ij}(C_{ij}), y)$

= exchange rate of subproject j of project P_i with priority i for foreign currency $V_{ij}(C_{ij})$ of supplier country C_{ij} at year y (local rand per foreign currency)

At year y = 0, $X_{ij0} = X_{ij}(V_{ij}(C_{ij}), 0)$ which is the exchange rate applicable in the base year of planning.

Foreign supply real rand value

This paragraph converts the foreign supply real value in a foreign currency to a foreign supply real value in a local currency, i.e. in rand. If a foreign organisation is involved, $Rf^r_{ijk} = M^r_{ijk} * X_{ijy}$ which is the real rand value of foreign supply of phase k of subproject j of project P_i with priority i. This is necessary to convert foreign currency into local rands. For a subproject, the total real rand value of foreign supply is $Rf^r_{ij} = \sum Rf^r_{ijk}$, k = 1, ... , 9. For a project, the total real rand value of foreign supply is $Rf^r_i = \sum Rf^r_{ij}$, j = 1, ..., S_i where S_i = number of subprojects of project P_i with priority i. The total real rand value of foreign supply of all projects is $Rf^r = \sum Rf^r_i$.

Local supply real rand value

If a local organisation is involved, $Rl^r_{ijk} = M^r_{ijk}$ which is the real rand value of local supply of phase k of subproject j of project P_i with priority i. For a subproject the total real rand value is $Rl^r_{ij} = \sum Rl^r_{ijk}$ for k = 1, ... , 9 . The total real rand value for a project is $Rl^r_i = \sum Rl^r_{ij}$ for j = 1, ..., S_i where S_i = number of subprojects of project P_i with priority i. The total real rand value for the local supply for all projects is $Rl^r = \sum Rl^r_i$.

Total real rand value

The phase value in real rand value is $R^r_{ijk} = Rl^r_{ijk}$ or Rf^r_{ijk}, i.e. the local **or** foreign supply, which is the real rand value of total supply of phase k of subproject j of project P_i with priority i. For a subproject, the total local **or** foreign supply in real rand value is $R^r_{ij} = \sum R^r_{ijk}$ for k = 1, ... , 9.

The **assumption** is made that a subproject with all its phases can be acquired from either a local or a foreign supplier but not both. The reason is to separate the information per subproject in order to simplify the calculations.

The total supply of a project, i.e. local and foreign supply, is $R^r_i = \sum R^r_{ij}$ for j = 1, ..., S_i where S_i is the number of subprojects of project P_i with priority i. The total supply of local and foreign supplies for all projects in real rand is $R^r = \sum R^r_i$. R^r can also be defined as $Rl^r + Rf^r$.

Project scheduling sectors

The project scheduling sectors have been defined in Chapter 4. This paragraph describes how the different phases are coupled to a sector.

Define τ as a project scheduling sector where $\tau \in \{1,2,3,4\}$, thus confirming 4 project scheduling sectors.

Sector 1 consists only of phase 1, i.e. the combined **concept/ definition** phase, thus sector $\tau = 1 \supset$ {phase k = 1}. **Sector 2** consists of all six phases which are part of **development** as described in Chapter 4, thus sector $\tau = 2 \supset$ {phases k = 2 to 7}. **Sector 3** is the project **qualification** sector and consists of one phase, thus sector $\tau = 3 \supset$ {phase k=8}. **Sector 4** is the **production** sector and consists of one phase, thus sector $\tau = 4 \supset$ {phase k=9}.

per sector

For a specific sector τ, determine the **total real rand value** for all phases of all subprojects for a project that falls in sector τ. Let the total real rand value of all phases of a subproject in a sector be $R^r_{ij\tau} = \sum R^r_{ijk}$, for $k \in$ of all phases of subproject j that belongs to sector τ. Then, the total real rand value of all subprojects in a sector is $R^r_{i\tau} = \sum R^r_{ij\tau}$ for $j = 1, ..., S_i$ indicating all the subprojects that belong to project P_i with priority i in sector τ.

per sector and per subproject

The minimum and maximum duration for each sector is determined. In Chapter 4 it was mentioned that for each phase a phase value in a local or foreign currency is given, as well as a minimum and maximum duration in which a phase can be completed. It was further stated that the minimum and maximum duration will be used as duration limits without having an effect on the initial phase value, i.e. as long as a phase is completed within the minimum and maximum durations, the phase value will remain constant in real terms. This phase value can only be changed if the scope of the work of that phase changes.

The **minimum duration** of a sector related to a subproject of a project is $Tmin_{ij\tau} = \sum \delta Tmin_{ijk}$, which is the summation of the individual minimum durations of all the phases in sector τ. The **maximum duration** of a sector related to a subproject of a project is $Tmax_{ij\tau} = \sum \delta Tmax_{ijk}$, which is the summation of the individual maximum durations of all the phases in sector τ.

At this stage, the minimum and maximum duration for a subproject j have been calculated for sector τ.

per sector and per project

The next step is to calculate the minimum and maximum durations for each sector τ and for the project.

The assumption is made that all subprojects run concurrently and are for technical reasons independent of each other, but for scheduling purposes are related with respect to the scheduling sectors. Thus, for a sector, the minimum duration $Tmin_{i\tau} = \max \{Tmin_{ij\tau}\}$ for $j = 1, ..., S_i$, i.e. minimum duration for a sector is the maximum value of all minimum durations for each subproject in a sector. On the other hand, the maximum duration $Tmax_{i\tau} = \max \{Tmax_{ij\tau}\}$ for $j = 1, ..., S_i$, i.e. maximum duration for a sector is the maximum value of all maximum durations for each subproject in a sector.

The average time per sector τ for project i is $Tav_{i\tau} =$ integer $((Tmax_{i\tau} + Tmin_{i\tau})/2)$, which is an average between the minimum and maximum values and a value rounded off to a discrete time unit. The average time for a sector is an arithmetic calculation and is not equal to the true expected duration of the sector.

per project

Once the minimum and maximum durations for the sectors are determined, the project's minimum and maximum duration can now be calculated. These calculations show the absolute minimum and maximum durations in which a project can be completed. As previously explained, a project can be completed in any duration between the minimum and maximum duration, both inclusive, without changing the real value of the project.

The absolute minimum duration for a project will be $Tmin_i = \sum Tmin_{i\tau}$ for $\tau = 1, ..., 4$ and the absolute maximum duration for a project will be $Tmax_i = \sum Tmax_{i\tau}$ for $\tau = 1, ..., 4$.

The average duration for the project is $Tav_i = \sum Tav_{i\tau}$ for $\tau = 1, ..., 4$. The average duration of a project is used as the **initial duration T^0_i** for that project during the process of scheduling the pseudo projects in the following modules of this chapter, i.e. $T^0_i = Tav_i$. It allows manipulation of the duration between the minimum and the maximum durations during the implementation of pseudo operations later on in the chapter. Alternatively to $T^0_i = Tav_i$, let $T^0_i = Tmin_i$, i.e. where the minimum project duration is taken as the initial pseudo project duration. These two approaches will be investigated in Chapter 6 in the case study evaluation. Once the project's initial duration is determined, let the uniform intensity in real rands per time unit of **local supply** per project be $Il^r_i = Rl^r_i / T^0_i$ and the uniform intensity in real rands per time unit of **foreign supply** per project be $If_i = Rf_i / T^0_i$. Define $T = \sum T^0_i$, the total initial duration of all projects. T will be used in the initial pseudo scheduling in Part 3 of this module.

In future research, a method of determining the pseudo project's weighted initial duration according to certain criteria could be investigated. This possibility has not been evaluated in the research project and will therefore not form part of this research project.

Fit best eta profile to pseudo project data

It is now necessary to determine a cash flow profile for the pseudo projects from the raw project data. The aim is to determine the type of cash flow profile, as described in Chapter 4, as well as the η -value for each project. As previously explained, the η-value identifies how far below the project's uniform intensity the first month's cash flow will be. If η is negative, the first month's cash flow will be above the uniform intensity of the project.

For project P_i with priority i, define the beginning of sector τ as $B_{i\tau}$ and the end of the same sector as $E_{i\tau}$. The end of any sector is $E_{i\tau} = B_{i\tau} + Tav_{i\tau} - 1$. The beginning of sector 1 is $B_{i1} = 1$, i.e. the cash flow starts at the first time unit. The beginning of sectors 2, 3 and 4 is $B_{i\tau} = B_{i\tau-1} + Tav_{i\tau-1}$.

For every sector of a project, the total real value $R^r_{i\tau}$ as well as the initial duration $Tav_{i\tau}$ are known. Let t be the time index of the project running from time unit t = 1 to Tav_i. The real uniform intensity for every sector is $R^r_{i\tau} / Tav_{i\tau}$. Define the real uniform **actual** cash flow data for the project as $I^r_{it} = R^r_{i\tau} / Tav_{i\tau}$ with $t = B_{i\tau}$ to $E_{i\tau}$ for $\tau = 1$ to 4. In Figure 5.1, I^r_{it} represents the actual data.

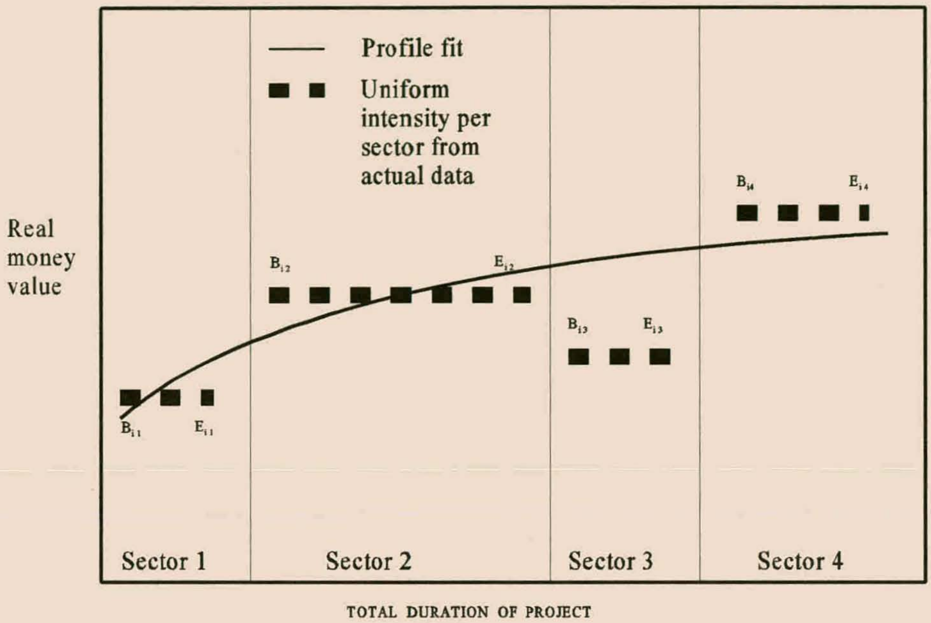


Figure 5.1: Eta profile fit to actual data of a project.

The next step is to find a theoretical fit of a cash flow profile with that of the actual data and presented in real cash flows over the makespan of the project. A number of five **eta cash flow profiles** have been developed in Chapter 4. The five profiles are defined respectively as follows:

1 is uniform profile, 2 is a straight line profile, 3 is a semi-parabolic profile with a zero slope at the end of the makespan, 4 is a semi-parabolic profile with a zero slope at the beginning of the makespan, and 5 is parabolic profile with a zero slope in the middle of the makespan.

Define σ as the eta-profile number from 1 to 5 and σ^*_i as the eta-profile number which will be allocated to project P_i with priority i. σ^*_i is unknown at this stage and must be found. As defined in Chapter 4, η is a factor which describes how far below or above the project's uniform intensity the first month's cash flow will be with $-1 \leq \eta \leq 1$. The aim will be to find η^*_i which will be the eta value of the cash flow profile σ^*_i.

The following method is proposed to find σ^*_i and η^*_i :

For $\sigma_i = 1$ to 5 in steps of 1 and $\eta_i = -1$ to 1 in steps of .01, find σ^*_i and η^*_i such that $\sum (I^r_{it} - f_{it})^2$ is a minimum with t = 1 to T^0_i. This means that an eta profile is selected that will fit the actual data best.

I^r_{it} is the real uniform cash flow as obtained from the actual data and f^r_{it} is the theoretical discrete eta cash flow profile as derived in Appendix C. To determine f^r_{it}, choose T^0_i ($Tmin_i \le T^0_i \le Tmax_i$) = Tav_i as the initial duration of project P_i with priority i. R^r_i is the real rand value of project P_i with priority i and is known. Thus, with σ_i , η_i , T_i and R^r_i known, calculate the constants α_i , β_i and γ_i for the function $f^r_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$ with $t = 1, ..., T_i$ and $t \in \mathbb{N}$, as explained in Appendix C.

The result is σ^*_i and η^*_i which represents the best theoretical fit of a eta profile to the actual project's data.

<u>Summary of Part 1</u>

The raw project data have been converted into a pseudo project with a best fit eta profile σ^*_i and its associated η^*_i for project P_i with priority i. Tav_i has been taken as the initial pseudo project duration $\mathbf{T^0_i}$ with $\mathbf{Tmin_i} \le T^0_i \le \mathbf{Tmax_i}$ and $\mathbf{I^r_i = R^r_i / T^0_i}$ is the project's uniform intensity in real rands per time unit over the project's timespan of T^0_i. These parameters will be used in Part 3 of this module in the initial pseudo scheduling process.

Part 2 : Macro economy preparation

<u>Introduction</u>

This part deals with the macro economy preparation for initial scheduling. Two areas are considered as macro economy information, namely the escalation of a project's cost over a number of years and the allocated budget.

The **escalation** (a weighted annual escalation) of a project's cost will be the joint effect of two factors, namely **inflation rates** and **changes in exchange rates**. The escalation is a weighted annual escalation because the project's data have been converted into a single pseudo project and thus do not represent actual data.

Since the proposed model works in time units of months, the annual budget, which has been allocated to complete the selected number of projects, will also have to be converted to monthly time units. This conversion is done by means of the modified Gompertz method as explained in Chapter 4.

Both the above factors are necessary for the initial project scheduling, as will be explained in Part 3 of this module.

Weighted annual escalation

A project consists of a number of subprojects. As assumed in Chapter 3, each subproject can be acquired from either a local or a foreign supplier but not from both. Every supplier can have a different inflation rate. The exchange rate between the local and foreign currencies usually fluctuates. It is therefore necessary to determine a single annual escalation factor for every pseudo project over the planning horizon. This is done by means of a **weighted annual escalation** based on the ratio between the local and foreign rand values, and the total rand value of the project.

Let μ_{ij} (C_{ij}, y) be the inflation rate for supplier country C_{ij} and let X_{ijy} be the local exchange rate for that country for subproject j of project P_i with priority i at year y. In calculations that follow, changes in exchange rates are calculated as the difference in exchange rates of two consecutive years. Because of the fact that for year y = 1, the change in exchange rate is the difference between the exchange rates for year y and year y-1, the exchange rate for year 0 is needed. For this purpose, let $X_{ij0} = X_{ij1}$ i.e., the previous exchange rate at year 0 = the exchange rate at year 1. This results in a zero change in exchange rate with a zero escalation.

Define W_{iy} as the **total weighted annual escalation** (a percentage) for project P_i with priority i at year y, which is equal to the sum of the local (Wl_{iy}) and foreign (Wf_{iy}) weighted annual escalation where

$$Wf_{iy} = \sum \left\{ \left\{ \left\{ 1 + \frac{\mu_{ijy}}{100} \right\} * \left\{ 1 + \frac{X_{ijy} - X_{ij(y-1)}}{X_{ij(y-1)}} \right\} \right\} - 1 \right\} * 100 * \left(\frac{Rf^{\,r}_{\;ij}}{R^{r}_{\;i}} \right)$$

and

$$Wl_{iy} = \sum \mu_{ijy} * \left(\frac{Rl^{\,r}_{\;ij}}{R^{r}_{\;i}} \right)$$

where j = 1, ... , S_i and y = 1, ..., N_y with $\mathbf{N_y}$ the number of years in the planning horizon.

<u>Conversion of annual budget to monthly nominal cash flow: Modified Gompertz</u>

Given: η_g as the Gompertz eta value and m_e as the month in which the modified Gompertz curve is equal to the average monthly cash flow.

Let π_y be the annual compound rate at which the budget is growing (percentage) and let $\boldsymbol{\Gamma}^{\mathbf{r}}_{\;\mathbf{y}}$ be the annual budget in real rands.

Define G_y as a growth factor per annum where $G_y = G_{y-1} * \{1 + \pi_y /100)$ for y = 1, ..., N_y and with $G_0 = 1$.
Then the nominal annual budget is $\Gamma^{n}_{\;y} = \Gamma^{r}_{\;y} * G_y$ and the average nominal monthly budget intensity is $I\Gamma^{n}_{\;m} = \Gamma^{n}_{\;y} / 12$. With η_g , m_e and $I\Gamma^{n}_{\;m}$ known, **determine** $\Gamma^{n}_{\;m}$, the **monthly**

budget in nominal terms from the modified Gompertz algorithm. (See Appendix B for the algorithm.)

Note : Within a specific financial year, the value of that year's budget stays the same and will not be time-adjusted due to growth, inflation or any other escalation or de-escalation. This means that the annual growth figure for a financial year can be used to convert the monthly nominal budget to a monthly real budget, i.e. $\Gamma^{r}_{m} = \Gamma^{n}_{m} / G_y$.

Summary of Part 2

Two macro parameters have been determined, namely a weighted annual escalation factor (W_{iy}) for project P_i with priority i and Γ^{n}_{m} the monthly budget in nominal terms over the planning horizon. These parameters will be used in Part 3, initial pseudo project scheduling.

Part 3 : Initial pseudo project scheduling

Introduction

This part deals with the pseudo project scheduling as part of the initial macro scheduling process. Scheduling is done with the money in **nominal terms**. The nominal monthly budget (obtained from Part 2) is used while each pseudo project's real cash flow (obtained from Part 1) is adjusted with the project's weighted annual escalation (obtained from Part 2), which will eventually be converted into a weighted monthly escalation.

The aim of this part is to determine an initial schedule of pseudo projects that will form the departure point in optimising the scheduling of the pseudo projects with a final macro free optimisation (Module 2), followed, if required, by a final macro constrained optimisation (Module 3).

Escalation factor

The weighted annual escalation of each project (W_{iy}) is converted into a monthly escalation factor over the planning horizon. Let $w_{i\,m}$ be the monthly escalation factor for project P_i with priority i per month m running from month 1 to month N_m, where $N_m = N_y$ (number of years under consideration) * 12 months.

Define r as a monthly escalation rate and let $w_{i\,0} = 1$. Let $r = 100*[(1 + W_{iy} / 100)^{(1/12)} - 1]$. Then $w_{i\,m} = w_{i\,(m-1)} * (1 + r/100)$ where $y = 1, ..., N_y$, $i = 1, ..., P_i$, and $m = 1, ..., N_m$.

Proof: Assuming that the effect of a monthly escalation at a monthly compound rate is equal to the effect of an annual escalation at an annual compound rate within a single financial year, then

$$
\begin{aligned}
(1 + r/100)^{12} &= (1 + W_{iy} / 100)^{1} \\
(1 + r/100) &= (1 + W_{iy} / 100)^{1/12} \\
r/100 &= (1 + W_{iy} / 100)^{1/12} - 1 \\
r &= 100 * [(1 + W_{iy} / 100)^{1/12} - 1].
\end{aligned}
$$

Pseudo scheduling

Introduction

This section covers the method to initially schedule the pseudo projects. The real annual budget has been converted into a nominal monthly budget. For each project a monthly escalation factor has been determined. Every project has been converted into a pseudo project with an eta cash flow profile in real terms and an associated eta value. It is unknown at this stage when any of the pseudo projects will start and end.

The aim of this section will then be to initially schedule all pseudo projects under consideration in such a way that the cumulative nominal costs of these projects are less than or equal to the cumulative nominal budget at the end of the total duration. This also applies to interim scheduling of projects until the last project has been scheduled. The selected number of projects must also be scheduled in a minimum total duration.

The principle that applies to the scheduling of pseudo projects is that of Russell [80], who noted that cash flow, or budget in the case of the research problem, is treated as a resource and if unused is carried over to the next time interval. This principle is used for the peudo sheduling of projects and is explained in the remaining part of Module 1 of this chapter.

Initial scheduling of pseudo projects

The objective is to schedule all pseudo projects in the shortest possible time, subject to priority constraints and nominal budget limitations.

Define te^f as the final finishing time of the last scheduled project after all projects have been scheduled. **Find** te^f such that it is a minimum and that $\Sigma R^n_i \leq \Sigma \Gamma^n_m$ where m = 1, ..., te^f and i = 1, ..., P where P is the total number of projects under consideration.

Scheduling of pseudo project with priority 1

When project with priority 1 is scheduled and the finishing date $te_{i=1}$ is now known, the cumulative available nominal budget from time t = 1 to time $te_{i=1}$ must be greater than the total nominal cost of project 1. This is to ensure that enough funds in nominal terms are available to execute the project.

Let $te_{i=0} = 1$, the end of the non-existing project with priority 0 and $ts_{i=1} = 1$, the starting time of project with priority 1. Then the finishing time of project with priority 1 will be $te_{i=1} = ts_{i=1} + T^0_{i=1} - 1$, subject to the priority rule that $te_{i=1} \geq te_{i=0}$. Note that for the project with priority 1

$te_{i=1} \geq te_{i=0}$. This will be the earliest scheduling of the project with priority 1.

The next step will be to evaluate whether enough funds are available for this first project with priority 1. If Γ^{n}_{m} was identified as the monthly nominal budget that is available for the period 1 to the end of the planning horizon, then define ${}_{n}\Gamma^{n}_{im}$ as a **new** monthly nominal budget that is available for the same period but only after the monthly budget consumption of the previous projects have been subtracted from Γ^{n}_{m}.

Determine $\Sigma\, {}_{n}\Gamma^{n}_{(i=1)\,m}$ where m = 1, ..., $te_{i=1}$. In the case of the first project with priority 1, ${}_{n}\Gamma^{n}_{(i=1)\,m} = \Gamma^{n}_{m}$. Then determine $\Sigma\, R^{n}_{(i=1)\,h}$, the total nominal cost of the project, where h $= ts_{i=1}, \ldots, te_{i=1}$ and where $R^{n}_{(i=1)\,h} = f^{r}_{it} * w_{ih}$ with $f^{r}_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$ where $t = h - ts_{i=1} + 1$ as determined from $h = t + ts_{i=1} - 1$.

If $\Sigma\, {}_{n}\Gamma^{n}_{(i=1)\,m} \geq \Sigma\, R^{n}_{(i=1)\,h}$, use $ts_{i=1}$ and $te_{i=1}$ as the initial starting and finishing times of pseudo project with priority 1. If $\Sigma\, {}_{n}\Gamma^{n}_{(i=1)\,m} < \Sigma\, R^{n}_{(i=1)\,h}$, increase both $ts_{i=1}$ and $te_{i=1}$ (forward scheduling) incrementally by the same amount until $\Sigma\, {}_{n}\Gamma^{n}_{(i=1)\,m}$ is for the first time greater than $\Sigma\, R^{n}_{(i=1)\,h}$. The new values of $ts_{i=1}$ and $te_{i=1}$ at this point in time will be used as the initial starting and finishing times of pseudo project 1. It should be noted that there will always be a positive amount of funds available to schedule a project. It is possible that ${}_{n}\Gamma^{n}_{i=m}$ can be negative for monthly periods, but as long as $\Sigma\, {}_{n}\Gamma^{n}_{im}$ is positive, this is not of concern.

Once project 1 is scheduled from $ts_{i=1}$ to $te_{i=1}$, calculate the new or remaining monthly nominal budget after the monthly nominal project costs have been deducted from the original available monthly nominal budget, and which will be available for projects 2 to P. This is determined as ${}_{n}\Gamma^{n}_{(i=2)\,m} = {}_{n}\Gamma^{n}_{(i=1)\,m} - R^{n}_{(i=1)\,h}$ where m = 1, ..., 12 x the years under consideration.

Scheduling of pseudo project with priority i ($i \geq 2$)

The earliest finishing time for the project with priority i is also the finishing time for the project with priority i-1. The definition that was given for the priority rule is that the project with the lower priority cannot be completed before the project with the higher priority.

Let $te_i = te_{i-1}$ so that the priority rule that $te_i \geq te_{i-1}$ can be adhered to. Then $ts_i = te_i - T^0_i + 1$.

Determine $\Sigma\, {}_n\Gamma^n{}_{im}$ where m = 1, ..., te_i and $\Sigma\, R^n{}_{ih}$, the total nominal cost of the project, where $h = ts_i, \ldots, te_i$ and where $R^n{}_{ih} = f^r{}_{it} * w_{ih}$ with $f^r{}_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$ where $t = h - ts_i + 1$ as determined from $h = t + ts_i - 1$.

If $\Sigma\, {}_n\Gamma^n{}_{im} \geq \Sigma\, R^n{}_{ih}$, use ts_i and te_i as the initial starting and finishing times of pseudo project with priority i. If $\Sigma\, {}_n\Gamma^n{}_{im} < \Sigma\, R^n{}_{ih}$, increase both ts_i and te_i (forward scheduling) incrementally by the same amount until $\Sigma\, {}_n\Gamma^n{}_{im}$ is for the first time greater than $\Sigma\, R^n{}_{ih}$. The new values of ts_i and te_i at this point in time will be used as the initial starting and finishing times of pseudo project i.

Once project i is scheduled from ts_i to te_i, calculate the new or remaining monthly nominal budget after the monthly nominal project costs have been deducted from the original available monthly nominal budget, and which will be available for projects i+1 to P. This is determined as ${}_n\Gamma^n{}_{(i+1)m} = {}_n\Gamma^n{}_{im} - R^n{}_{ih}$ where m = 1, ..., 12 x the years under consideration.

Repeat this process for all projects under consideration with priorities i = 1 to P. The scheduling of the final project P gives ts_p and te_p. Let $te^f = te_p$, the finishing time of all projects.

Summary of Part 3

After the initial pseudo project scheduling is completed, an initial scheduling baseline is established on which the subsequent macro optimisation process is based. The initial pseudo project **duration** is still the same, while the initial **starting** and **finishing** times of a pseudo project are now established for the first time. The three abovementioned parameters will most probably all change during the final macro free scheduling process (Module 2) in order to find a near optimal schedule.

Summary of Module 1

A pseudo project can be constructed from project data and has a total real value, a minimum, maximum and an initial duration. An eta profile with its respective η-value is calculated for the pseudo project in real terms. A weighted annual escalation factor is determined for each project over the planning horizon, which is converted into a monthly escalation factor. The annual real budget is converted into a monthly nominal budget.

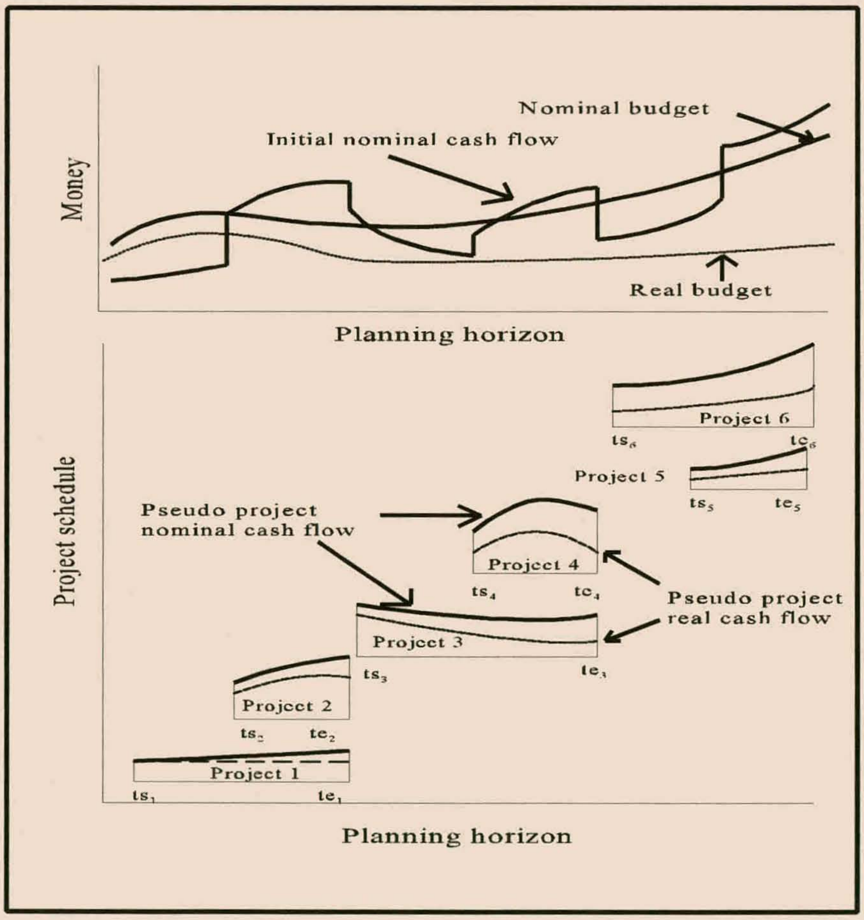


Figure 5.2 Initial pseudo project schedule.

The pseudo projects are initially scheduled (see Figure 5.2) according to their priorities. To be able to initially schedule these projects, each project's real eta cash flow profile is converted into a nominal cash flow profile by making use of the project's monthly weighted escalation factor. The projects are then scheduled so that the cumulative available budget is equal to or greater than the cumulative cost of the project.

Each project has an initial starting and finishing date, an initial duration and a real cash flow profile which can be converted into a nominal cash flow profile giving an initial schedule of all pseudo projects under consideration. The finishing date of the last project that has been scheduled is taken as the finishing date for the overall planning horizon.

5.3 Module 2 : Final macro free scheduling

Introduction

This module deals with the final macro free scheduling of the pseudo projects in nominal terms. It is covered in two parts namely Part 1, to select the best pseudo operation to improve a schedule, and Part 2, to implement the pseudo operation on the existing schedule to obtain a new schedule. The final macro free scheduling can only be done once the initial pseudo scheduling has been completed.

Part 1 : Selecting pseudo operation

Introduction

In the previous module the pseudo projects were initially scheduled, which resulted in a monthly nominal cash flow for all of the projects and which can be compared with the monthly nominal budget. This comparison is done by finding a single value, which is the summation of the squared value of the monthly difference between the nominal budget and the total nominal cost of all projects in that month. The objective of this Part 1 is to improve on the initial macro schedule, i.e. to reduce the single value as described above. This is done by means of six pseudo operations which are selected to apply to an existing schedule in order to deliver a new improved schedule.

Mathematical objective

The initial macro schedule is taken as the baseline to meet the objective, which is to minimise the summation of the square of the monthly difference between the nominal budget and total nominal costs of all projects per month over the planning horizon, i.e. to minimise $\sum_m(\Gamma^n_m - \sum_i R^n_{im})^2$ $\forall$ m = 1 to te^f and $\forall$ i = 1 to P.

As before, the monthly nominal project cost is $R^n_{im} = f^r_{it} * w_{im}$ $\forall$ m = ts_i to te_i and with t = m - ts_i + 1. $R^n_{im} = 0$ when m < ts_i and when m > te_i.

Pseudo project operations

Six pseudo project operations are defined, namely shift right, shift left, shrink right, shrink left, stretch right and stretch left.

Definitions of pseudo project operations

Let ρ = number of time units to **shift**

where ρ^R_i = number of right shift units and

ρ^L_i = number of left shift units.

Let ν = number of time units to **shrink**

where ν^R_i = number of right shrink units and

ν^L_i = number of left shrink units.

Let λ = number of time units to **stretch**

where λ^R_i = number of right stretch units and

λ^L_i = number of left stretch units.

Figure 5.3 will be used to explain the pseudo project operations. Three projects are shown each with their respective priorities i-1, i and i+1 where i-1 reflects a higher priority than i, which is in turn a higher priority than i+1.

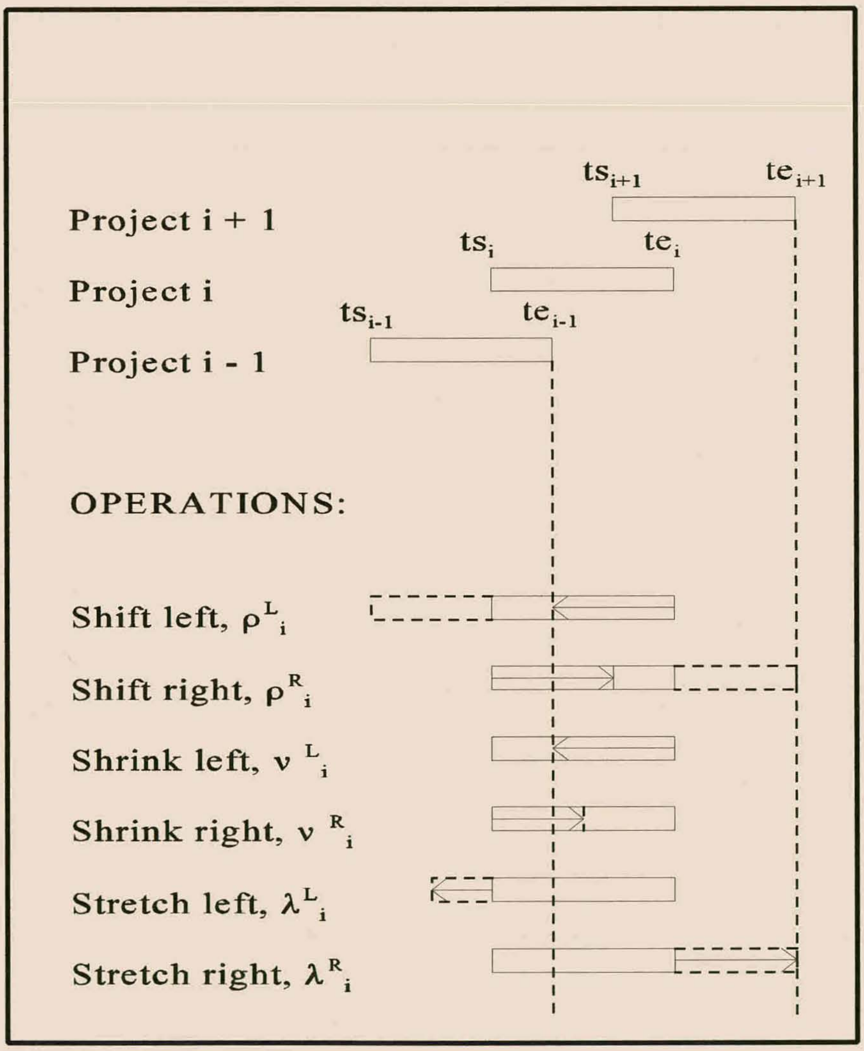


Figure 5.3 : Possible pseudo operations per single project.

The figure shows the possible pseudo operations that can be exerted on project i. The priority rules that were explained in Chapter 4 are used in order to show the maximum number of pseudo operation movements.

Method

Let $\Omega^0 = \sum_m(\Gamma^n_m - \sum_i R^n_{im})^2$ based on the initial macro schedule. The objective is to find one pseudo project operation $O^1_i \in \{\rho^R_i, \rho^L_i, \nu^R_i, \nu^L_i, \lambda^R_i, \lambda^L_i\}$ for project i during iteration 1 that will produce a maximum reduction of Ω^0 $\forall$ i. This method will be further described in Part 2: implementation of pseudo project operation. The following paragraphs describe in detail how the pseudo operations are developed.

Shift operation

<u>Shift left</u>

The maximum number of time units a project can be shifted to the left is
$\rho^L_i = \min\{(ts_i - 1), (te_i - te_{(i-1)})\}$ where $(ts_i - 1)$ prevents project i from starting before time 1 and $(te_i - te_{(i-1)})$ prevents project i from finishing before project i-1. If $(te_i - te_{(i-1)}) < 0$ then $\rho^L_i = 0$, which can only be possible in one instance, namely when project i is a running project and because of the fact that $ts_i = 1$, it is possible that $te_i < te_{(i-1)}$. This principle will also apply to other pseudo operations.

ρ^L_i is the maximum number of time units a project can be shifted to left. Define <u>**no**</u> as the possible number of time units that a project can be left shifted, i.e. <u>no</u> = 1 to ρ^L_i. For example, if $\rho^L_i = 3$, then no can be 1, 2 or 3, thus identifying <u>no</u> as a variable.

Define ${}_nts_i = ts_i$ - no as the **new** starting time of project i after a specific number of left shifts (<u>no</u>)

has been chosen according to rules that will be explained in Part 2, the implementation of the pseudo project operation.

The only time project i can affect Ω^0 is during the project's duration from ts_i to te_i . If the project is left shifted for no units, Ω^0 will also be affected for no units left of ts_i. At this stage only the effect of a possible left shift is evaluated and not the actual implementation.

If it is assumed that a number of no time units for left shift must be evaluated, then define ${}_eR^n_{i(m+no)} = f^r_{it} * w_{i(m+no)}$ as the **existing** nominal rands for the project at original time durations and ${}_nR^n_{im} = f^r_{it} * w_{im}$ as the **new** nominal rands for the project at new time durations.

${}_eR^n_{i(m+no)}$ and ${}_nR^n_{im}$ are determined for t = 1 to T_i ($T_i = T^0{}_i$) where $m = t + {}_nts_i - 1$.
$f^r_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$ as before.

Further, define $\boldsymbol{\Omega^{\rho L1}{}_i}$ as the sum of the square of the monthly difference between the nominal budget and the nominal cost of all projects if project i would have been left shifted for no of time units, with $\Omega^{\rho L1}{}_i = \Sigma[\,\Gamma^n{}_m - (R^n{}_m - {}_eR^n{}_{im} + {}_nR^n{}_{im})\,]^2$. The principle that is used here is to **subtract** the original effect of project i prior to no left shifts from the initial monthly nominal project costs and then to **add** the new effect of project i after no of left shifts of project i. It is therefore not necessary to again evaluate the full planning horizon from t = 1 to T.

Finally, it is necessary to select no with $1 \leq no \leq \rho^L{}_i$ to find the minimum (min) of $\Omega^{\rho L1}{}_i$. Therefore, min $\Omega^{\rho L1}{}_i$ = min $\{\Omega^{\rho L1}{}_i$ for no = 1 to $\rho^L{}_i\}$. The min $\Omega^{\rho L1}{}_i$ will be used later on when a decision will be made as to which pseudo operation, with its associated number of moves no, must be chosen that will give a minimum for project i, i.e. min Ω_i.

The same principles that have been used in the explanation of the left shift operation also apply to the other pseudo operations and will therefore not be explained in detail again.

Shift right

The maximum number of time units a project can be shifted to the right is $\rho^R_i = te_{(i+1)} - te_i$ where $(te_{(i+1)} - te_i)$ prevents project i to finish after project i + 1. As before, if $(te_{(i+1)} - te_i) < 0$ then $\rho^R_i = 0$.

Define ${}_nts_i = ts_i +$ no where ${}_nts_i$ is the new starting time of project i after right shift and no is the number of time units to right shift and no runs from 1 to ρ^R_i.

Analogous to the left shift operation, define ${}_eR^n_{i(-no)} = f^r_{it} * w_{i(-no)}$ as the existing nominal rands for the project at original time durations and ${}_nR^n_{i\,m} = f^r_{it} * w_{im}$ as the new nominal rands for the project at new time durations. ${}_eR^n_{i(-no)}$ and ${}_nR^n_{i\,m}$ are determined for t = 1 to T_i with $m = t + {}_nts_i - 1$. As before $f^r_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

For the right shift operation, $\Omega^{\rho R1}_i = \Sigma[\Gamma^n_m - (R^n_m - {}_eR^n_{im} + {}_nR^n_{i\,m})]^2$ for number of right shifts = no and min $\Omega^{\rho R1}_i = \min\{\Omega^{\rho R1}_i$ for no = 1 to $\rho^R_i\}$.

Shrink operation

Shrink left

The maximum number of time units a project can be shrunk to the left is $\nu^L_i = \min[(te_i - te_{(i-1)}), (T_i - Tmin_i)]$ where $(te_i - te_{(i-1)})$ prevents project i from finishing before project i-1 and where $(T_i - Tmin_i)$ prevents project i from reducing its duration to less than the minimum duration of the project. As before, if $(te_i - te_{(i-1)}) < 0$ then $\nu^L_i = 0$.

Define ${}_nts_i = ts_i$ where ${}_nts_i$ is the new starting time of project i after left shrink and no = 1 to ν^L_i is the number of time units to left shrink.

Define ${}_{e}R^{n}_{i\,m} = f^{r}_{it} * w_{i\,m}$ as the existing nominal rands for the project at original time durations for t = 1 to T_i with $m = t + {}_{n}ts_i - 1$. As before $f^{r}_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

Define ${}_{n}R^{n}_{i\,m} = f^{r}_{it} * w_{i\,m}$ as the new nominal rands for the project at new time durations for t= 1 to T_i - no with $m = t + {}_{n}ts_i - 1$. As before, $f^{r}_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

For the shrink left operation, $\Omega^{vL1}_{i} = \Sigma[\,\Gamma^{n}_{m} - (R^{n}_{m} - {}_{e}R^{n}_{im} + {}_{n}R^{n}_{i\,m})\,]^2$ for number of left shrinks = no and $\min \Omega^{vL1}_{i} = \min \{\Omega^{vL1}_{i}$ for no = 1 to $v^{L}_{i}\}$.

<u>Shrink right</u>

The maximum number of time units a project can be shrunk to the right is $v^{R}_{i} = T_i - Tmin_i$ where $(T_i - Tmin_i)$ prevents project i from shrinking to a duration less than the minimum duration of the project.

Define ${}_{n}ts_i = ts_i + no$ where ${}_{n}ts_i$ is the new starting time of project i after right shrink and <u>no</u> is the number of time units to right shrink and <u>no</u> = 1 to v^{R}_{i}.

Define ${}_{e}R^{n}_{i(-no)} = f^{r}_{it} * w_{i(-no)}$ as the existing nominal rands for the project at original time durations for t = 1 to T_i and where $m = t + {}_{n}ts_i - 1$. As before $f^{r}_{t} = \alpha_i t^2 + \beta_i t + \gamma_i$.

Define ${}_{n}R^{n}_{i\,m} = f^{r}_{it} * w_{im}$ as the new nominal rands for the project at new time durations for t= 1 to T_i - no where $m = t + {}_{n}ts_i - 1$. As before $f^{r}_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

For the shrink right operation, $\Omega^{vR1}_{i} = \Sigma[\,\Gamma^{n}_{m} - (R^{n}_{m} - {}_{e}R^{n}_{im} + {}_{n}R^{n}_{i\,m})\,]^2$ for number of right shrinks = no and $\min \Omega^{vR1}_{i} = \min \{\Omega^{vR1}_{i}$ for no = 1 to $v^{R}_{i}\}$.

Stretch operation

Stretch left

The maximum number of time units a project can be stretched to the left is $\lambda^L_i =$ min { (ts_i - 1), ($Tmax_i$ - T_i) } where (ts_i - 1) prevents project i from starting before time 1 and ($Tmax_i$ - T_i) prevents project i from stretching too much so that the project duration is greater than the maximum project duration.

Define ${}_nts_i = ts_i$ - no where ${}_nts_i$ is the new starting time of project i after left stretch and no = 1 to λ^L_i is the number of time units to left stretch.

Define ${}_eR^n{}_{i(m+no)} = f^r{}_{it} * w_{i(m+no)}$ as the existing nominal rands for the project at original time durations for t = 1 to T_i and where m = t + ${}_nts_i$ - 1. As before $f^r{}_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

Define ${}_nR^n{}_{im} = f^r{}_{it} * w_{im}$ as the new nominal rands for the project at new time durations for t= 1 to T_i + no where m = t + ${}_nts_i$ - 1. As before $f^r{}_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

For the stretch left operation, $\Omega^{\lambda L1}{}_i = [\, \Gamma^n{}_m - (R^n{}_m - {}_eR^n{}_{im} + {}_nR^n{}_{im})\,]^2$ for number of left stretches = no and min $\Omega^{\lambda L1}{}_i$ = min $\{\Omega^{\lambda L1}{}_i$ for no = 1 to $\lambda^L{}_i\}$.

Stretch right

The maximum number of time units a project can be stretched to the right is λ^R_i = min { ($Tmax_i$ - T_i) , ($te_{(i+1)}$ - te_i) } where ($Tmax_i$ - T_i) prevents project i from stretching too much such that the project duration is greater than the maximum project duration and ($te_{(i+1)}$ - te_i) prevents project i from finishing after project i + 1. As before, if ($te_{(i+1)}$ - te_i) < 0 then λ^R_i = 0.

Define ${}_n ts_i = ts_i$ where ${}_n ts_i$ is the new starting time of project i after right stretch and no = 1 to λ^R_i is the number of time units to right stretch.

Define ${}_e R^n_{i\,m} = f^r_{i\,t} * w_{i\,m}$ as the existing nominal rands for the project at original time durations for t = 1 to T_i where $m = t + {}_n ts_i - 1$. As before $f^r_{i\,t} = \alpha_i t^2 + \beta_i t + \gamma_i$.

Define ${}_n R^n_{i\,m} = f^r_{i\,t} * w_{i\,m}$ as the new nominal rands for the project at new time durations for t = 1 to T_i + no where $m = t + {}_n ts_i - 1$. As before $f^r_{i\,t} = \alpha_i t^2 + \beta_i t + \gamma_i$.

For the right stretch operation, $\Omega^{\lambda R1}_i = \Sigma[\Gamma^n_m - (R^n_m - {}_e R^n_{i\,m} + {}_n R^n_{i\,m})]^2$ for number of right stretches = no and min $\Omega^{\lambda R1}_i$ = min $\{\Omega^{\lambda R1}_i$ for no = 1 to $\lambda^R_i\}$.

Selected operation for iteration 1

During iteration 1, all six pseudo operations have been evaluated for project i. For project i, find Ω^1_i which is the minimum of min $\Omega^{\rho L1}_i$, min $\Omega^{\rho R1}_i$, min $\Omega^{\nu L1}_i$, min $\Omega^{\nu R1}_i$, min $\Omega^{\lambda L1}_i$, min $\Omega^{\lambda R1}_i$. Ω^1_i will then represent the best improvement on Ω^0 which is based on the initial pseudo schedule. Define Ω^{*1}_i as best improved value on Ω^0 for all projects which have been evaluated during iteration 1 and which is the minimum of Ω^1_i $\forall$ i. For Ω^{*1} the associated pseudo operation and no of moves whether shift, shrink or stretch are then known.

Thus, for iteration 1, select project i with $O^{*1}_i \in \{\rho^R_i, \rho^L_i, \nu^R_i, \nu^L_i, \lambda^R_i, \lambda^L_i\}$, which is the selected operation with no^{*1}_i number of moves. The implementation of the above operation is described in Part 2 of this module.

Take note that for iteration 2, $\Omega^2 = \Omega^{*1}$.

Selected operation for iteration f

Continue with iteration f so that each iteration constitutes $\Omega^f < \Omega^{f-1}$ with the associated pseudo operation. Stop when Ω^f cannot be less than Ω^{f-1} or limit the number of iterations f to a maximum value. The final $\Omega^f = \sum_m(\Gamma^n_m - \sum_i R^n_{im})^2$ for $\forall$ m produces final values for ts^*_i, te^*_i and T^*_i $\forall$ i. Although Ω^0 has been progressively reduced through each iteration, Ω^f is not necessarily an optimal value.

Project priorities, according to which the projects will be scheduled, are prescribed by higher authority. This is the case in Fendley [32] and for the research problem. Fendley makes use of a priority rule in order to schedule the activities or projects. One example of a priority rule used by Fendley is to schedule the project or activity with the shortest duration first. Another example is the priority rule of first-in-first-out. Although these specific priority rules are not used to schedule the pseudo projects, the principle of a priority rule applies in selecting one of the six pseudo operations which should be implemented during each iteration. Priority is given to the operation that will result in the largest improvement of the cumulative squared deviation from the pseudo cash flow compared with the budget. This principle was also used by Woodworth [107].

Woodworth [107] further applied the left shift as well as right shift type of operations. It has been explained in Part 1 of Module 2 of this chapter that, apart from the left and right shift operations, shrink and stretch operations have also been included in the ensemble of operations, increasing the number of operations from two to six. Smith-Daniels [83] also made use of the right shift principle.

It was mentioned in the literature overview at the beginning of this dissertation (Doersch *et al* [27]), that the lengthening and shortening of the duration of an activity would be investigated. This lengthening and shortening of a project or activity are related to the stretch and shrink pseudo operations respectively of the research problem, which form an integral part of the macro scheduling of pseudo projects.

Boctor [9] proposed the use of tandem or <u>multi-heuristics</u> whereby the most efficient rules (heuristics), as decided through his research, are chosen to be used in a tandem scheduling approach. Although six pseudo operations are used in the research problem, only a single pseudo operation was implemented during each iteration, which resulted in an improved schedule. Although the pseudo operations of the research problem are not used in a specific order, as in the case explained by Boctor, the principle of multi-heuristics was used together with the sum-of-the square principle as proposed by Woodworth [107].

Part 2 : Implementation of pseudo project operation

<u>Introduction</u>

For each iteration as described in Part 1 of this module, a pseudo operation has been selected that will improve on a previous Ω. This operation is also connected to a specific project i. Part 2 of this module deals with the implementation of that selected pseudo operation which covers the shifting, shrinking or stretching of the project. The result is a final pseudo project macro schedule. The input for any of the six possible pseudo operations is the same, namely i, which is the identified project, no_i, which is the number of moves necessary to implement the pseudo operation, R^r_i, which is the total real value of the project, T_i, which is the latest duration of the project, and η^*_i and σ^*_i from which constants α_i, β_i and γ_i are determined from the eta profile formulation.

This Part 2 then describes the method of pseudo operation implementation after the pseudo operation for a specific project has been selected in Part 1 of this module.

<u>Definitions</u>

Define ${}_{n-}R^n_m$ as the **new** total monthly nominal cash flow as **reduced** with the project's existing monthly cash flow and ${}_{n+}R^n_m$ as the **new** total monthly nominal cash flow as **increased** with the project's new monthly cash flow. The use of these two definitions will be explained in the subsequent paragraphs, which explain the implementation of the pseudo operations.

Only one of the following pseudo operations will be implemented during an iteration. In order to understand the method, an example will be given at the end of the shift left operation.

Operation shift left : $O^{\rho L}{}_i$

Define the new starting time of project i after the pseudo operation has been implemented as ${}_n ts_i = ts_i - no$ with $no = no_i$.

Determine ${}_{n-}R^n{}_{(m + no)} = {}_eR^n{}_{(m + no)} - f^r{}_{it} * w_{i(m + no)}$ which is the reduction of the total existing nominal cash flow with the nominal cash flow of project i running at the original project times and ${}_{n+}R^n{}_m = {}_{n-}R^n{}_m + f^r{}_{it} * w_{im}$ which is the increase of ${}_{n-}R^n{}_m$ with the nominal cash flow of project i running from a new starting date but for the same duration. Both ${}_{n-}R^n{}_{(m + no)}$ and ${}_{n+}R^n{}_m$ are determined for $t = 1$ to T_i where $m = t + {}_n ts_i - 1$.

The final result of the pseudo operation is a new schedule with $ts_i \leftarrow ts_i - no$, $te_i \leftarrow te_i - no$ and $T_i \leftarrow T_i$. This shows that the project has new starting and finishing dates and that the duration remains the same.

Example:
Let $ts_i = 17$ and $T_i = 5$, then $te_i = ts_i + T_i - 1 = 17+5-1 = 21$. The months over which project i is running is m = 17 to 21 and let $no = no_i = 1$. Then ${}_n ts_i = ts_i - no = 17 - 1 = 16$.

The calculations will be done for a period $t = 1$ to T_i , i.e. from 1 to 5. Then $m = t + {}_n ts_i - 1 = t + 16 - 1 = t + 15$. Substitute the values for m and no in the equation ${}_{n-}R^n{}_{(m + no)} = {}_eR^n{}_{(m + no)} - f^r{}_{it} * w_{i(m + no)}$ which results in ${}_{n-}R^n{}_{(t+16)} = {}_eR^n{}_{(t+16)} - f^r{}_{it} * w_{i(t+16)}$ with t running from 1 to 5. If $t = 1$ then the equation becomes ${}_{n-}R^n{}_{(17)} = {}_eR^n{}_{(17)} - f^r{}_{i1} * w_{i(17)}$. Thus, the month subscript runs from 17 to 21.

Once ${}_{n-}R^{n}_{(m+no)}$ has been determined over the period m=17 to m=21, calculate ${}_{n+}R^{n}_{m}$. Substitute the values for m in the equation ${}_{n+}R^{n}_{m} = {}_{n-}R^{n}_{m} + f^{r}_{it} * w_{im}$ which results in ${}_{n+}R^{n}_{(t+15)} = {}_{n-}R^{n}_{(t+15)} + f^{r}_{it} * w_{i(t+15)}$ with t running from 1 to 5. If t = 1 then the equation becomes ${}_{n+}R^{n}_{(16)} = {}_{n-}R^{n}_{(16)} + f^{r}_{it} * w_{i(16)}$. Thus the month subscript runs now from 16 to 20.

This explains how the total nominal monthly cash flow is reduced with project i's current nominal cash flow and how it is eventually increased with project i's new nominal cash flow after the pseudo operation has been implemented.

As this approached is followed through with the subsequent pseudo operations, only a skeleton explanation will be given for each pseudo operation.

Operation shift right : O^{pR}_{i}

Let no = no_i and ${}_{n}ts_i = ts_i + no$. Determine ${}_{n-}R^{n}_{(m-no)} = {}_{e}R^{n}_{(m-no)} - f^{r}_{it} * w_{i(m-no)}$ and ${}_{n+}R^{n}_{m} = {}_{n-}R^{n}_{m} + f^{r}_{it} * w_{im}$ for t = 1 to T_i and with $m = t + {}_{n}ts_i - 1$. The final result of the operation is a new schedule with $ts_i \leftarrow ts_i + no$, $te_i \leftarrow te_i + no$ and $T_i \leftarrow T_i$.

Operation shrink left : O^{vL}_{i}

Let no = no_i and ${}_{n}ts_i = ts_i$. Determine ${}_{n-}R^{n}_{m} = {}_{e}R^{n}_{m} - f^{r}_{it} * w_{im}$ and for t = 1 to T_i with $m = t + {}_{n}ts_i - 1$.

The following step is different from the previous calculation in that the duration of the project has changed and that a new f^{r}_{it} will have to be calculated for $T_i \leftarrow T_i - no$, R^{r}_{i} , η^{*}_{i} , σ^{*}_{i} . This also implies that new constants α_i ,β_i and γ_i will be calculated for the eta cash flow curve.

Determine ${}_{n+}R^{n}_{m} = {}_{n-}R^{n}_{m} + f^{r}_{it} * w_{im}$ for t = 1 to T_i - no and with $m = t + ts_i^{n} - 1$. The final result of the operation is a new schedule with $ts_i \leftarrow ts_i$, $te_i \leftarrow te_i - no$ and $T_i \leftarrow T_i - no$.

Operation shrink right : $O^{\nu R}{}_{i}$

Let no = no_i and ${}_n ts_i = ts_i$ + no . Determine ${}_{n-}R^n{}_{(m - no)} = {}_eR^n{}_{(m - no)} - f^r{}_{it} * w_{i(m - no)}$ for t = 1 to T_i with m = t +${}_n ts_i$ - 1. For $T_i \leftarrow T_i$ - no, $R^r{}_i$, $\eta^*{}_i$, and $\sigma^*{}_i$, determine new constants α_i, β_i and γ_i. Determine ${}_{n+}R^n{}_m = {}_{n-}R^n{}_m + f^r{}_{it} * w_{im}$ for t = 1 to T_i - no with m = t +${}_n ts_i$- 1. The final result of the operation is a new schedule with $ts_i \leftarrow ts_i$ + no, $te_i \leftarrow te_i$ and $T_i \leftarrow T_i$ - no.

Operation stretch left : $O^{\lambda L}{}_{i}$

Let no = no_i and ${}_n ts_i = ts_i$ - no. Determine ${}_{n-}R^n{}_{(m + no)} = {}_eR^n{}_{(m + no)} - f^r{}_{it} * w_{i(m + no)}$ for t = 1 to T_i with m = t +${}_n ts_i$ - 1. For $T_i \leftarrow T_i$ + no , $R^r{}_i$,$\eta^*{}_i$, and $\sigma^*{}_i$, determine new constants α_i ,β_i and γ_i. Determine ${}_{n+}R^n{}_m = {}_{n-}R^n{}_m + f^r{}_{it} * w_{im}$ for t = 1 to T_i + no with m = t +${}_n ts_i$ - 1. The final result of the operation is a new schedule with $ts_i \leftarrow ts_i$ - no, $te_i \leftarrow te_i$ and $T_i \leftarrow T_i$ + no.

Operation stretch right : $O^{\lambda R}{}_{i}$

Let no = no_i and ${}_n ts_i = ts_i$. Determine ${}_-R^n{}_m = {}_eR^n{}_m - f^r{}_{it} * w_{im}$ for t = 1 to T_i with m = t +${}_n ts_i$- 1. For $T_i \leftarrow T_i$ + no , $R^r{}_i$, $\eta^*{}_i$ and $\sigma^*{}_i$, determine new constants α_i ,β_i and γ_i. Determine ${}_{n+}R^n{}_m = {}_{n-}R^n{}_m + f^r{}_{it} * w_{im}$ for t = 1 to T_i + no with m = t +${}_n ts_i$ - 1. The final result of the operation is a new schedule with $ts_i \leftarrow ts_i$, $te_i \leftarrow te_i$ + no and $T_i \leftarrow T_i$ + no.

Summary of Part 2

After the final pseudo operation has been implemented and the final pseudo schedule has been obtained (see Figure 5.4), the values for ts_i , te_i and T_i as determined after the final iteration will be used as final values which are defined as follows:

$ts^*{}_i$ = the final starting time of the project,

te^*_i = the final finishing time of the project, and

$T^*_i = te^*_i - ts^*_i + 1$ = the final duration of the project.

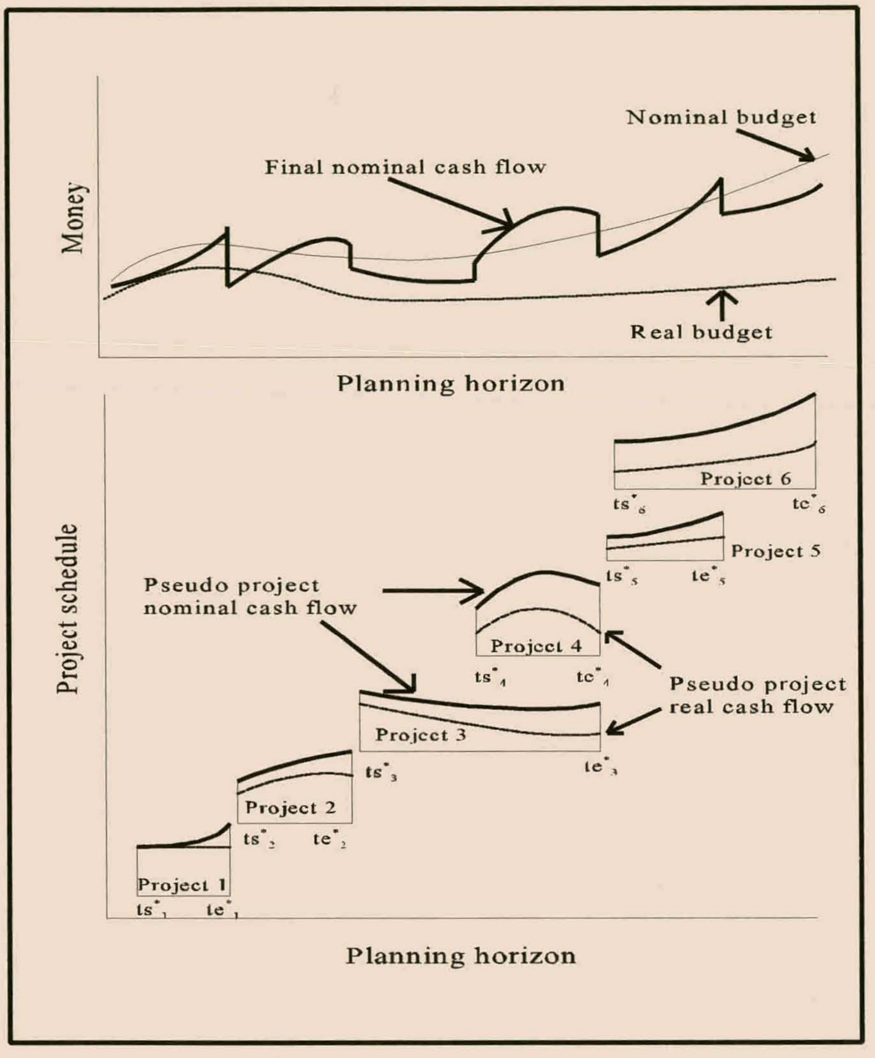


Figure 5.4 : Final pseudo project schedule.

With project i being scheduled, its final nominal cash flow per month m R^{fn}_{im} , which is determined from the equation for the eta profile and escalated with the applicable escalation factor per month, is also determined. This R^{fn}_{im} is then used for the project's detail optimisation which is explained in Module 4, final micro scheduling. Analogous to the macro project scheduling, R^{fn}_{im} will become the available budget according to which the phases and subprojects of the project will be scheduled.

During the data input, a required date for the completion of a project is obtained. The question will be asked if the user of the model would like to force the requirement to have the project completed by a required date, i.e. that the completion date constraint for a specific project is switched on. If one or more project completion dates are switched on, the next module, i.e. Module 3, final macro constrained scheduling, is compulsory. If none of the required completion dates are switched on, then start directly with Module 4: final micro scheduling. The final results of the final macro free scheduling are used as a starting point for the final macro constrained scheduling.

5.4 Module 3: Final macro constrained scheduling

Introduction

This section deals with the final macro constrained scheduling and can only be determined after the macro free scheduling has been completed as explained in Module 2. The constrained scheduling is required whenever one or more projects are constrained by a required completion date, i.e. when a constraint is switched on. The aim is to establish an initial macro constrained schedule (Part 1) with the corresponding nominal cash flow and then to further optimise it to a final macro constrained schedule (Part 2).

Part 1 : Establishing initial constrained schedule at macro pseudo level

A free optimised schedule presents the starting time, finishing time , duration and cash flow profile information of each project, as well as the total nominal cash flow per month over the planning horizon. All projects that have a required completion date must be investigated to see whether the free completion times are within the time limitations of the constrained completion dates.

Projects which violate the required date constraints must be either **shifted or shrunk** to the left until they satisfy the constraints. Any pseudo operation which moves the project's finishing time to the right, i.e. a later completion date, is excluded from the following evaluation process as the implementation of these operations will violate the required completion date constraint. The priority rule must also be checked.

Assumption : If for instance two projects x and y exist with required completion date constraints, and if according to their priorities, $te_x \leq te_y$, then the required completion dates will be such that $te^r_x \leq te^r_y$. If this is not the case, then the project priorities were allocated wrongly.

Let p be the first project of which the required completion date te^r_p is a constraint. Then for i = 1 to p, identify the first project, and thereafter all subsequent projects, where $te_i > te^r_p$. This project, identified as project i, can either be shifted or shrunk left. See Figure 5.5.

The question is, which one of the two pseudo operations shall have precedence. A holistic approach is adopted when taking a decision is this regard. As this Part 1 deals with the establishing of the <u>initial constrained schedule</u> and because of the fact that the <u>final constrained scheduling</u> must still take place, as will be explained in Part 2 of this module, the <u>shift left operation</u> will take precedence over the shrink left pseudo operation during the initial constrained scheduling. Both of these pseudo operations come into effect during the final constrained scheduling. This aspect in finding the pseudo operation that will take precedence during the initial constrained scheduling, will be investigated in future research.

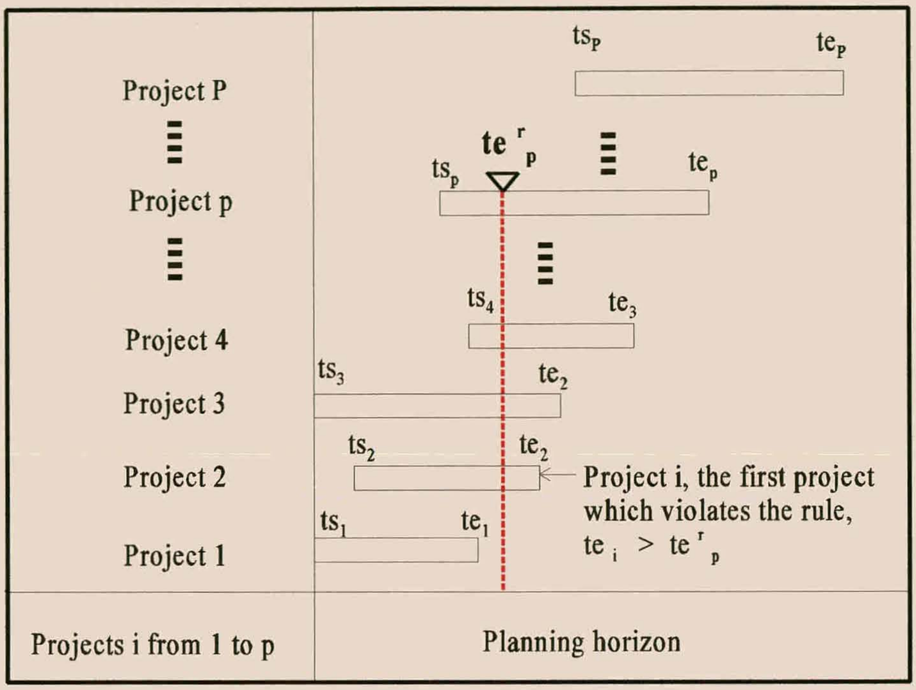


Figure 5.5 : Establishing of initial constrained schedule.

Shift left

The maximum number of time units project i can be shifted left is $\rho^L_i = \min\{(ts_i - 1), (te_i - te_{(i-1)}), (te_i - te^r_p)\}$ where $(ts_i - 1)$ prevents project i from starting before time 1, $(te_i - te_{(i-1)})$ prevents project i from finishing before project i-1, and $(te_i - te^r_p)$ prevents project i from finishing before te^r_p. As before, if $(te_i - te_{(i-1)}) < 0$ then $\rho^L_i = 0$.

Let ${}_nts_i = ts_i -$ <u>no</u> where ${}_nts_i$ is the new starting time of project i after left shift and <u>no</u> is the number of time units to left shift and <u>no</u> $= \rho^L_i$. As before, determine ${}_eR^n_{i(m+no)} = f^r_{it} * w_{i(m+no)}$ and ${}_nR^n_{im} = f^r_{it} * w_{im}$ for t = 1 to T_i where $m = t + {}_nts_i - i$. As before, $f^r_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

If projects $i \leq p$ is still violating the rule that $te_i \leq te^r_p$, then continue with the shrink left pseudo operation.

Shrink left

The maximum number of time units project i can be shrunk left is $v^L_i = \min \{ (te_i - te_{(i-1)}), (te_i - te^r_p), (T_i - Tmin_i)\}$ where $(te_i - te_{(i-1)})$ prevents project i from finishing before project i-1, $(te_i - te^r_p)$ prevents project i from finishing before te^r_p and $(T_i - Tmin_i)$ prevents the duration of project i from being reduced to a duration less than the minimum duration. If $(te_i - te_{(i-1)}) < 0$ then $v^L_i = 0$.

Let ${}_nts_i = ts_i$ where ${}_nts_i$ is the new starting time of project i after left shrink and no $= v^L_i$ is the number of time units to left shrink. Determine ${}_eR^n_{i\,m} = f^r_{it} * w_{i\,m}$ for $t = 1$ to T_i where $m = t + {}_nts_i - 1$. As before, $f^r_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$. Then determine ${}_nR^n_{i\,m} = f^r_{it} * w_{im}$ for $t = 1$ to T_i - no where $m = t + {}_nts_i - 1$. As before, $f^r_{it} = \alpha_i t^2 + \beta_i t + \gamma_i$.

It is important to note that due to constraints and the priority rule, it may happen that $te_p > te^r_p$ after both of the above pseudo operations have been implemented. In this case the particular project p will adopt te_p as the required completion date, i.e. $te^r_p = te_p$.

See Figure 5.6 for a presentation of the change in nominal cash flow after the free optimised schedule has been amended to form an initial constrained schedule.

Part 2: Further optimising of constrained schedule at macro pseudo level

This section is carried out the same way as paragraph 5.3 Module 2: final macro free scheduling, except that the required completion date for a project and the priority rule cannot be violated. Once this part has been completed, the final micro scheduling can commence.

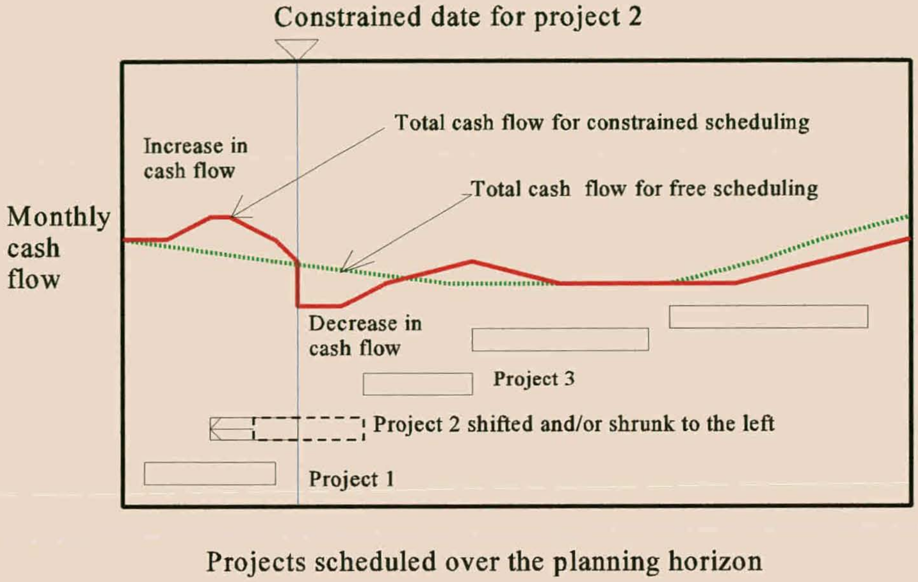


Figure 5.6 : Initial constrained scheduling.

Summary of Module 3

The final macro free schedule (Module 2) is now converted into a final macro constrained schedule where any of the project completion dates are switched on. Projects that are switched on will be finished before or on the required completion date as opposed to the other projects which will be completed at dates as determined by the optimisation process, in this case the final macro constrained scheduling process.

5.5 Module 4 : Final micro scheduling

Introduction

This module deals with the design principles, preparation for and implementation of the final micro scheduling of projects. The basic requirement in order to implement the final micro scheduling, is that either the final free or constrained macro scheduling must be completed. The original data that has been entered for each project will be used to execute the final scheduling.

Part 1 : Design principles of final micro scheduling

Introduction

A single project is scheduled during the initial pseudo macro scheduling. The nominal cash flows of the pseudo project are obtained while minimising the sum of the squares of all differences in project nominal cash flows and budget per month. This nominal cash flow of a pseudo project is part of an optimised schedule. If the phases and subprojects can be so scheduled that the difference between the nominal cash flow of the final schedule and the nominal pseudo cash flow is zero, then the original objective of minimising the sum of the squares of all differences of project nominal cash flows and budget per month will stay the same for all projects.

The objective for the micro scheduling is then to minimise the differences between final and pseudo project nominal cash flow. The smaller this difference is, the closer the result will be to the optimised macro schedule.

Micro scheduling rules

Chapter 4 described the various project scheduling sectors. This paragraph deals with the rules for scheduling phases and subprojects of a project within these sectors.

Sector 1 has been described as a combination of the concept and definition acquisition phases. Only two scheduling possibilities exist, namely all subprojects start at the beginning of the sector and then could end at different times, or all subprojects end at the end of the sector and then could start at different times. It is possible that a subproject could start at the beginning and end at the end of the sector. The start of the concept/definition phase of all subprojects does not have to coincide with the beginning of sector one. The scheduling rule that the concept/definition phase of all subprojects must end at the end of sector 1, i.e. right justified, is chosen here.

Sector 2 covers all subproject development and test and evaluation phases. It excludes the final system integration, test and evaluation, and qualification. The scheduling rule which is chosen here is that the last phase of all subprojects must end at the end of sector 2, i.e. right justified. The reason is that it would be better to start later with the development of a subproject but end as close as possible to the start of production, which take places in sector 4. The pre-production can be entered in either sector 4 or sector 3, which is the system test and evaluation phase. In this way the industry is being helped to prevent long durations of zero activity on the production line. The start of the subprojects in sector 2 can be any time after the beginning of the sector.

Sector 3 covers the final system integration, test and evaluation, and qualification. This sector starts immediately after the end of sector 2, i.e. left justified, and continues until completed.

Sector 4 is the production phase and can only be started after the completion of sector 3. To minimise zero activity on the production lines, production of all subprojects starts immediately, i.e. left justified, after the completion of sector 3. Sector 4 continues until the last production of any subproject has been completed.

Gonguet [35] made use of the left justified principle whereby all activities were scheduled as early as possible. The same principle applies to the research problem, with a slight modification. In the foregoing paragraphs the scheduling principles of right and left justified scheduling are used. At the macro level projects were scheduled according to project priority rules. Now, at a micro level and within a specific scheduling sector, subprojects are scheduled according to the left and right justified principles. The difference between the method used by Gonguet and that of the research problem is that all subprojects of a project within a specific sector will either end at the end or start at the beginning of the sector, depending on the sector which is under consideration.

Although the left and right justified rules have been chosen as set out above, other combinations would be possible. These are not considered in this research, however as they do not fit in the frame of reference of the research problem.

Summary of Part 1

Micro scheduling rules are established for each scheduling sector. The aim for sectors 1 and 2 will be to schedule all phases within these sectors in such a way that the schedule of phases for each subproject will be right justified, as opposed to sectors 3 and 4 where all phases will be left justified.

Part 2 : Preparation for micro scheduling

Introduction

Before the implementation of the micro scheduling takes place, it is necessary to identify the required data in order to do the final micro scheduling. Original data, such as supplier countries and applied currencies, as well as exchange rates are used in the preparation (Part 2) and the implementation (Part 3) processes. Data from the final pseudo (free or constrained) scheduling are also needed in order to do the micro scheduling. Each project is individually optimised and does not influence any of the other projects as the macro scheduling was applied to all projects.

The aim of Part 2 will be to determine all constants and variables for the micro optimisation process and to search for all feasible combinations of phase schedules within a project that will reduce the accumulated difference between the actual cash flow of the project and that of the cash flow of the pseudo project, which will be dealt with in Part 3.

Data from original phase data (already defined)

Data from the original phase data have already been defined as C_{ij} = supplier country of subproject j of project i, V_{ij} = currency in which the value was estimated for subproject j of project i and X_{ij} = exchange rate which apply for subproject j of project i.

$Rl^r_{ijk} = M^r_{ijk}$ and $Rf^r_{ijk} = M^r_{ijk} * X_{ij\,(y=0)}$ as explained in Module 1, Part 1 of this chapter. In the same Part 1, $\delta Tmin_{ijk}$, $\delta Tmax_{ijk}$ and δTav_{ijk} have been determined $\forall$ i = 1 to P_i, $\forall$ j = 1 to S_i and $\forall$ k = 1 to ϕ_{ij}.

Data from final pseudo (free or constraint) scheduling

At the end of the final pseudo scheduling, i.e. Module 2 and Module 3, the following information has been determined:

te^f, which is the end of schedule after final pseudo scheduling,
Γ^n_m, $\forall$ m = 1 to te^f, the available monthly budget,
W_{iy}, $\forall$ y = 1 to N_y, which is the annual escalation for project i,
w_{im}, $\forall$ m = 1 to te^f, which is the monthly escalation for project,
$Tmin_i$ = minimum time in which project i can be completed,
$Tmax_i$ = maximum time in which project i can be completed,
$Tmin_{i\tau}$ = minimum time in which sector τ of project i can be completed,
$Tmax_{i\tau}$ = maximum time in which sector τ of project i can be completed,
ts^*_i = the final starting time of each project i,
te^*_i = the final ending time of each project i,

$T^*_i = te^*_i - ts^*_i + 1$, the final duration of project i,

σ^*_i = selected profile for project i,

η^*_i = selected eta value for project i, and

R^r_i = total real rands for project i.

With T^*_i, R^r_i, σ^*_i and η^*_i, calculate profile constants α_i, β_i and γ_i, $f^r_{im} = \alpha_i t^2 + \beta_i t + \gamma_i$ and $f^n_{im} = f^r_{im} * w_{im}$ for t = 1 to T^*_i where $m = t + ts^*_i - 1$.

Determine sector variables and constants

The aim is to determine $T^*_{i\tau}$, the final duration of sector τ, with $Tmin_{i\tau} \leq T^*_{i\tau} \leq Tmax_{i\tau}$, for $\tau = 1, ..., 4$ so that $\sum T^*_{i\tau} = T^*_i$, i.e. equal to the final project duration as obtained from the final pseudo schedule. All possible combinations where $\sum T_{i\tau} = T_{i(\tau=1)} + T_{i(\tau=2)} + T_{i(\tau=3)} + T_{i(\tau=4)} = T^*_i$ will be investigated in order to find the final schedule, as will be explained in the remaining part of Module 4 of this chapter. When a specific $T_{i\tau}$ ends up as the final schedule which is optimised, then $T^*_{i\tau} = T_{i\tau}$ for τ = 1 to 4.

The following procedure must be used to find all possible combinations:

Define T_τ as a variable for the duration of sector τ. Then for $T_\tau = Tmin_{i\tau}$ to $Tmax_{i\tau}$ and for τ = 1 to 4, find each combination where $\Sigma T_\tau = T^*_i$. In each case where $\Sigma T_\tau = T^*_i$ define $T_{i\tau} = T_\tau$. Out of all cases where $T_{i\tau} = T_\tau$, there will be **one case where $T^*_{i\tau} = T_{i\tau} = T^*_i$, the final optimised value**, which will be determined later on. The total number of combinations out of which the cases can be selected which must be investigated, could be a very large number. Let $d_{i\tau} = Tmax_{i\tau} - Tmin_{i\tau} + 1$ be the difference between the maximum and minimum duration of sector τ which is also the total number of different values $T_{i\tau}$ can be. The total number of combinations from which $\sum T_{i\tau} = T^*_i$ can be selected = $\Pi(d_{i\tau})$ for τ = 1 to 4, i.e. $d_{i1} * d_{i2} * d_{i3} * d_{i4}$. This will be the correct method to follow. If a large number of projects are analysed and if computer time is a problem, then this method may not be followed and it would be quicker to search for only a few combinations where $\sum T_{i\tau} = T^*_i$ in order to save computer time.

The next method is proposed for the research problem to reduce the number of combinations and will be explained by means of an example. As this is not the best solution, it provides a basis from which future research can be conducted in order to find a method where all "suitable" combinations can be investigated.

Let $d_{i\tau} = Tmax_{i\tau} - Tmin_{i\tau} + 1$ be the difference between the maximum and minimum duration of sector τ of project i and define $D_i = \Sigma\ d_{i\tau}$ and $Tmin_i = \Sigma\ Tmin_{i\tau}$ for $\tau = 1, \dots , 4$.

Define $d_{i\tau} / D_i$ the weight of the difference of sector τ to the sum of the differences for all the sectors which is indicating the relative value of sector τ compared to the other sectors. Next, a value $T^w_{i\tau}$, which is a weighted duration of each sector relative to the total duration T^*_i. Define $T^w_{i\tau} = Tmin_{i\tau} + d_{i\tau} / D_i * (T^*_i - Tmin_i)$ which is a non-discrete value. The second term is the weighted proportion of the excess of total project duration over the minimum project duration, which is added to the sector's minimum time to give the sector time $T^w_{i\tau}$. This gives a single combination of $\sum T^w_{i\tau} = T^*_i$ but in this case the sector duration $T^w_{i\tau}$ is a non-discrete value for τ = 1 to 4 which is not allowed as the time units, which is in this case months, should be discrete values. From this one combination, which is in non-discrete values, a small number of possible combinations can be constructed but in discrete values.

The aim is now to find a number of discrete values for $T_{i\tau}$ but which is close to the non-discrete value of $T^w_{i\tau}$. The reason why $T_{i\tau}$ should be close to $T^w_{i\tau}$ is again to prevent too many possible combinations. For the research problem, determine $T_{i\tau}$ where $[\text{integer } T^w_{i\tau}] \leq T_{i\tau} \leq [\text{integer } (T^w_{i\tau} + 1)]$, for $\tau = 1 \dots, 4$ with $\sum T_{i\tau} = T^*_i$, thus giving $T_{i(\tau=1)} + T_{i(\tau=2)} + T_{i(\tau=3)} + T_{i(\tau=4)} = T^*_i$. If $T_{i\tau} > Tmax_{i\tau}$, then $T_{i\tau} = Tmax_{i\tau}$. It should be noted that in this case only two values are investigated, i.e. one discrete below and above the non-discrete value $T^w_{i\tau}$. Other possible combinations can be investigated in future research. As before, there exists a combination where $\sum T_{i\tau} = T^*_i$ which is the optimised schedule, thus resulting in $T^*_{i\tau} = T_{i\tau}$, the final sector durations.

Example:

Let $T^*_i = 120$ as the final duration of project i.

	Sector 1	Sector 2	Sector 3	Sector 4
$Tmin_{i\tau}$	20	40	9	30
$Tmax_{i\tau}$	28	56	15	42
$d_{i\tau} = Tmax_{i\tau} - Tmin_{i\tau} + 1$	9	17	7	13
$D_i = 9 + 17 + 7 + 13 = 46$				
$Tmin_i = 20 + 40 + 9 + 30 = 99$				
$T^w_{i\tau} = Tmin_{i\tau} + d_{i\tau} / D_i * (T^*_i - Tmin_i)$	24.109	47.761	12.196	35.935
Integer of $T^w_{i\tau}$	24	47	12	35
Integer of $(T^w_{i\tau} + 1)$	25	48	13	36

If the number of possible combinations would be determined, this number would be 9*17*7*13=13,923 compared to the fewer number of combinations = 2*2*2*2 = 16.

If for instance $T_{i\tau}$ was determined where [integer $T^w_{i\tau}$] - 1 $\leq T_{i\tau} \leq$ [integer $(T^w_{i\tau} + 2)$], for $\tau = 1 ..., 4$, the boundaries for $T_{i\tau}$ would have been:

(Integer of $T^w_{i\tau}$) -1	23	46	11	34
Integer of $(T^w_{i\tau} + 2)$	26	49	14	37

This would give more combinations in a wider range to investigate and would be equal to 4*4*4*4 = 256.

Thus, as seen from the example, combinations will be formed where $T_{i1} + T_{i2} + T_{i3} + T_{i4} = T^*_i = 120$ for $T_{i1} = 24$ to 25, $T_{i2} = 47$ to 48, $T_{i3} = 12$ to 13 and T_{i4} 35 to 36. These combinations will be used as a basis from which follow-on calculations will be done. It can be seen that this method reduces the number of combinations from the original possible number of combinations.

It is necessary to give some **background** before continuing with the mathematical formulation. At this stage project i is scheduled with a total duration of T^*_i and having a starting time of ts^*_i and a finishing time of te^*_i. The duration of each sector is defined as $T^*_{i\tau}$ where $\Sigma\, T^*_{i\tau} = T^*_i$ for $\tau = 1$ to 4. Each project has a pseudo cash flow profile in the form of $f^r_i = \alpha^*_i t^2 + \beta^*_i t + \gamma^*$ where t is discrete values from 1 to T^*_i. This cash flow profile runs across the sector boundaries. The aim is now to determine **sector constants** for each combination, thus going from a project level to a sector level. For each sector, the starting and finishing times as well as the starting and finishing slopes of the cash flow profile must be determined. These values will be used during the final optimising process. The starting and finishing slopes of the cash flow profile in each sector, are determined from $f^r_i = \alpha^*_i t^2 + \beta^*_i t + \gamma^*$. These slopes will again be used in Module 4, Part 3, the implementation of the final micro schedule. Define $\theta_i = df/dt = 2\alpha^*_i t + \beta^*_i$ as the slope of the pseudo cash flow profile of project i at time t. For each sector define $ts_{i\tau}$ as the starting time, $te_{i\tau}$ as the finishing time, $\theta s_{i\tau}$ as the starting slope and $\theta e_{i\tau}$ as the finishing slope. The constants for each sector can now be determined:

Sector 1

$ts_{i\,(\tau=1)} = ts^*_i$ the starting time of sector 1

$te_{i\,(\tau=1)} = ts_{i\,(\tau=1)} + T^*_{i\,(\tau=1)} - 1$ the finishing time of sector 1

$\theta s_{i\,(\tau=1)} = 2\alpha_i + \beta_i$ the starting slope of the cash flow profile in sector 1

$\theta e_{i\,(\tau=1)} = 2\alpha_i\, T^*_{i\,(\tau=1)} + \beta_i$ the finishing slope of the cash flow profile in sector 1

The same definitions apply to the next three sectors.

Sector 2

$ts_{i(\tau=2)} = te_{i(\tau=1)} + 1$

$te_{i(\tau=2)} = ts_{i(\tau=2)} + T^*_{i(\tau=2)} - 1$

$\theta s_{i(\tau=2)} = 2\alpha_i (T^*_{i(\tau=1)} + 1) + \beta_i$

$\theta e_{i(\tau=2)} = 2\alpha_i (T^*_{i(\tau=1)} + T^*_{i(\tau=2)}) + \beta_i$

Sector 3

$ts_{i(\tau=3)} = te_{i(\tau=2)} + 1$

$te_{i(\tau=3)} = ts_{i(\tau=3)} + T_{i(\tau=3)} - 1$

$\theta s_{i(\tau=3)} = 2\alpha_i (T^*_{i(\tau=1)} + T^*_{i(\tau=2)} + 1) + \beta_i$

$\theta e_{i(\tau=3)} = 2\alpha_i (T^*_{i(\tau=1)} + T^*_{i(\tau=2)} + T^*_{i(\tau=3)}) + \beta_i$

Sector 4

$ts_{i(\tau=4)} = te_{i(\tau=3)} + 1$

$te_{i(\tau=4)} = ts_{i(\tau=4)} + T^*_{i(\tau=4)} - 1$

$\theta s_{i(\tau=4)} = 2\alpha_i (T^*_{i(\tau=1)} + T^*_{i(\tau=2)} + T^*_{i(\tau=3)} + 1) + \beta_i$

$\theta e_{i(\tau=4)} = 2\alpha_i (T^*_{i(\tau=1)} + T^*_{i(\tau=2)} + T^*_{i(\tau=3)} + T^*_{i(\tau=4)}) + \beta_i$

For a specific combination of $T^*_{i\tau}$ for $\tau = 1$ to 4, the starting and finishing times and slopes are now known.

<u>Determine subproject schedule constants per sector</u>

This paragraph determines specific subproject constants per sector, namely the limitations of a subproject within a sector. The following variables are defined:

$Tmin_{ij\tau}$ as the minimum duration of subproject j in sector τ

$Tmax_{ij\tau}$ as the maximum duration of subproject j in sector τ

$te_{ij\tau}$ as the starting time of subproject j in sector τ

$ts_{ij\tau}$ as the finishing time of subproject j in sector τ

$R^r_{ij\tau}$ as the real value of subproject j in sector τ

$R^r_{i\tau}$ as the real value of project j in sector τ

$T^0_{ij\tau}$ as the initial duration of subproject j in sector τ

Sector 1

Sector 1 consists of only one phase per subproject. Let $Tmin_{ij(\tau=1)} = \delta Tmin_{ij(k=1)}$ and let $Tmax_{ij(\tau=1)} = \delta Tmax_{ij(k=1)}$ as obtained from earlier calculations. The finishing times of the sectors have been determined in the previous paragraphs and are therefore known. The finishing time of the subproject within the sector is then equal to the finishing time of the sector, i.e. $te_{ij(\tau=1)} = te_{i(\tau=1)}$. The initial duration of the sector is $T^0_{ij(\tau=1)}$ and is set as $Tmax_{ij(\tau=1)}$, the maximum duration subproject j will be in sector τ. As all the subprojects in sector τ will be right justified, the starting time for subproject j in sector τ is $ts_{ij(\tau=1)} = te_{i(\tau=1)} - T^0_{ij(\tau=1)} + 1$ which is a backward scheduling. If the starting time of the subproject j in sector τ, $ts_{ij(\tau=1)}$ is earlier (or $\leq$) than the starting time of sector τ, $ts_{i(\tau=1)}$, then $ts_{ij(\tau=1)} = ts_{i(\tau=1)}$. This is to prevent the subproject from starting earlier than the sector. Also $R^r_{ij(\tau=1)} = R^r_{ij(k=1)}$ and $R^r_{i(\tau=1)} = \sum R^r_{ij(\tau=1)}\ \forall j$.

Note : The above explanations also apply to the following sectors and will not be explained in detail again. Only different aspects will be explained.

Sector 2, which consists of six phases per subproject.

As explained at the beginning of this chapter where the definitions of various parameters were given and explained, $\delta Tmin_{ijk}$ and $\delta Tmax_{ijk}$ are the minimum and maximum durations for phase k of subproject j of project i. The assumption was made that the final duration of a phase may be any value from $\delta Tmin_{ijk}$ to $\delta Tmax_{ijk}$ and that such a value will not change the scope of the work and that the cost of the phase will not be affected as such, therefore allowing durations from $\delta Tmin_{ijk}$ to $\delta Tmax_{ijk}$ as feasible durations.

$Tmin_{ij\,(\tau=2)} = \sum \delta Tmin_{ijk}$ for k = 2 to 7
$Tmax_{ij\,(\tau=2)} = \sum \delta Tmax_{ijk}$ for k = 2 to 7
$T^0_{ij(\tau=2)} = Tmax_{ij\,(\tau=2)}$
$te_{ij\,(\tau=2)} = te_{i\,(\tau=2)}$ (because of the scheduling rule that all the subprojects will be right justified)
$ts_{ij\,(\tau=2)} = te_{i\,(\tau=2)} - T^0_{ij(\tau=2)} + 1$ but if $ts_{ij\,(\tau=2)} \leq ts_{i\,(\tau=2}$ then $ts_{ij\,(\tau=2} = ts_{i\,(\tau=2}$
$R^r_{ij\,(\tau=2)} = \sum R^r_{ijk}$ for k = 2 to 7
$R^r_{i\,(\tau=2)} = \sum R^r_{ij\,(\tau=2)}\ \forall j$

Sector 3, which consists of only one phase per subproject.

$Tmin_{ij\,(\tau=3)} = \delta Tmin_{ij\,(k=8)}$
$Tmax_{ij\,(\tau=3)} = \delta Tmax_{ij\,(k=8)}$
$T^0_{ij\,(\tau=3)} = Tmax_{ij\,(\tau=3)}$
$ts_{ij\,(\tau=3)} = ts_{i\,(\tau=3)}$ (because of the scheduling rule that all the subprojects will be left justified)
$te_{ij\,(\tau=3)} = ts_{i\,(\tau=3)} + T^0_{ij\,(\tau=3)} - 1$ but if $te_{ij\,(\tau=3)} > te_{i\,(\tau=3)}$ then $te_{ij\,(\tau=3)} = te_{i\,(\tau=3)}$
$R^r_{ij\,(\tau=3)} = R^r_{ij\,(k=8)}$
$R^r_{i\,(\tau=3)} = \sum R^r_{ij\,(\tau=8)}\ \forall j$

Sector 4, which consists of only one phase per subproject.

$Tmin_{ij\,(\tau=4)} = \delta Tmin_{ij\,(k=9)}$
$Tmax_{ij\,(\tau=4)} = \delta Tmax_{ij\,(k=9)}$

$T^0_{ij(\tau=4)} = Tmax_{ij(\tau=4)}$

$ts_{ij(\tau=4)} = ts_{i(\tau=4)}$ (because of the scheduling rule that all the subprojects will be left justified)

$te_{ij(\tau=4)} = ts_{i(\tau=4)} + T^0_{ij(\tau=4)} - 1$ but if $te_{ij(\tau=4)} > te_{i(\tau=4)}$ then $te_{ij(\tau=4)} = te_{i(\tau=4)}$

$R^r_{ij(\tau=4)} = R^r_{ij(k=9)}$

$R^r_{i(\tau=4)} = \sum R^r_{ij(\tau=4)}\ \forall j$

Subproject search ranges per sector

For each sector investigate all possible durations from the minimum to the maximum duration of the sector in order to find a final starting and final finishing time for each sector. Again, all possible combinations must be investigated, which will be formed by the various durations of each sector. The aim of this paragraph is to determine search ranges for each subproject in each sector. See Figure 5.7 to follow the forming of the search ranges. The dotted range in the figure identifies the search range of the sector.

In sectors 1 and 2 the subprojects will be right justified. The earliest starting time of the subproject will be the finishing time of the sector **minus** the maximum duration of the subproject **plus** 1. This date will be defined as the starting date of the search range. The latest starting time of the subproject will be the finishing time of the sector **minus** the minimum duration of the project **plus** 1. This date will be defined as the ending (finishing) date of the search range.

In sectors 3 and 4, the subprojects will be left justified. The earliest finishing time of the subproject will be the starting time of the sector **plus** the minimum duration of the subproject **minus** 1. This date will be defined as the starting date of the search range. The latest finishing time of the subproject will be the starting time of the sector **plus** the maximum duration of the project **minus** 1. This date will be defined as the ending (finishing) date of the search range.

Sector 1

The starting time of the search range is $sts_{ij(\tau=1)} = te_{i(\tau=1)} - Tmax_{ij(\tau=1)} + 1$ and the ending time of the search range is $ets_{ij(\tau=1)} = te_{i(\tau=1)} - Tmin_{ij(\tau=1)} + 1$.

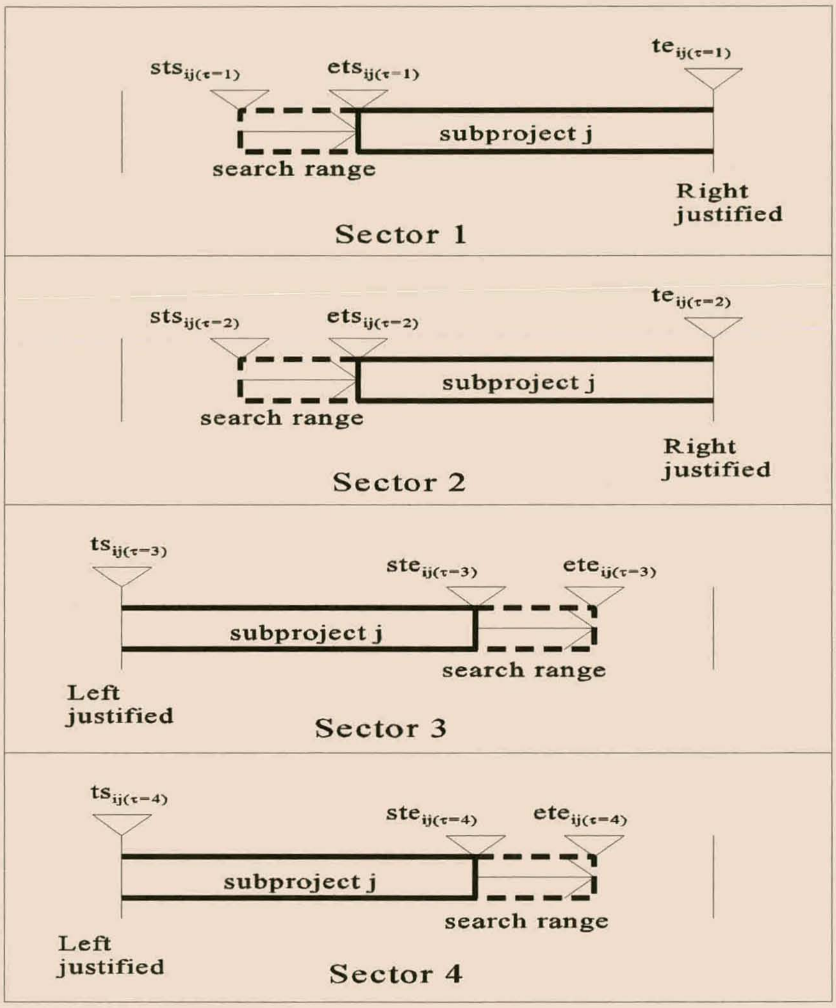


Figure 5.7 : Search ranges per subproject and per sector.

Sector 2

The starting time of the search range is $sts_{i\,j\,(\tau=2)} = te_{i\,(\tau=2)} - Tmax_{ij\,(\tau=2)} + 1$ and the ending time of the search range is $ets_{i\,j\,(\tau=2)} = te_{i\,(\tau=2)} - Tmin_{ij\,(\tau=2)} + 1$.

Sector 3

The starting time of the search range is $ste_{i\,j\,(\tau=3)} = ts_{i\,(\tau=3)} + Tmin_{ij\,(\tau=3)} - 1$ and the ending time of the search range is $ete_{i\,j\,(\tau=3)} = ts_{i\,(\tau=3)} + Tmax_{ij\,(\tau=3)} - 1$.

Sector 4

The starting time of the search range is $ste_{i\,j\,(\tau=4)} = ts_{i\,(\tau=4)} + Tmin_{ij\,(\tau=4)} - 1$ and the ending time of the search range is $ete_{i\,j\,(\tau=4)} = ts_{i\,(\tau=4)} + Tmax_{ij\,(\tau=4)} - 1$.

The above sector search ranges apply to every subproject of a project within a sector.

Summary of Part 2

At the beginning of Part 2, preparation for micro scheduling, it was first described how combinations are found in order to determine $T^*_{i\tau}$, the final durations for each sector, and how the number of combinations are reduced to save computer time. Now at the end of Part 2, search ranges are determined from which the final starting times for subprojects in sectors 1 and 2 as well as final ending times for subprojects in sectors 3 and 4 will be determined, as will be explained in Part 3, implementation of final micro scheduling.

The recommended way will be to investigate all possible combinations of the starting and ending times of the subprojects in sector 1 and 2, and sectors 3 and 4 respectively. As in the case of determining $T^*_{i\tau}$, the number of possible combinations will also be large and is therefore reduced to save computing time. Although the following approach is adopted for the research problem, it is also proposed that this aspect of finding better search methods should be investigated in further research. The analogy that is adopted is that of the optimising technique used in linear programming where all variables are evaluated at extreme points. Thus, for the research problem only the values for the beginning and ending of the search ranges will be evaluated. It is again emphasised that this search method should be further investigated in future research.

All the necessary information has been determined to allow implementation of the final micro schedule as described on Part 3.

Part 3 : Implementation of final micro scheduling

Introduction

In Module 1 of this chapter, the initial scheduling of the pseudo projects was implemented, giving the initial macro schedule. In Module 2 this initial schedule was transformed into a final macro pseudo schedule, and in the case of Module 3, the final macro constrained schedule. The result of the macro scheduling is that every project has a starting and finishing time as well as a pseudo cash flow profile.

In Part 1 and Part 2 of Module 4, design principles and the necessary preparation for micro scheduling have been done. In Part 3, the implementation of the micro scheduling is done. In the previous modules, all projects were used in order to find a final macro pseudo schedule. Now that a macro schedule has been determined, a single project at a time will now be optimised, and this will continue until all individual projects are optimised.

This section deals with the scheduling of all phases and subprojects per project and per project scheduling sector.

Given a specific project i, find $t^*s_{ij\,(\tau=1)}$, $t^*s_{ij\,(\tau=2)}$, $t^*e_{ij\,(\tau=3)}$ and $t^*e_{ij\,(\tau=4)}$ for $j = 1, ..., S_i$ and where

$sts_{ij\,(\tau=1)} \leq t^*s_{ij\,(\tau=1)} \leq ets_{ij\,(\tau=1)}$,

$sts_{ij\,(\tau=2)} \leq t^*s_{ij\,(\tau=2)} \leq ets_{ij\,(\tau=2)}$,

$ste_{ij\,(\tau=3)} \leq t^*e_{ij\,(\tau=3)} \leq ete_{ij\,(\tau=3)}$,

and $ste_{ij\,(\tau=4)} \leq t^*e_{ij\,(\tau=4)} \leq ete_{ij\,(\tau=4)}$ so that $\sum (R^{fn}_{im} - R^{*n}_{im})^2$ is a minimum for for $m = ts^*_i$ to te^*_i where R^{fn}_{im} is the final pseudo project cash flow and R^{*n}_{im} is the final optimal cash flow of project i.

Subproject sector scheduling

The following variables have been determined in Part 2:

$R^r_{i\tau}$ = the real rand value of sector τ of project i,

$R^r_{ij\tau}$ = the real rand value of subproject j of project i in sector τ,

$\theta s_{i\tau}$ = the slope of the pseudo profile at the beginning of sector τ, and

$\theta e_{i\tau}$ = the slope of the pseudo profile at the end of sector τ.

The slopes will be used in subsequent sections in order to determine the cash flow profiles for each sector and for each subproject in a sector. Sector and subproject profiles will be based on the project's pseudo cash flow profile and on the value of the subproject in the sector compared to the total value of all subprojects in that sector.

Constants of cash flow profile per subproject and per sector

Let $T^*_{ij\tau}$ = the optimal duration of each subproject per sector τ of project i. It is assumed that each and every subproject within a sector will take the form of the pseudo cash flow profile within the sector. This assumption is made in order to simplify the calculations which follow. Other methods to simulate profiles for each subproject of a project should be investigated in future research. The start and end slope of the subproject will be *pro rata* to the start and end slopes of the sector of the pseudo cash flow profile, which is based on the value of the project in a sector. The pseudo slopes are used to determine the slopes for each subproject and for each sector. These subproject values per sector will be used to simulate the subproject cash flow profile in a sector. The calculations are as follows: For a parabolic curve, let $\theta s_{ij\tau} = \theta s_{i\tau} * R^r_{ij\tau} / R^r_{i\tau}$ and $\theta e_{ij\tau} = \theta e_{i\tau} * R^r_{ij\tau} / R^r_{i\tau}$. As before, let $f = \alpha t^2 + \beta t + \gamma$ with $df/dt = 2\alpha t + \beta$. At $t = 1$, $\theta s_{ij\tau} = 2\alpha + \beta$ and at $t = T^*_{ij\tau}$, $\theta e_{ij\tau} = 2\alpha T^*_{ij\tau} + \beta$ resulting in $\alpha_{ij\tau} = (\theta e_{ij\tau} - \theta s_{ij\tau}) / [2 * (T^*_{ij\tau} - 1)]$ and $\beta_{ij\tau} = \theta s_{ij\tau} - 2\alpha_{ij\tau}$ which are the constants for the cash flow profile for sector τ of subproject j of project i.

As before (see Appendix C formula C.38)

$$\therefore \frac{R}{\bar{t}} = I = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha + \frac{1}{2}(\bar{t}+1)\beta + \gamma$$

Substitute $\alpha_{ij\tau}$ and $\beta_{ij\tau}$ in the above equation and solve for $\gamma_{ij\tau}$

$$\gamma_{ij\tau} = \frac{R^c_{ij\tau}}{T^*_{ij\tau}} - \frac{(T^*_{ij\tau}+1)(2T^*_{ij\tau}+1)}{6}\alpha_{ij\tau} - \frac{1}{2}(T^*_{ij\tau}+1)\beta_{ij\tau}$$

If $T^*_{ij\tau} = 1$ then $\alpha_{ij\tau} = \beta_{ij\tau} = 0$. Once the constants have been determined, cash flow profiles for each sector can be calculated.

Sector 1

Let $R^r_{i(\tau=1)}$ = the real rand value of sector $\tau=1$ of project i,
$R^r_{ij(\tau=1)}$ = the real rand value of subproject j of project i in sector $\tau = 1$,
$\theta s_{i(\tau=1)}$ = the slope of the pseudo profile at the beginning of sector $\tau = 1$,

$\theta e_{i\,(\tau=1)}$ = the slope of the pseudo profile at the end of sector $\tau = 1$, and

$T^*_{ij\,(\tau=1)} = te_{i\,(\tau=1)} - ts^*_{ij\,(\tau=1)} + 1$, the duration of each subproject per sector of project i.

Then determine $\alpha_{ij\,(\tau=1)}$, $\beta_{ij\,(\tau=1)}$, $\gamma_{ij\,(\tau=1)}$, $\theta s_{ij\,(\tau=1)}$ and $\theta e_{ij\,(\tau=1)}$.

Define w^a_{ijm} : w^a_{ijm} is equivalent to w_{im} but in this case the actual inflation rate and exchange rate (if applicable) are used to calculate the escalation factor. It is not a weighted escalation factor, but actual for the subproject over the project's makespan.

$R^{sn}_{ijm(\tau=1)} = (\alpha_{ij\,(\tau=1)}\, t^2 + \beta_{ij\,(\tau=1)}\, t + \gamma_{ij\,(\tau=1)}) * w^a_{ijm}$ which is the nominal monthly cash flow per subproject per sector for $t = 1$ to $T^*_{ij\,(\tau=1)}$ where $m = t + ts^*_{ij\,(\tau=1)} - 1$ (or $m = ts^*_{ij\,(\tau=1)}$ to $ts^*_{ij\,(\tau=1)} + T^*_{ij\,(\tau=1)} - 1$). If $R^{sn}_{ijm\,(\tau=1)} < 0$ for any m, adjust $\theta_{si(\tau=1)}$ and $\theta_{ei(\tau=1)}$ incrementally as per Table 5.1 so that $R^{sn}_{ijm\,(\tau=1)} \geq 0\ \forall$ m.

Finally for sector 1, $R^{sn}_{im(\tau=1)} = \sum_j R^{sn}_{ijm(\tau=1)}$ for $j = 1$ to S_i and $\forall$ m, which is the summation of the actual nominal cash flows of all subprojects within the sector.

Sector 2

$R^r_{i\,(\tau=2)}$ = the real rand value of sector τ=2 of project i,

$R^r_{ij\,(\tau=2)}$ = the real rand value of subproject j of project i in sector τ=2,

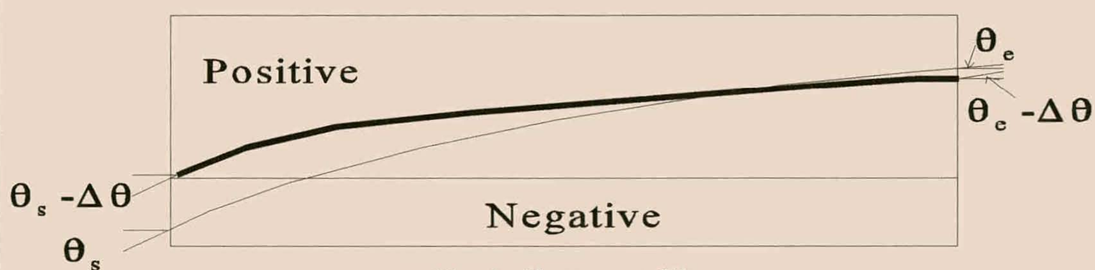
$\theta s_{i\,(\tau=2)}$ = the slope of the pseudo profile at the beginning of sector τ=2,

$\theta e_{i\,(\tau=2)}$ = the slope of the pseudo profile at the end of sector τ=2, and

$T^*_{ij\,(\tau=2)} = te_{i\,(\tau=2)} - ts^*_{ij\,(\tau=2)} + 1$, the duration of each subproject per sector of project i.

Determine $\alpha_{ij\,(\tau=2)}$, $\beta_{ij\,(\tau=2)}$, $\gamma_{ij\,(\tau=2)}$, $\theta s_{ij\,(\tau=2)}$ and $\theta e_{ij\,(\tau=2)}$ and $R^{sn}_{ijm(\tau=2)} = (\alpha_{ij\,(\tau=2)}\, t^2 + \beta_{ij\,(\tau=2)}\, t + \gamma_{ij\,(\tau=2)}) * w^a_{ijm}$ which is the nominal monthly cash flow per subproject per sector and with w^a_{ijm} as defined previously for $t = 1$ to $T^*_{ij\,(\tau=2)}$ where $m = t + ts^*_{ij\,(\tau=2)} - 1$ (or $m = ts^*_{ij\,(\tau=2)}$ to $ts^*_{ij\,(\tau=2)} + T^*_{ij\,(\tau=2)} - 1$). If $R^{sn}_{ijm\,(\tau=2)} < 0$ for any m, adjust $\theta_{si(\tau=2)}$ and $\theta_{ei(\tau=2)}$ incrementally as per Table 5.1 so that $R^{sn}_{ijm(\tau=2)} \geq 0\ \forall$ m. Finally for the sector 2, $R^{sn}_{im(\tau=2)} = \sum_j R^{sn}_{ijm(\tau=2)}$ for $j = 1$ to S_i and $\forall$ m.

Case	If θ_s	If θ_e	Then operation on θ_s	Then operation on θ_e
1	> 0	> 0	$\theta_s - \Delta\theta$	$\theta_e - \Delta\theta$
2			$\theta_s - \Delta\theta$	$\theta_e - \Delta\theta$
3	< 0	< 0	$\theta_s + \Delta\theta$	$\theta_e + \Delta\theta$
4			$\theta_s + \Delta\theta$	$\theta_e + \Delta\theta$
5	> 0	< 0	$\theta_s - \Delta\theta$	$\theta_e - \Delta\theta$
6			$\theta_s - \Delta\theta$	$\theta_e - \Delta\theta$
7	< 0	> 0	$\theta_s + \Delta\theta$	$\theta_e + \Delta\theta$
8			$\theta_s + \Delta\theta$	$\theta_e + \Delta\theta$



Cash flow profile

Notes:

1. θ is in radiants
2. $\Delta\theta$ is a small positive value
3. Increase $\Delta\theta$ in very small increments so that $R^{sn}_{ijm\tau} \geq 0 \ \forall \ m$
4. The operation is in effect a rotation, with no change in signs

Table 5.1 : Changes to θ_s and θ_e due to negative cash flow values.

Note: As there are six phases per subproject in sector 2, and calculations have been made for the subprojects within a sector, further refinement will be necessary in order to finally optimise the phases. These calculations are shown in the next subparagraph 'Phase scheduling'.

Sector 3

Let $R^r_{i\,(\tau=3)}$ = the real rand value of sector τ=3 of project i,
$R^r_{i\,j\,(\tau=3)}$ = the real rand value of subproject j of project i in sector τ=3,
$\theta s_{i\,(\tau=3)}$ = the slope of the pseudo profile at the beginning of sector τ=3,
$\theta e_{i\,(\tau=3)}$ = the slope of the pseudo profile at the end of sector τ=3, and
$T^*_{ij\,(\tau=3)} = te^*_{ij\,(\tau=3)} - ts_{i\,(\tau=3)} + 1$, the duration of each subproject per sector of project i.

Then determine $\alpha_{ij\,(\tau=3)}$, $\beta_{ij\,(\tau=3)}$, $\gamma_{ij\,(\tau=3)}$, $\theta s_{ij\,(\tau=3)}$ and $\theta e_{ij\,(\tau=3)}$ and $R^{s\,n}_{ijm(\tau=3)} = (\alpha_{ij\,(\tau=3)}\,t^2 + \beta_{ij\,(\tau=3)}\,t + \gamma_{ij\,(\tau=3)}) * w^a_{ijm}$ which is the nominal monthly cash flow per subproject per sector and with w^a_{ijm} as defined previously for t = 1 to $T^*_{ij\,(\tau=3)}$ where $m = t + ts^*_{ij\,(\tau=3)} - 1$ (or m = $ts^*_{ij\,(\tau=3)}$ to $ts^*_{ij\,(\tau=3)} + T^*_{ij\,(\tau=3)} - 1$). If $R^{sn}_{ijm\,(\tau=3)} < 0$ for any m, adjust $\theta_{si(\tau=3)}$ and $\theta_{ei(\tau=3)}$ incrementally as per Table 5.1 so that $R^{sn}_{ijm\,(\tau=3)} \geq 0\ \forall$ m. Finally for sector 3, $R^{sn}_{im(\tau=3)} = \sum_j R^{s\,n}_{ijm(\tau=3)}$ for j = 1 to S_i and $\forall$ m.

Sector 4

Let $R^r_{i\,(\tau=4)}$ = the real rand value of sector τ=4 of project i,
$R^r_{i\,j\,(\tau=4)}$ = the real rand value of subproject j of project i in sector τ=4,
$\theta s_{i\,(\tau=4)}$ = the slope of the pseudo profile at the beginning of sector τ=4,
$\theta e_{i\,(\tau=4)}$ = the slope of the pseudo profile at the end of sector τ=4, and
$T^*_{ij\,(\tau=4)} = te^*_{ij\,(\tau=4)} - ts_{i\,(\tau=4)} + 1$, the duration of each subproject per sector of project i.

Then determine $\alpha_{ij\,(\tau=4)}$, $\beta_{ij\,(\tau=4)}$, $\gamma_{ij\,(\tau=4)}$, $\theta s_{ij\,(\tau=4)}$ and $\theta e_{ij\,(\tau=4)}$ and $R^{s\,n}_{ijm(\tau=4)} = (\alpha_{ij\,(\tau=4)}\,t^2 + \beta_{ij\,(\tau=4)}\,t + \gamma_{ij\,(\tau=4)}) * w^a_{ijm}$ which is the nominal monthly cash flow per subproject per sector and w^a_{ijm} as defined previously for t = 1 to $T^*_{ij\,(\tau=4)}$ where $m = t + ts^*_{ij\,(\tau=4)} - 1$ (or m = $ts^*_{ij\,(\tau=4)}$ to $ts^*_{ij\,(\tau=4)}$

$+ T^{*}_{ij\,(\tau=4)} - 1)$. If $R^{sn}_{ijm\,(\tau=4)} < 0$ for any m, adjust $\theta_{si(\tau=4)}$ and $\theta_{ei(\tau=4)}$ incrementally as per Table 5.1 so that $R^{sn}_{ijm\,(\tau=4)} \geq 0 \; \forall$ m. Finally for sector 4, $R^{sn}_{im(\tau=4)} = \sum_j R^{s\,n}_{ijm(\tau=4)}$ for $j = 1$ to S_i and $\forall$ m.

The total monthly value of all subprojects is then the monthly values of each sector added together, giving $R^{sn}_{im} = \sum_\tau R^{s\,n}_{im\tau}$ for $\tau = 1$ to 4 such that $\sum (R^{f\,n}_{im} - R^{sn}_{im})^2$ is a minimum for m $= ts^{*}_{i}$ to te^{*}_{i}. This is not the final optimal cash flow. $R^{*\,n}_{im}$ must still be determined once the phases have been optimised. At the end of the subproject scheduling, the final starting and finishing times as well as the simulated cash flow profile are known.

Phase scheduling

Once the optimising at subproject level has been completed, final optimising at phase level will be possible. Because sectors 1, 3 and 4 all have only one phase, phase scheduling will only be executed in sector 2. The following paragraphs explain how to schedule the phases of a subproject within the starting and finishing times of the subproject.

For sectors 1, 3 and 4:

Only one phase per subproject must be optimised, giving trivial results, namely that

$R^{\phi n}_{im(\tau=1)} = R^{sn}_{im(\tau=1)}$,

$R^{\phi n}_{im(\tau=3)} = R^{sn}_{im(\tau=3)}$,

$R^{\phi n}_{im(\tau=4)} = R^{sn}_{im(\tau=4)}$, and where $R^{\phi n}_{im\tau}$ is the cash flow of project i at phase level in sector τ. The starting and finishing times of the phase in a sector will therefore be the same as the starting and finishing times of the subproject.

Sector 2

Sector 2 has more than one phase per subproject and will therefore need some kind of optimisation as against sectors 1, 3 and 4.

Let per project i, $R^{r}_{ij(\tau=2)}$ = the real rand value of subproject j in sector τ=2,
$R^{r}_{ijk(\tau=2)}$ = the real rand value of phase k of subproject j in sector τ=2,
$\theta s_{ij\ (\tau=2)}$ = the slope of the cash flow profile at the beginning of subproject j per sector τ=2,
$\theta e_{ij\ (\tau=2)}$ =the slope of the cash flow profile at the end of subproject j per sector τ=2, and
$T^{*}_{ijk\ (\tau=2)}$ = the optimal duration of phase k per subproject j per sector τ=2 where
$\delta Tmin_{ijk} \leq T^{*}_{ijk\ (\tau=2)} \leq \delta Tmax_{ijk}$ and $T^{*}_{ij\ (\tau=2)} = \sum_k T^{*}_{ijk\ (\tau=2)}$ for k = 2 to 7. This is so because it was assumed that the phases are sequential. It also implies that the starting time of the first phase of the subproject is equal to the starting time of the subproject, and that the finishing time of the last phase of the subproject is equal the finishing time of the subproject.

This results in the following phase starting and finishing times which are determined by means of backward scheduling. As previously defined, the subprojects in sector 2 are right justified, which implies that the last phase of the subproject in sector 2 must end at the finishing time of the subproject, namely te^{*}_{ij}, thus $te^{*}_{ij\ (k=7)} = te^{*}_{ij}$. The rest of the starting and finishing times are as follows:

$ts^{*}_{ij\ (k=7)} = te^{*}_{ij\ (k=7)} - T^{*}_{ij(k=7)} + 1,$
$te^{*}_{ij\ (k=6)} = ts^{*}_{ij\ (k=7)} - 1,$
$ts^{*}_{ij\ (k=6)} = te^{*}_{ij\ (k=6)} - T^{*}_{ij(k=6)} + 1,$
$te^{*}_{ij\ (k=5)} = ts^{*}_{ij\ (k=6)} - 1,$
$ts^{*}_{ij\ (k=5)} = te^{*}_{ij\ (k=5)} - T^{*}_{ij(k=5)} + 1,$
$te^{*}_{ij\ (k=4)} = ts^{*}_{ij\ (k=5)} - 1,$
$ts^{*}_{ij\ (k=4)} = te^{*}_{ij\ (k=4)} - T^{*}_{ij(k=4)} + 1,$
$te^{*}_{ij\ (k=3)} = ts^{*}_{ij\ (k=4)} - 1,$
$ts^{*}_{ij\ (k=3)} = te^{*}_{ij\ (k=3)} - T^{*}_{ij(k=3)} + 1,$
$te^{*}_{ij\ (k=2)} = ts^{*}_{ij\ (k=3)} - 1,$ and
$ts^{*}_{ij\ (k=2)} = te^{*}_{ij\ (k=2)} - T^{*}_{ij(k=2)} + 1.$

The above starting and finishing times are the final times in relation to the overall planning horizon.

It is now necessary to determine the starting and finishing times of each phase relative to the starting time of the subproject. These times are used to determine the starting and finishing slopes of the phase in relation to the cash flow profile of the subproject.

Define ts_{ijk} as the starting time and te_{ijk} as the finishing time of phase k in relation to the starting time ts^*_{ij} of the subproject. Then $ts_{ijk} = ts^*_{ijk} - ts^*_{ij} + 1$ and $te_{ijk} = te^*_{ijk} - ts^*_{ij} + 1$ from which the starting and finishing slopes can be determined, giving $\theta s_{ijk} = 2\ \alpha_{ij\,(\tau=2)}\ ts_{ijk} + \beta_{ij\,(\tau=2)}$ and $\theta e_{ijk} = 2\ \alpha_{ij\,(\tau=2)}\ te_{ijk} + \beta_{ij\,(\tau=2)}$. As before, these starting and finishing slopes are used to determine the eta cash flow profile constants of a phase, namely $\alpha_{ijk\,(\tau=2)}$, $\beta_{ijk\,(\tau=2)}$, $\gamma_{ijk\,(\tau=2)}$.

For each phase, determine $R^{\phi\,n}_{ijkm(\tau=2)} = (\alpha_{ijk\,(\tau=2)}\, t^2 + \beta_{ijk\,(\tau=2)}\, t + \gamma_{ijk\,(\tau=2)}) * w^a_{ijm}$, the nominal monthly cash flow per phase per sector 2 for every subproject and for t = 1 to $T^*_{ijk\,(\tau=2)}$ where $m = t + ts^*_{ijk\,(\tau=2)} - 1$ (or $m = ts^*_{ijk\,(\tau=2)}$ to $ts^*_{ijk\,(\tau=2)} + T^*_{ijk\,(\tau=2)} - 1$).

Per subproject

The monthly nominal cash flow for subproject j in sector τ and for $m = ts^*_{ij\,(\tau=2)}$ to $te^*_{ij\,(\tau=2)}$ is $R^{\phi n}_{ijm(\tau=2)} = \sum_k R^{\phi\,n}_{ijkm(\tau=2)}$ for k = 1 to ϕ_j.

Per project

The monthly nominal cash flow for project i in sector τ and for $m = ts^*_{i\,(\tau=2)}$ to $te^*_{i\,(\tau=2)}$ is $R^{\phi n}_{im(\tau=2)} = \sum_k R^{\phi\,n}_{ijm(\tau=2)}$ for j = 1 to S_i.

<u>Final optimisation</u>

Thus, there is a phase ϕ with associated $R^r_{ijk}\ T^*_{ijk}$, ts^*_{ijk} and te^*_{ijk} with a final actual nominal cash flow of $R^{\phi\,n}_{ijkm}$ for $m = ts^*_{ijk}$ to te^*_{ijk} which, when accumulated, gives a near optimal nominal cash flow over the planning horizon of $R^{*\,n}_m = \sum_i \sum_j \sum_k R^{\phi\,n}_{ijkm}$ for k = 1 to ϕ_{ij}, j = 1 to S_j, and i =

1 to P so that $\sum (R^{f\,n}_{m} - R^{*\,n}_{m})^2$ is a minimum for m = 1 to te^{f*}.

Project budget requirements in real rands

Introduction

Once a near optimal schedule is found, projected costs in nominal rands should be converted to real required rands in order to budget for the projected cost of a project.

Method

At time m, the $R^{\phi n}_{ijkm}$ is the nominal amount required for phase k of subproject j of project i, which includes the original cost plus inflation and changes in exchange rate if applicable. This amount is then **de-escalated** by the budget annual growth factor G_y for all m within y.

The **additional cost**, due to inflation and changes in exchange rates, for phase ϕ during month m is that amount which is necessary to budget at year 0 over and above the original cost of the phase, calculated over the duration of the phase. See Figure 5.8.

The additional cost is ${}_{+}R^{\phi c}_{ijkm} = R^{\phi n}_{ijkm} / G_y - R^{\phi c}_{ijkm}$ for all m in financial year y.
Note: + indicates "additional".

${}_{+}R^{\phi c}_{ijkm}$ positive

In this case the escalation rate due to inflation and changes in exchange rate is much higher than the de-escalation rate. The change in exchange rate is also due to a weakening of the local currency against the foreign currency.

${}_{+}R^{\phi c}{}_{ijkm}$ *negative*

In this case the escalation rate due to inflation and changes in exchange rate is much lower than the de-escalation rate. The change in exchange rate is also due to a strengthening of the local currency against the foreign currency.

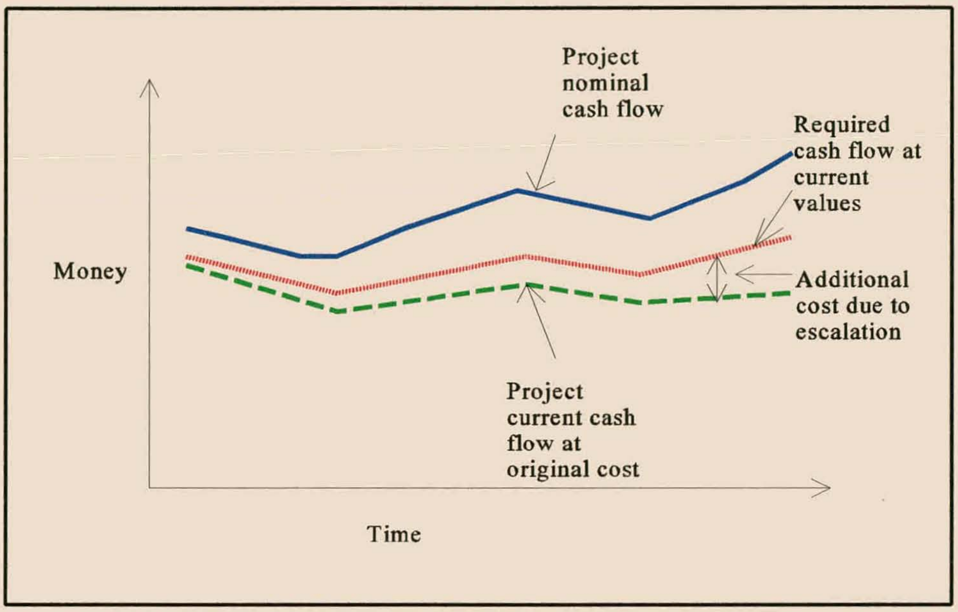


Figure 5.8 : Additional project costs.

<u>Summary of Part 3</u>

All phases of all subprojects of each project are now scheduled. For each phase, the duration, starting and finishing times, as well as the cash flow profile are known. The monthly nominal values of the cash flow profile are also converted into a required real cash flow as well as an original real cash flow. The required real cash flow values will be used in order to conduct an impact analysis (Module 5).

Summary of Module 4

Module 4 dealt with the final micro scheduling after the results for the final pseudo (free or constrained) scheduling were obtained. Final schedules of all phases and subprojects of each project, and additional and original project budgets in real rands are available for each phase of a project.

This known information will be used to perform an impact analysis on the chosen schedule, as described in the next module.

5.6 Module 5 : Impact analysis

Introduction

This part deals with the impact of the near optimal schedule on various areas, such as an engineering function (or division) with its programme management and quality assurance representatives respectively, local supplier organisations, and countertrade.

The basic building block to calculate the impact is the phase required real value together with information such as the near optimal phase duration, and the starting and finishing times of the phase as obtained from the near optimal schedule. The impact on a specific parameter is then calculated and accumulated over all phases and subprojects of a project and for all projects.

Impact parameters

Introduction

Impact parameters are defined as the major impact areas for which the impact will be calculated in real rands per month. Let χ^{uv}_{ijk} be any fraction so that $0 \leq \chi^{uv}_{ijk} \leq 1$ and u = the number of impact parameters and v the specific impact of u. Impact parameters are for example functional, industry, foreign countries or countertrade. The specific impact will be on a specific function, or company, or foreign country, or a specific aspect of countertrade.

Then the real value impact on impact parameter u and specific impact on function/division v is $R^{uv}_{ijk} = R^{\phi rc}_{ijk} * \chi^{uv}_{ijk}$ with $R^{\phi r}_{ijk}$ the real phase value of phase k.

Once the projects have been scheduled, the impact analysis is based on real values and defaults. The reason is that default values are listed in real values. Default values will have to be revised annually.

Functional impact : u=1

Impact on a function

The functional impact is the total impact in real rands of the near optimal schedule on functions such as Radar, Military Vehicles, Aircraft, Armour, Artillery, or any other function for which an impact analysis should be done. These functions will have an index v = 1 to $V_{u=1}$, the total number of functions per impact.

From the functional impact and default values, the relative manpower resources can be determined for every function.

Let ${}_dR^{uv}_k$ = default rand value of phase k for impact parameter u and specific impact v

${}_dT^{uv}{}_k$ = default time of phase k for impact parameter u and specific impact v

${}_dHR^{uvw}{}_k$ = default human resource requirement of phase k for impact parameter u and specific impact v for human resource type w

$HR^{uvw}{}_{ijkm}$ = actual human resource requirement of phase k for impact parameter u and specific impact v for human resource type w

The total real value of the phase connected to impact parameter u and specific impact v is $R^{u\,v}{}_{ijk} = R^{\phi r}{}_{ijk} * \chi^{uv}{}_{ijk}$. Then the real value per time unit (month) for phase k is $r^{u\,v}{}_{ijk} = R^{u\,v}{}_{ijk} / T^{*}{}_{ijk}$. The default real value per month for phase k is ${}_dr^{u\,v}{}_{ijk} = {}_dR^{u\,v}{}_{ijk} / {}_dT^{uv}{}_{ijk}$. Then $HR^{uvw}{}_{ijkm} = {}_dHR^{uvw}{}_k * r^{u\,v}{}_{ijk} / {}_dr^{u\,v}{}_{ijk}$ for $m = ts^{*}{}_{ijk}$ to $te^{*}{}_{ijk}$.

The total human resource planning is:

$HR^{uvw}{}_m = \sum_i \sum_j \sum_k HR^{uvw}{}_{ijkm}$ for $k = 1$ to 9, $j = 1$ to S_i and $i = 1$ to P for $\forall$ m. This is a time series for the human resource requirement for impact parameter u and specific impact v on human resource type w for the duration $m = 1$ to te^f.

Programme management

A relative figure for programme management requirement is determined from the functional impact. This relative figure represents a monthly requirement for programme managers per function for the capital acquisition of major weapon systems.

Quality assurance representatives

A relative figure for quality assurance representation is determined from the functional impact. This relative figure represents a monthly requirement for quality assurance representatives per division for the capital acquisition of major weapon systems.

Note: The impact on the parameters that follow is calculated in the same manner as described above.

Local industry impact : u = 2

Organisation impact

The organisation impact is the total impact of the near optimal schedule on local organisations such as supplier organisations, testing facilities, or other organisations which are for example service oriented. These organisations will have an index v = 1 to $V_{u=2}$, the total number of organisations per organisation impact.

The following subparagraphs describe possible extensions to the research problem but will not be covered in the case study in Chapter 6.

Programme management

A relative figure for programme management requirement is determined from the functional impact. This relative figure represents a monthly requirement for programme managers per function for the capital acquisition of major weapon systems.

Quality assurance representatives

A relative figure for quality assurance representation is determined from the functional impact. This relative figure represents a monthly requirement for quality assurance representatives per function for the capital acquisition of major weapon systems.

System engineers

A relative figure for system engineers is determined from the functional impact. This relative figure represents a monthly requirement for system engineers per organisation for the capital acquisition of major weapon systems.

Engineers

A relative figure for engineers is determined from the functional impact. This relative figure represents a monthly requirement for engineers per organisation for the capital acquisition of major weapon systems.

Scientists

A relative figure for scientists is determined from the functional impact. This relative figure represents a monthly requirement for scientists per organisation for the capital acquisition of major weapon systems.

Technicians

A relative figure for technicians is determined from the functional impact. This relative figure represents a monthly requirement for technicians per organisation for the capital acquisition of major weapon systems.

Artisans

A relative figure for artisans is determined from the organisation impact. This relative figure represents a monthly requirement for artisans per organisation for the capital acquisition of major weapon systems.

<u>Foreign country impact : u = 3</u>

The foreign country impact is the total impact of the near optimal schedule on foreign countries. These countries will have an index v = 1 to $V_{u=3}$, the total number of countries per foreign country impact.

Countertrade impact : u = 4

The total countertrade impact is the total impact of the near optimal schedule on countertrade. The countertrade will have an index v = 1 to $V_{u=4}$. From the total countertrade impact, the direct, indirect and commercial countertrade are determined.

Sensitivity analysis

Introduction

This section deals with the sensitivity analysis by changing some of the input in order to determine the results of different scenarios that may occur in future. The different scenarios will result in various impact analyses in order to establish a baseline with upper and lower limits which can be used during negotiations within a decision-making process. Negotiations are intended for those role players who would like to negotiate a better overall cash flow for a specific function, while others might like to increase the budget during specific years in order to finish a specific project earlier than anticipated.

This model is in total a decision support model and cannot therefore provide precise and exact answers. It is meant to present different scenarios with results so that the role players can make better decisions. Sensitivity in this regard is then to change the input so that different scenarios can be presented.

Method

The sensitivity analysis can be approached from either the macro or micro side of the problem. The macro approach will deal with changes in budget, budget growth, project priorities, exchange and inflation rates. The micro approach will deal with changes in minimum and maximum phase completion times, possible money changes, and changes which could alter the impact analysis, such as functional allocation of the work and possible organisations. The sensitivity analysis will give trends for each combination of the variables mentioned.

Negotiations

The different results, because of pre-determined different input, will prompt decision makers to select the best alternative, after which the variables that have been used for that alternative will be finally entered into the model and will at least be kept frozen for a financial year.

Summary of impact analysis

The impact is calculated from the final micro schedule and phase associated values. The impact gives either a financial loading in real rands of an impact parameter or a relative human resource loading on a specific impact area. These impacts, together with data from scheduled projects, subprojects and phases, are used to either allocate more funds to a specific project or to change priorities of the projects in order to achieve a more desired impact. Once a sensitivity analysis is done, the best or most suitable alternative is chosen.

5.7 Summary of mathematical formulation

This paragraph gives a summary of the mathematical formulation that has been developed as a solution to the research problem. Although a detailed summary was given at the beginning of Chapter 5, it is repeated here for the sake of completeness:

Step 1 and 2 (Chapter 4, Section 4.2, Finances and economics): Convert the available budget in real terms into a nominal budget and convert the annual nominal budget into a monthly budget.

Step 3: Establish a pseudo project (**Module 1, Part 1**) from data obtained from all phases of all subprojects within a project and for all projects. The data per phase, which is necessary to determine a pseudo project, are the phase value in real terms and the minimum and maximum duration in which a phase can be completed. Determine the minimum and maximum duration for each pseudo project. The initial duration of a pseudo project is calculated as the average between the minimum and maximum duration of the project. Determine four scheduling sectors, namely concept/definition, development, qualification and production sectors. Each sector will have a minimum and a maximum duration. The summation of the minimum and maximum durations of the four sectors is equal to the minimum and maximum duration of the pseudo project. Find the best fit cash flow profile for the pseudo project based on the data as obtained from the phase information. At the end of step 3 the following information is known, namely the pseudo project cash flow profile in real terms, which in total is equivalent to the total project cost, and a duration for the pseudo project, which is between a minimum and a maximum duration of the pseudo project. What is not known, are the starting and finishing dates of the pseudo project.

Step 4: The next step is to calculate a weighted annual escalation factor (**Module 1, Part 2**) for each pseudo project. The inflation rates and changes in exchange rates for each subproject of a project are taken into account in determining the weighted annual escalation factor for a project.

Step 5 : According to the project priorities, schedule the pseudo projects (**Module 1, Part 3**) into an initial pseudo schedule by 'packing' a selected number of projects into the shortest possible time so that the cumulative nominal value of all the projects at a specific time is less than or equal to the cumulative nominal budget at that time. Real cash flows of pseudo projects are then converted into cash flows in nominal terms by taking into account a weighted escalation factor applicable to that pseudo project.

Step 6 : Determine a 'free' optimising schedule (**Module 2, Part 1 and Part 2**) by minimising the overall deviation of the nominal cash flow of all pseudo projects from the nominal budget over the final planning horizon. This is done by means of six pseudo scheduling operations, or heuristics, namely left and right shift, left and right shrink, and left and right stretch, depending on the scheduling constraints to which the pseudo project is subjected. The result of this step is a 'free' optimised pseudo schedule with a duration, starting and finishing dates, and cash flow profile in nominal terms for each pseudo project.

Step 7 : This step is optional, depending on the requirements of the operator. If expected dates for the completion of pseudo projects have been entered into the model as constraints, and these constraints have been activated, then from a 'free' optimised schedule determine a 'constrained' optimised schedule (**Module 3, Part 1 and Part 2**) by minimising the overall deviation of the nominal cash flow of all pseudo projects from the nominal budget over the final planning horizon, but subject to completion date constraints. The result is a final 'constrained' schedule with cash flow profiles, starting and finishing dates, and durations of each pseudo project.

Step 8 : Once a final pseudo schedule (whether free or constrained) has been determined, a detailed project optimisation (**Module 4, Part 1, Part 2 and Part 3**) can be conducted. Firstly, the subprojects are so optimised that the deviation from the cash flows of all subprojects of the project's required cash flow profile as obtained in the final pseudo schedule is a minimum. Secondly, the phases within a sector are so optimised that the deviation from the phase cash flow for the subproject's cash flow is a minimum.

In both the above cases, nominal values of each subproject are determined with actual inflation rates and changes in exchange rates. This, in other words, is not a weighted escalation, but an actual escalation of each subproject within a project.

Step 9 : Once all the projects have been optimised, the actual predicted nominal cash flows must be converted to real value predicted cash flows (**Module 4, Part 3**). There are two conversions, namely the de-escalation of the final nominal cash flow to a **required real cash flow**, and a conversion to the **original real values**. The de-escalation to required real cash flows is calculated with the annual growth rate of the budget, while the de-escalation to original real values is based on the actual inflation rates and changes in exchange rates. The difference between the required real cash flow and the original real cash flow is the additional cost that must be planned for due to inflation and changes in exchange rates. The result of step 9 is a schedule of all phases with starting and finishing dates, and a predicted required real cash flow profile. This schedule is the **near optimal schedule** based on the input data of the model and the allocated budget.

Step 10 : Based on the final starting and finishing times of each phase and the corresponding required real cash flow of each phase, calculate various impacts (**Module 5**) such as required real cash flows of groups of selected projects, required real cash flows of specific local organisations, cash flows of specific engineering functions or divisions, and the corresponding human resources requirement of the functions for the planning horizon.

6. Case study

6.1 Introduction

This chapter considers a number of selected projects. The objective is to use project data that are used in practice and that will cover almost all possible combinations in order to show the full scope of the model. Macro economic information was the best information available at the time when the case study was analysed.

Owing to the sensitivity of certain information on the selected projects, project information has been slightly modified so that it cannot be identified as a single, specific project. Projects are identified sequentially, i.e. project 1, project 2, etc. Names of organisations, supplier countries and engineering functions have been simulated to reflect a real situation as closely as possible.

The aim of the case study is to show the behaviour of the model under various conditions and to determine issues that should be considered in practice in order to improve current approaches.

6.2 Model data

Description of selected projects

Eleven projects were selected from a list of real projects. Projects may be running currently or could be future projects. The data per project have been prepared by the respective programme managers and are thus actual data but, as mentioned already, no actual project or subproject names are given. Phase estimates are given in 1998/99 financial year money value.

Details of the selected projects are set out in Appendix D. Each project is broken down into a maximum of 5 subprojects, and each subproject is broken down further into the 9 acquisition phases. Phases that do not apply to a particular project are left out and will be considered as null and void.

At subproject level the following information is provided:

- project status, whether current or future
- whether it is a local or a foreign contract
- if it is a foreign contract, the foreign country as well as the contract currency.

For every phase of a subproject the following information is provided:

- the phase value in a specified currency in 1998/99 financial year values
- the minimum duration necessary to complete the phase
- the maximum duration necessary to complete the phase
- the percentage of the phase value allocated to possible local organisations
- the percentage of the phase value allocated to direct, indirect, and commercial countertrade.

Macro information

At macro level the following information is given as described in Appendix E:

- list of engineering functions
- list of local organisations
- list of foreign countries
- list of inflation rates per country
- list of exchange rates per foreign currency
- annual budget in real terms
- growth rate of budget
- budget Gompertz values to simulate the in-year monthly budget

- project priority list.

Defaults

Appendix F describes the defaults for the engineering functions listed.

A table of defaults is given for each engineering function that will apply to a project, with default values for human resources requirements. One additional default table is added, namely that of OTHER to make allowance for uncertain or unknown situations.

The following functions each have their unique human resources requirements defaults:

- Aircraft
- Guided missile systems (GMS)
- Mechanised infantry
- Radar
- Support vehicles
- Telecommunications.

The following functions use the system default as their human resources requirement defaults:

- Other
- Air weapons
- Artillery
- Command and control
- Infantry weapons
- Aircraft logistics
- Quality.

6.3 Computer model run combinations

Introduction

A number of parameters, each with different options, are used to demonstrate the model. See Table 6.1 for a matrix of the different computer runs and combinations. Also refer to Appendix E for details of the macro information and different options that have been used. The parameters that have different options are priorities, initial project duration, constraints, budget, budget growth, inflation rates and changes in exchange rates.

Priorities

Option 1 Sequential priorities, i.e. where the original listing of projects has the same priority as the initial project number. This is also the initial sequence in which the projects should be completed.

Option 2 Mixed priorities, i.e. where the priorities are holistically changed in such a way that the sequence in which the projects will be completed will give a cumulative nominal cash flow closer to that of the cumulative available budget. Only one set of mixed priorities is used.

Initial project duration

Option 1 The initial pseudo project duration is taken as the minimum project completion time.

Option 2 The initial pseudo project duration is the average between the maximum and the minimum project completion time.

Note: The minimum and maximum durations are project input.

Parameters	Options	Run No	1A	1C	3A	3A 1	3F	2A	2C	4A	4F	1B	1D	3B	3B 1	2B	2D	4B
Priorities	2	Mixed priorities	x	x	x	x	x	x	x	x	x							
	1	Sequential priorities										x	x	x	x	x	x	x
Initial project duration	1	Minimum duration	x		x	x	x	x		x	x	x		x	x	x		x
	2	Average duration		x					x				x				x	
Constraints	1	Off	x	x	x	x		x	x	x		x	x	x	x	x	x	x
	2	Project 11 on					x				x							
Budget (see Appendix A)	1	Specific amount for 14 years R 450 m onwards	x	x														
	2	Average R 450 m per year										x	x					
	3	Average R 700 m per year						x	x									
	4	Average R 800 m per year														x	x	
	5	Specific amount for 15 years R 900 m onwards			x	x	x			x	x							
	6	New amount for 15 years R 900 m onwards												x	x			
	7	The same as option 6 but R 950 m onwards																x
Budget growth	1	2%						x	x	x	x					x	x	x
	2	0%	x	x	x	x	x					x	x	x	x			
Inflation rates	1	Applicable country rates						x	x	x	x					x	x	x
	2	0% country rates	x	x	x	x	x					x	x	x	x			
Exchange-rates	1	Applicable country rates				x	x	x	x	x	x				x	x	x	x
	2	Constant	x	x	x							x	x	x				
Final analysis		Actual schedules			Y	Y				Y				Y	Y			Y
		Impact analysis			Y					Y								

Notes: Y = Yes

Shaded columns = Runs taken as examples in Chapter 6.

Table 6.1: Matrix of computer runs and combinations

Constraints

Option 1 The constraint of all projects with regard to required completion time is "off".

Option 2 Only project 11's completion time is "on".

Budget

Introduction

It is necessary to explain the reason why different budget options are used to demonstrate the model. In practice, a total annual budget will be allocated to complete all projects within a specified planning horizon. For the research problem, only eleven projects were selected but with no specific total annual allocated budget. It is therefore necessary to establish such a budget to allow these eleven projects to be scheduled within a certain time.

Before the final budget options were fixed, two computer trial runs were executed in order to establish a budget baseline from which subsequent budget options can be determined. The first trial run was based on sequential projects but with zero escalation as a result of inflation rates and changes in exchange rates. An annual budget of R 450 million was chosen. The outcome of this trial run showed surpluses of funds during the first number of years, mainly due to precedence constraints which caused some following projects to be completed at a later stage while a lengthy project had to be completed earlier and was utilising only a small amount of the allocated budget.

The second trial run was based on mixed projects and was derived from the first trial run. It was a trivial exercise establishing mixed priorities so that projects could be completed as soon as possible and also to allow lengthy projects to be completed last. The results of the second trial run were used to establish the final annual budget for option 1, i.e. the annual cash flow requirements for this trial run became the annual budget. Due to the fact that other options had to cater for the possible increases due to inflation rates and changes in exchange rates, annual budgets for the other options had to be increased. These increases are arbitrary and will be used to compare the different computer runs with each other.

The following paragraphs describe each budget option in general:

Option 1 (Runs 1A and 1C)

An initial budget in real terms is allocated to complete the eleven projects under mixed priorities, with zero percent inflation and no changes in exchange rates and zero percent growth rate of the budget. A specific annual amount is chosen for 14 years and an average annual amount of R450 million is chosen for the remaining planning horizon. Take note that the fifteenth year's budget is equal to R 450 million and that the budgets of the remaining years were based on this amount.

Option 2 (Runs 1B and 1D)

An initial budget in real terms is allocated to complete the eleven projects under sequential priorities, with zero percent inflation and changes in exchange rates and zero percent growth rate of budget. An average annual amount of R450 million is chosen for the full planning horizon.

Option 3 (Runs 2A and 2C)

A final budget in real money terms is allocated to complete the eleven projects under mixed priorities and a certain percentage inflation, with changes in exchange rates and a percentage growth rate of the budget. An average annual budget of R700 million is chosen for the full planning horizon.

Option 4 (Runs 2B and 2D)

A final budget in real money terms is allocated to complete the eleven projects under sequential priorities and a percentage inflation, with changes in exchange rates and a percentage growth rate of budget. An average annual budget of R800 million is chosen for the full planning horizon.

Option 5 (Runs 3A, 3A1, 3F, 4A and 4F)

A specific annual budget in real money terms is allocated for 15 years with an average annual budget of R900 million for the remaining planning horizon to complete the eleven projects under mixed priorities and a percentage inflation, with changes in exchange rates and a percentage growth rate of budget.

Option 6 (Runs 3B and 3B1)

A specific annual budget in real money terms is allocated for 15 years with an average annual budget of R900 million for the remaining planning horizon to complete the eleven projects under sequential priorities and a percentage inflation, with changes in exchange rates and a percentage growth rate of budget.

Option 7 (Run 4B)

A specific annual budget in real money terms is allocated for 15 years and an average annual budget of R950 million for the remaining planning horizon to complete the eleven projects under sequential priorities and a percentage inflation, with changes in exchange rates and a percentage growth rate of budget.

Budget growth

Option 1 A real budget with an annual growth rate of 2%.

Option 2 A real budget with no annual growth rate.

Inflation rates

Option 1 The applicable inflation rates as annual percentages for each country, including the local country.

Option 2 Zero percent inflation rates for all supplier countries, including the local country.

Changes in exchange rates

Option 1

The exchange rates are equal to the predicted annual exchange rates. This means that there is a further escalation in the cost of the project due to a possible weakening of the local currency against the foreign currencies.

Option 2

The exchange rates for the following years are seen to be equal to the exchange rate in the first year of planning, i.e. constant over the planning horizon. This means that there is no further escalation of costs due to changes in exchange rates.

6.4 Description of results of computer model run of combinations

Introduction

The aim of this section is to describe or explain the results of each computer run as shown in Table 6.1. Although sixteen runs were computed, only runs 3A and 4A are used in Chapter 6 to fully demonstrate the different phases of the model and how it is utilised for planning purposes. The reason why these two are described in this chapter, is that they are the only two runs that fully demonstrate the computational process of pseudo, actual and impact analyses. All sixteen runs are described in Appendix G in order to consolidate all results in one appendix for easy access and reference. The graphical displays are found in Appendix H.

The results of runs 3A and 4A are discussed in three parts, namely Part 1: Pseudo analysis, Part 2: Actual analysis, and Part 3: Impact analysis. The comparison of all these results is dealt with in paragraph 6.5 of this chapter.

Part 1 : Pseudo analysis

The pseudo analysis is done to quickly obtain an overall schedule at project level before a final and actual schedule is determined. As mentioned earlier, only runs 3A and 4A are discussed in this chapter. The main differences between these two runs are seen in the data for the budget growth, inflation rates and exchange rates. In case 3A, the budget growth and inflation rates are set at zero, while the exchange rates are kept constant, thus assuming real budgets and zero escalation. This is used as a baseline against which case 4A is compared. In case 4A, percentages for the budget growth and inflation rates and exchange rates are entered into the model, thus recognising the differential between the growth in the budget and escalation of costs.

The following sections briefly explain the results of computer runs 3A and 4A.

Run 3A: (See Figures 6.1 and 6.2)

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off

Budget	5	Specific amount and R900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Budget and pseudo cash flow

Although runs 1A and 1C (see Appendix H, pages 2 and 4) show that huge annual surpluses and shortages can occur if the budget is allocated without taking the project's cash flow predictions into account, this run 3A shows that if the budget allocation is more or less the same as the nominal cash flow predictions, the huge differences between budget and cash flow are reduced. This means that after only one pseudo analysis the results of that analysis can be used to determine the budget that should be allocated.

Cumulative cash flow: Total R7 130 million

The cumulative nominal budget and cumulative nominal cash flow are virtually the same, which means that run 3A has reached a near optimal solution for a pseudo analysis.

Project scheduling: Ending month 180

The schedule shows that if the project priorities are carefully chosen, the initial and final schedule for each project will be approximately the same.

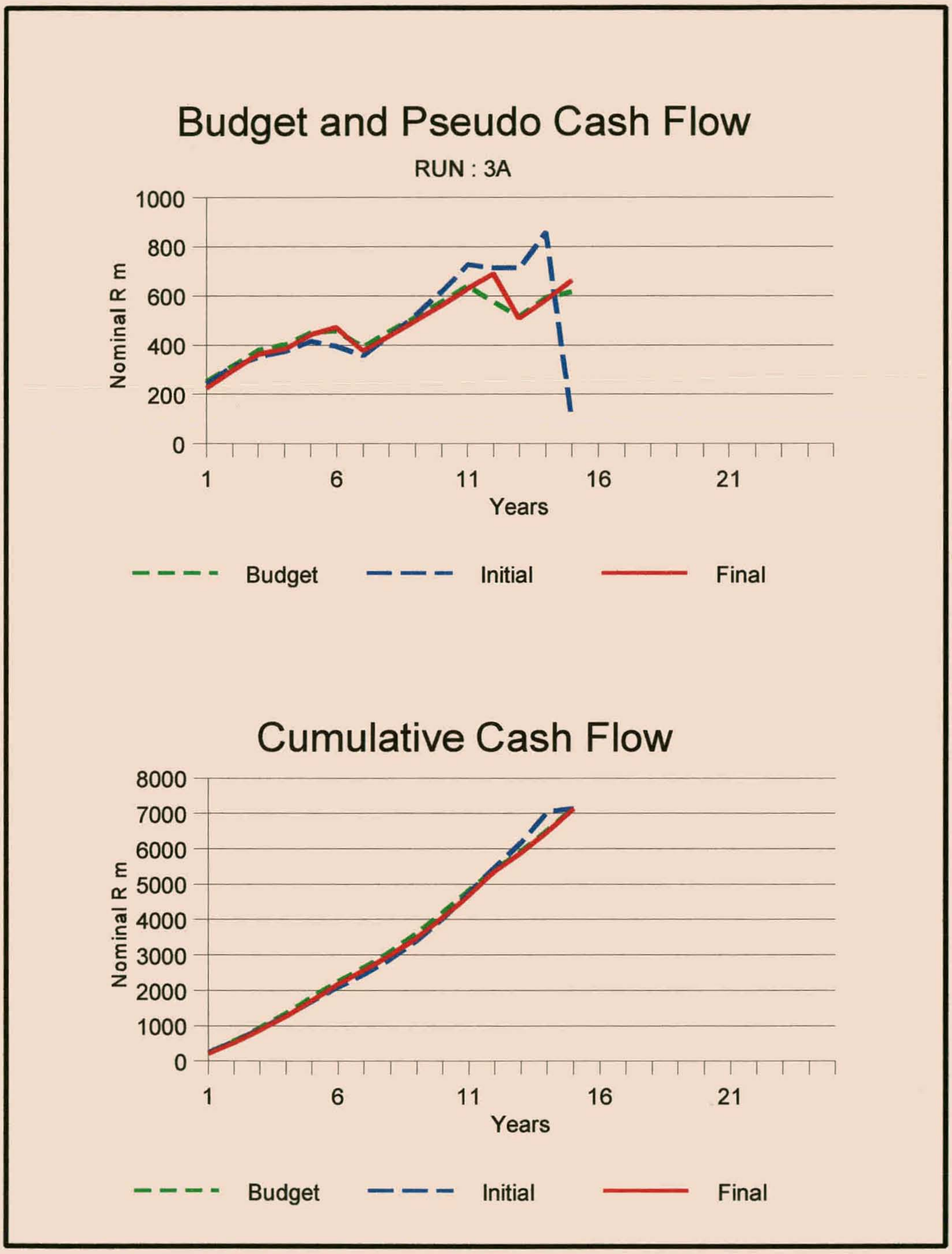
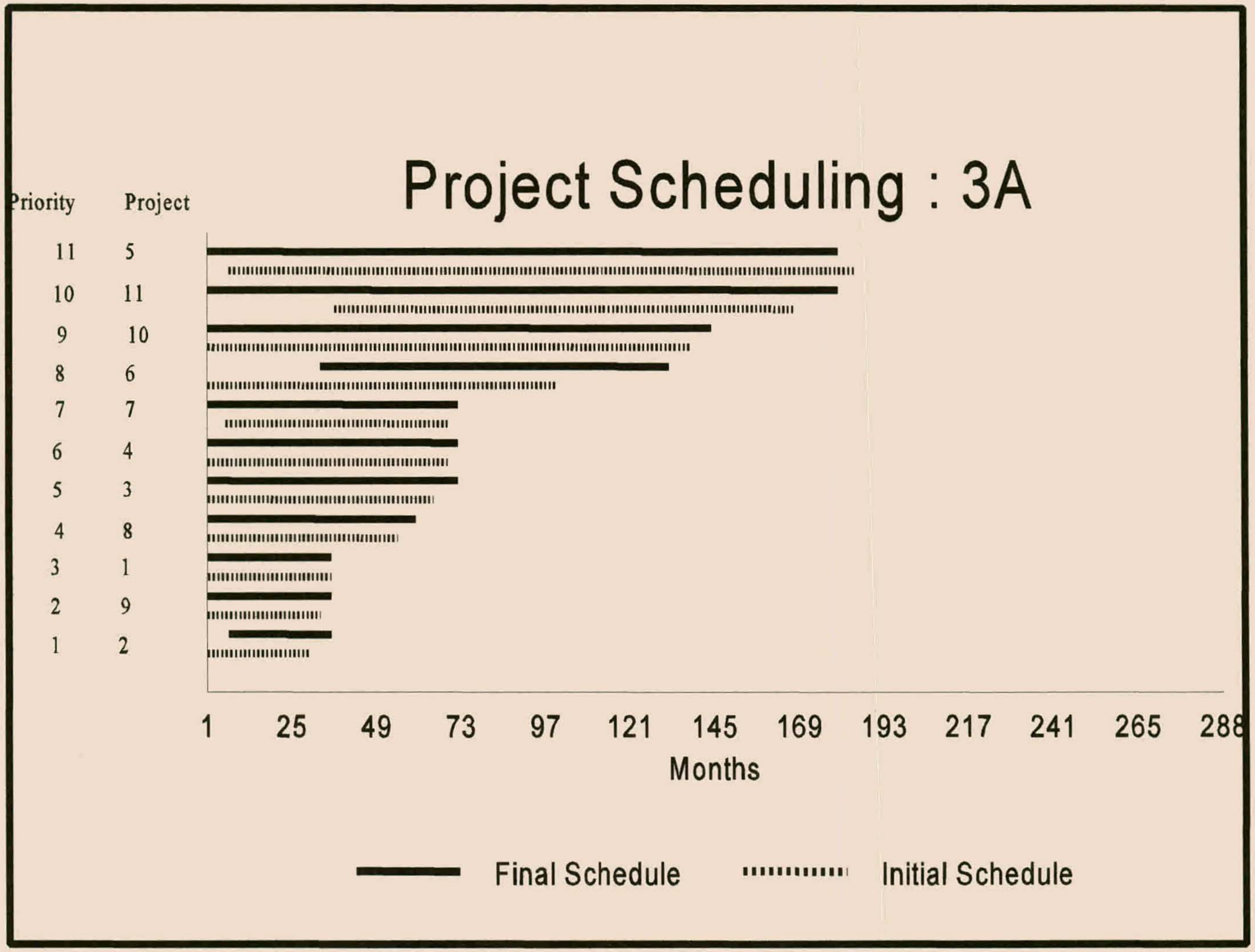


Figure 6.1: Pseudo cash flow in nominal terms for run 3A.

Figure 6.2: Pseudo project scheduling of run 3A.



<u>Run 4A</u>: (see Figures 6.3 and 6.4)

Data	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

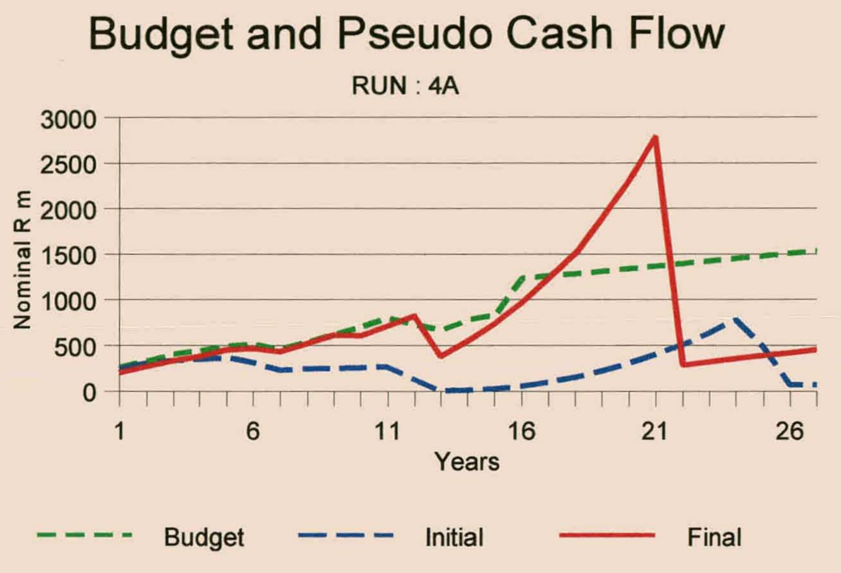
The result of run 4A clearly shows the pseudo optimisation from the initial to the final phase. The initial cumulated cash flow deviates further from the budget than the final cash flow, which is 'closer' to the budget. The large deviations during the last 10 years are due to the fact that, because of the escalation of cost due to inflation and changes in exchange rates, projects 5, 10 and 11 have been shifted to the right. Projects 10 and 11 in turn contribute approximately R4 000 million only for their production phases. Of these two, project 11 is causing the peak in the cash flow.

Cumulative cash flow: Total R20 480 million

From the cumulative nominal curve the optimising effect of the model, from the initial to the final phase, can again be seen. This run also shows the effect of escalation, compared with run 3A where escalation was not considered. The increase in nominal terms is R 13 350 million.

Project scheduling: Ending month 324

The increase in the planning horizon from month 180 (run 3A) to month 324 is due to the fact that funding shortages occur when the full annual escalation due to inflation and changes in exchange rates is taken into consideration in the scheduling of the eleven projects. This resulted in the right shift of almost all projects as compared with run 3A.



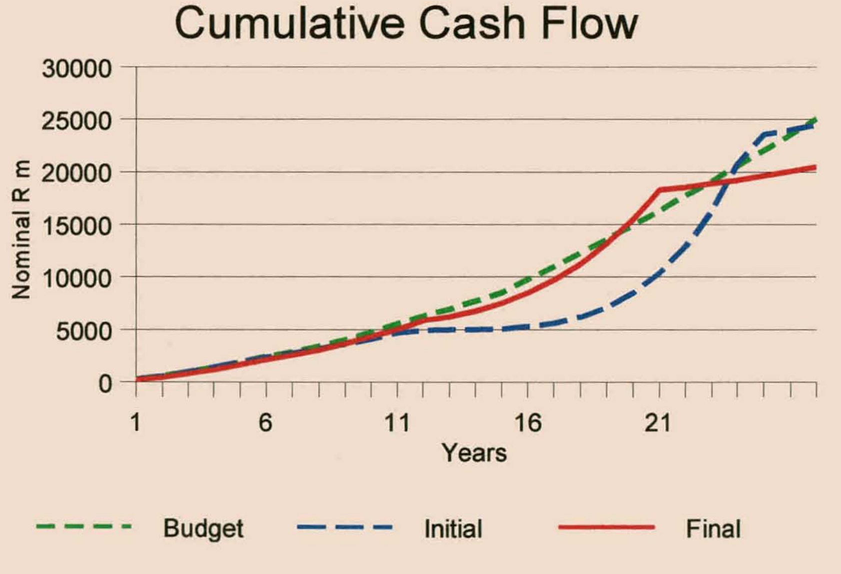


Figure 6.3: Pseudo cash flow in nominal terms for run 4A.

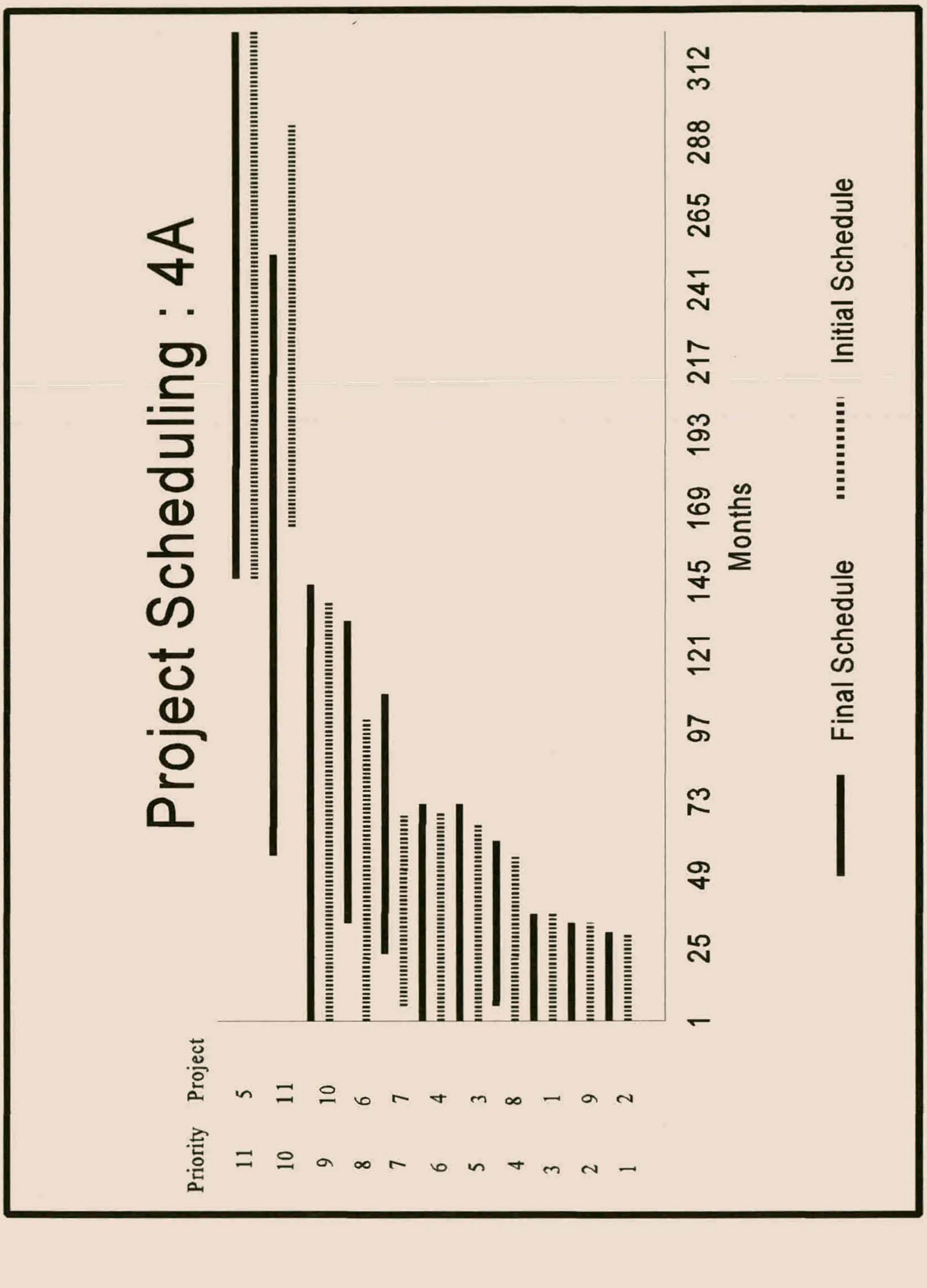


Figure 6.4: Pseudo project scheduling of run 4A.

Part 2 : Actual analysis

The subsequent paragraphs describe the results of the actual analyses that have been executed. Only runs 3A and 4A are taken to demonstrate the results in this chapter, while some of the other runs are shown in Appendix G. The first section of the results of each run, i.e. the final nominal pseudo *versus* actual cash flows, shows how the actual nominal results tend to follow the required pseudo cash flows. The second section, i.e. the real original *versus* requirement value, shows the final actual required values relative to the original values. The difference between the required and the original values gives the additional costs that should be added to the original values due to inflation and changes in exchange rates.

Run 3A : (see Figures 6.5 and 6.6)

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Final nominal pseudo (R7 130 million) versus actual (R7 130 million) cash flows

Figure 6.5 shows the trend of the actual cash flow to follow the pseudo cash flow curve. It should also be noted that as these graphs are based on only a small number of selected projects, the actual values may differ from the pseudo values. It nevertheless demonstrates the original assumption that if the actual cash flow values are close to the pseudo cash flow values of each project, the total actual cash flow values for all projects will also be close to the total pseudo cash flow values.

The cumulative cash flow curves for both the actual and pseudo cash flows show that they are close to each other. The fact that the actual value is the same as the total pseudo value (R7 130 million) is because no escalation is taken into consideration.

Real original (R7 130 million) versus requirement (R7 130 million) value (see Figure 6.6)

The real requirement is determined by de-escalating the nominal requirement with a factor derived from the budget growth. The real original value is the cost of the project based on the original real values which were used as input data.

The differences between the real original and requirement values represent the additional costs in real money terms to complete the projects and should be budgeted so that the correct amount of money will be available when the project is executed.

The reason why the cumulative real original and requirement values are the same for this run, is that no escalation was taken into consideration.

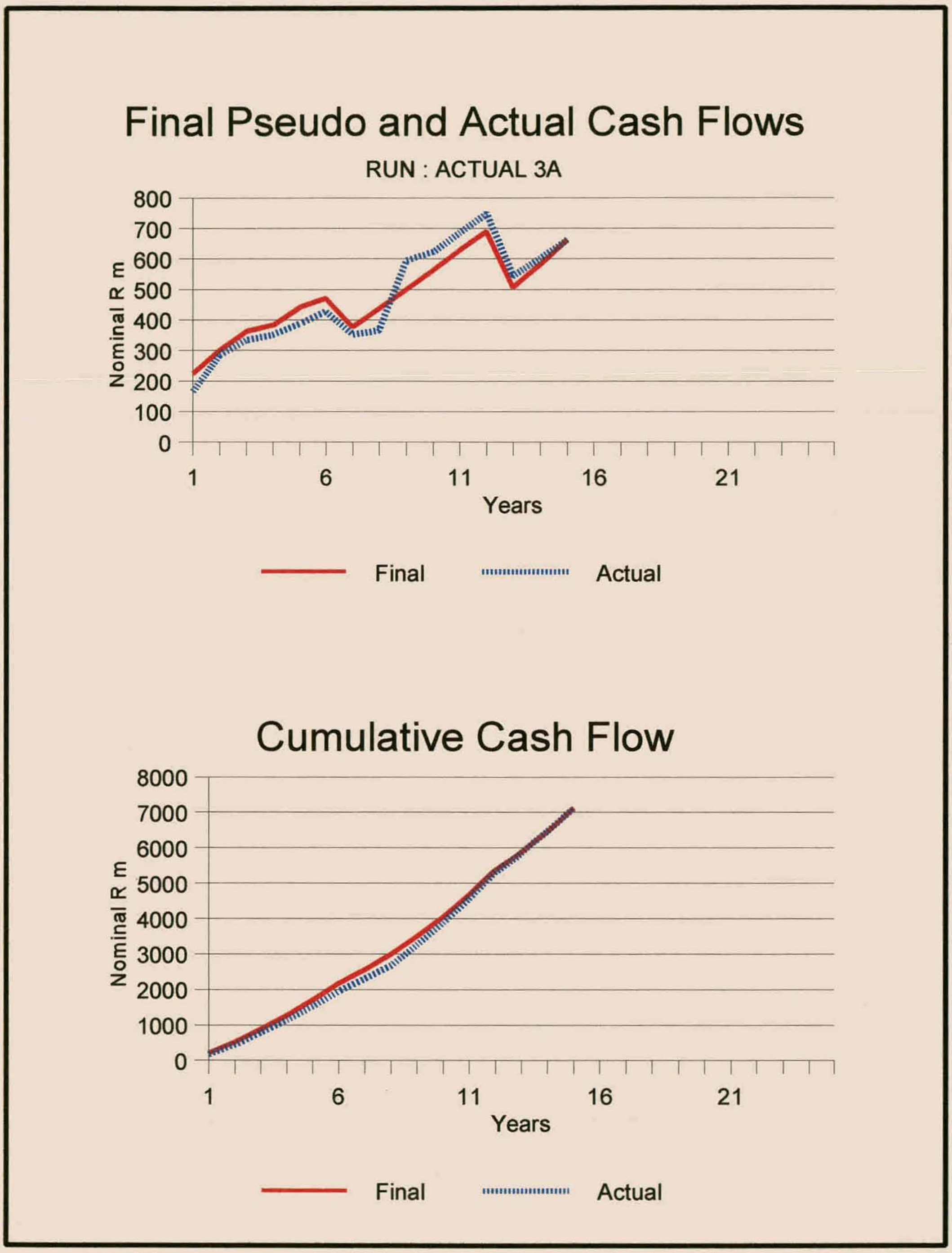
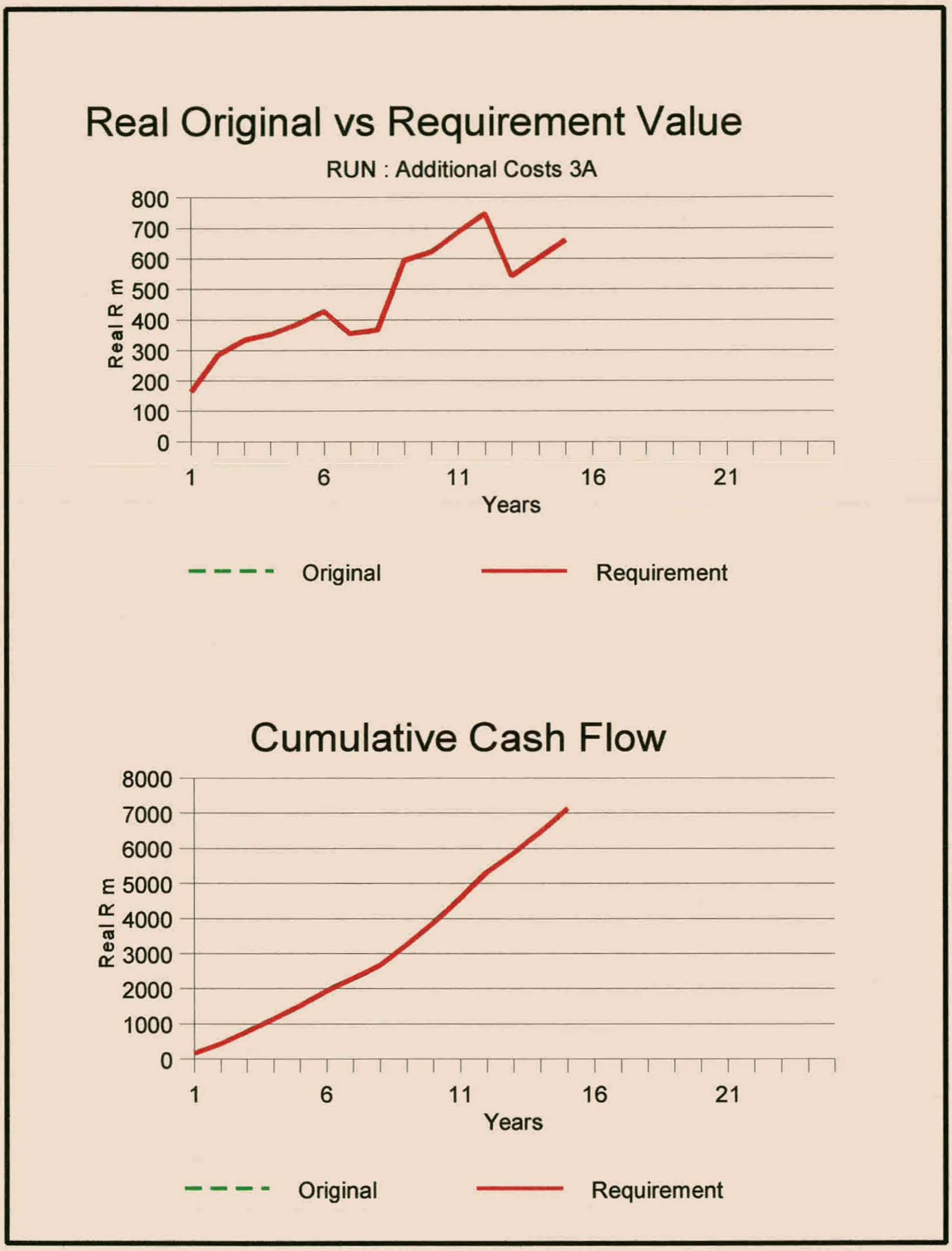


Figure 6.5: Final pseudo and actual cash flow in nominal terms for run 3A.



Note: In the above case, the original cash flow is equal to the requirement cash flow.

Figure 6.6: Original vs requirement cash flow in real terms for run 3A.

<u>Run 4A</u> : (see Figures 6.7 and 6.8)

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Final nominal pseudo (R20 477 million) versus actual (R21 189 million) cash flows

The difference between this run and run 3A is that in this run the full escalation due to inflation and changes in exchange rates is taken into consideration. The cumulative nominal actual value increases from R7 130 million to R21 189 million.

Real original (R7 130 million) versus requirement (R15 546 million) value

When the actual cash flows are de-escalated to real terms, a cumulative real requirement value of R15 546 million results, which is R8 416 million more than the original planned cash flow of R7 130 million for all the projects. This additional cost is due to inflation and changes in exchange rates.

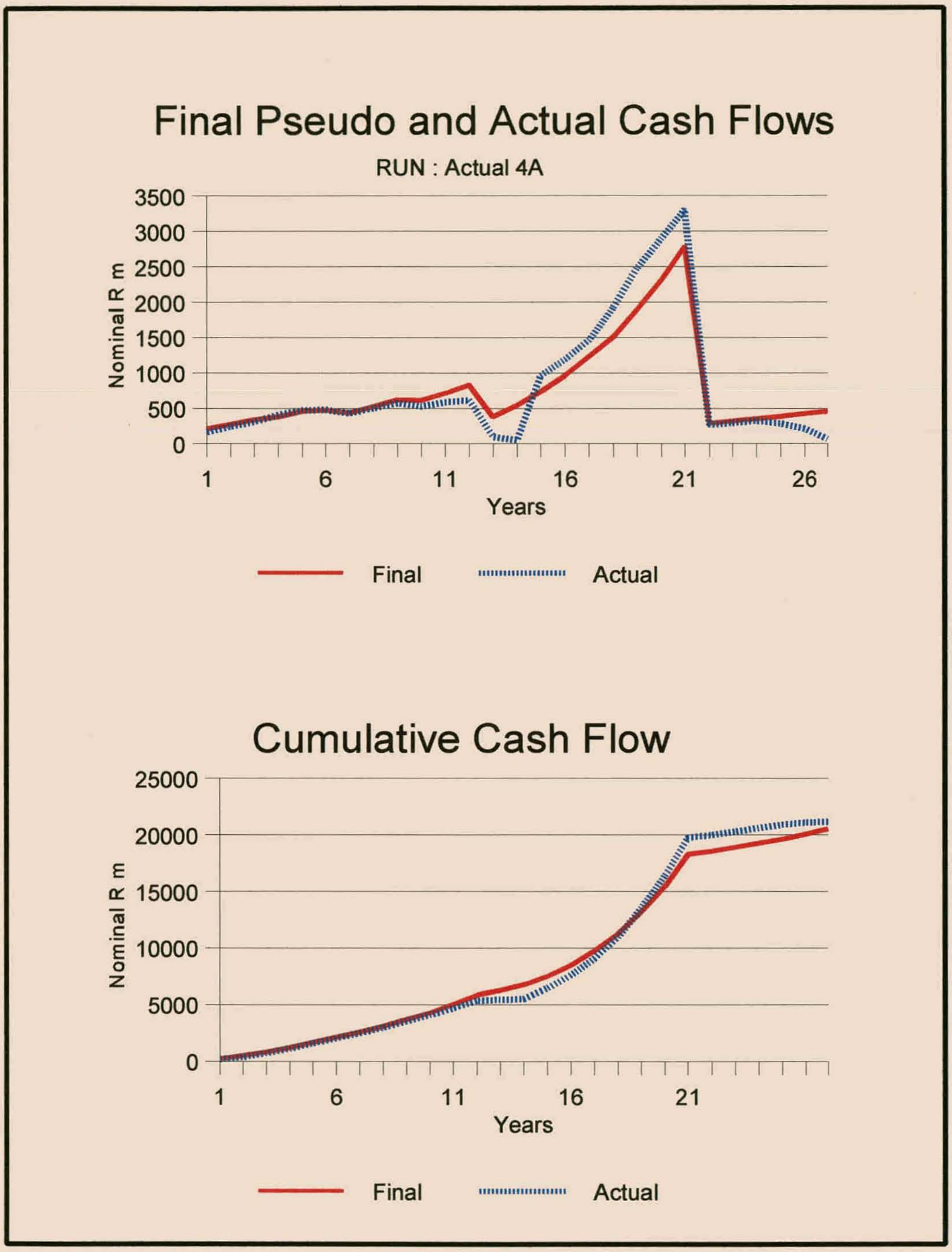
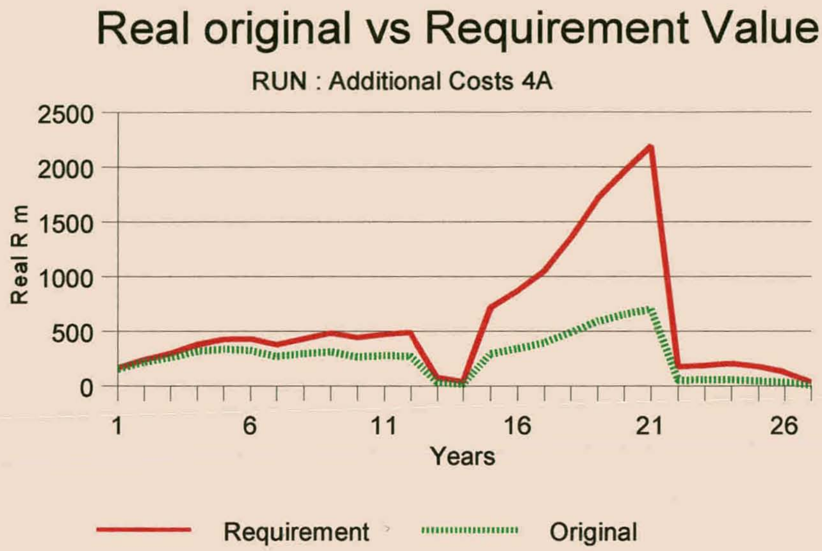
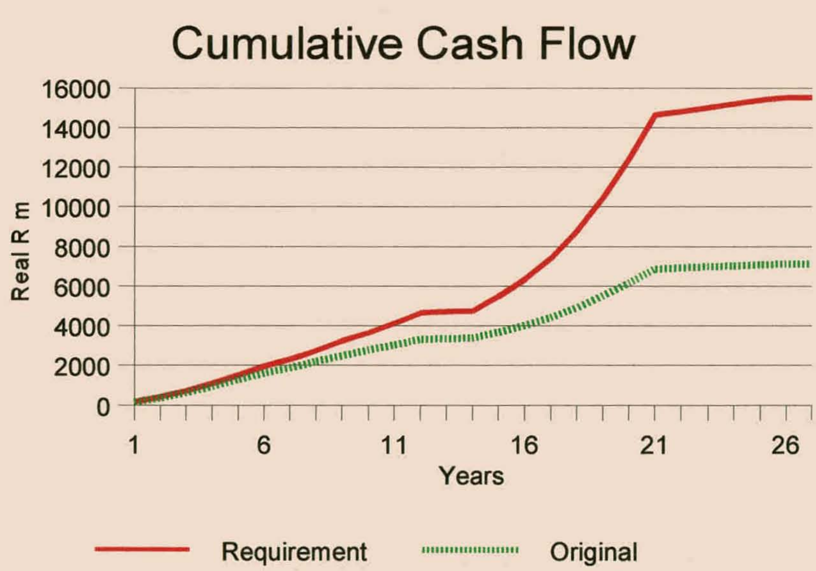


Figure 6.7: Final pseudo and actual cash flow in nominal terms for run 4A.





Note: The difference between the original and requirement cash flow graphs is the additional cost.

Figure 6.8: Original vs requirement cash flow in real terms for run 4A.

Part 3 : Impact analysis

The following section gives the results of the impact of the final actual results on parameters such as development, production, organisation, engineering function, programme management (PM), quality assurance (QA) representatives, supplier countries and direct countertrade. Not all parameters are presented and only one example of the aforesaid parameters is described due to the large number of examples and the similarity of most of the descriptions. Only runs 3A and 4A are taken as examples to show how the impact changes from one scenario, where no escalation is taken into consideration, to another scenario which takes account of escalation due to inflation and changes in exchange rates. Only graphs of run 4A are shown, while the comparison of the impact analyses between runs 3A and 4A is given in paragraph 6.5 of this chapter.

Runs 3A and 4A :

The main difference between run 3A and run 4A is that run 3A does not take escalation into consideration, while run 4A takes account of escalation due to inflation and changes in exchange rates. The following subparagraphs give a short description of the graphs as shown in Appendix H, pages 46 to 53. These graphs are based on all eleven projects of the case study.

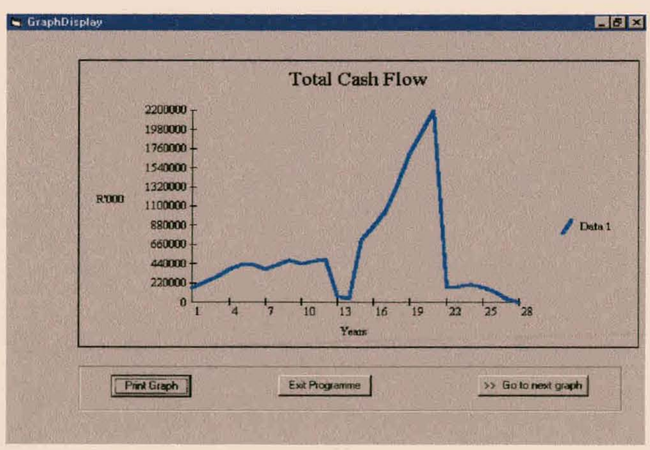


Figure 6.9: Total cash flow in real terms for run 4A.

Total cash flow

The total cash flow is the real required amount and represents the cash flow for any selected number of projects.

Organisation

Any organisation or a number of organisations of strategic importance can be selected to show the real required cash flow.

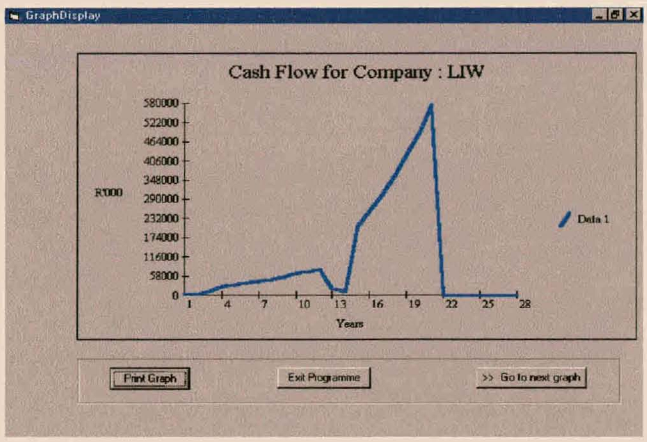


Figure 6.10: Organisation cash flow in real terms for run 4A.

Development and production

All related projects could, for example, be selected in order to predict the cash flow for the development and production phases in real required money terms. Other phases, such as concept/definition and system test and qualification, could also be evaluated.

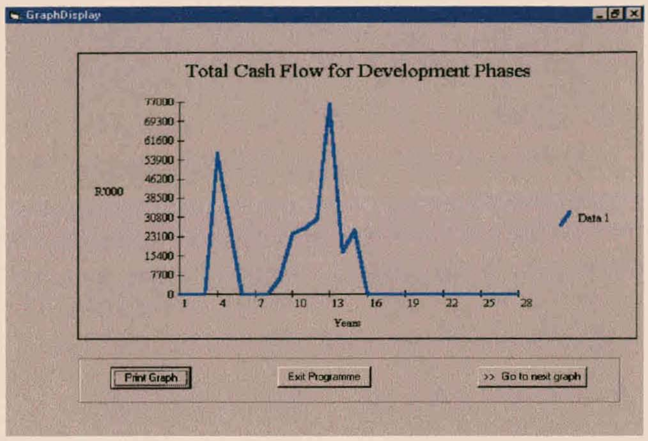


Figure 6.11: Total cash flow for development phases in real terms for run 4A.

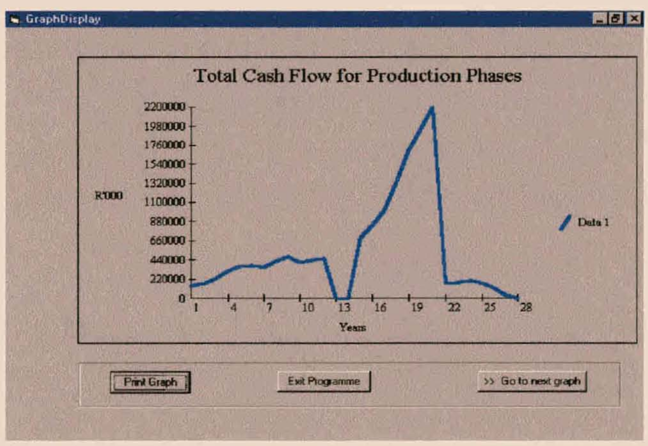


Figure 6.12: Total cash flow for production phases in real terms for run 4A.

Country

A country or a number of countries could be selected to see what impact the selected projects will have on them. The cash flow is also in real required money terms.

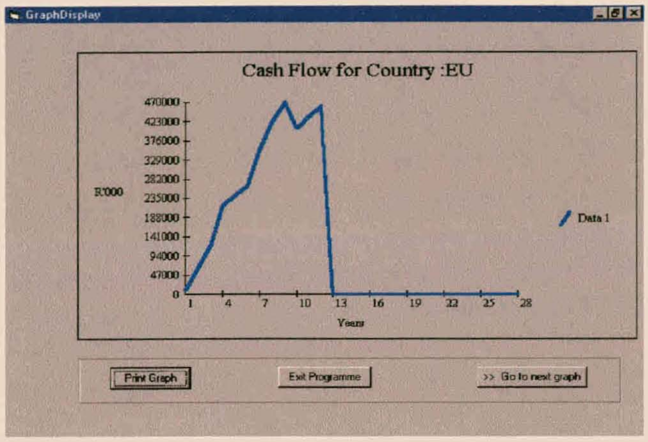


Figure 6.13: Cash flow for a country in real terms for run 4A.

Direct countertrade

Although countertrade, whether direct or indirect, could be realized some years after the money has been spent, or even after completion of the project, these graphs will give the user an idea of the cash flow profile and timespans that could be expected for countertrade. Planning for countertrade could then be done accordingly.

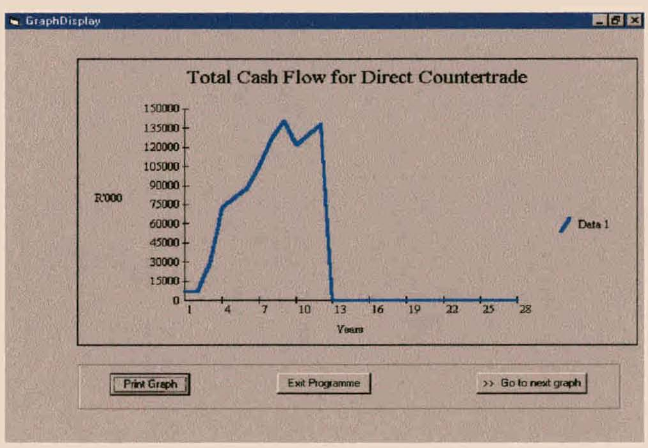


Figure 6.14: Total cash flow for direct countertrade in real terms for run 4A.

Engineering function

This graph represents the cash flow, in real money terms, that will be managed by a specific function or division for a subcollection of all projects.

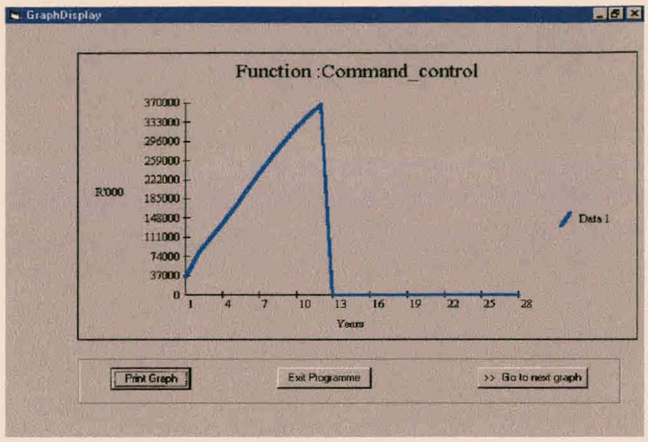


Figure 6.15: Cash flow for function in real terms for run 4A.

PM

This graph represents a relative figure for the number of programme managers that will be required to manage the subcollection of projects for a specific function. This figure is derived from the figures in the default tables of the functions and from the required cash flows in real terms for a specific phase. The impact can be determined on any number of projects that have been selected.

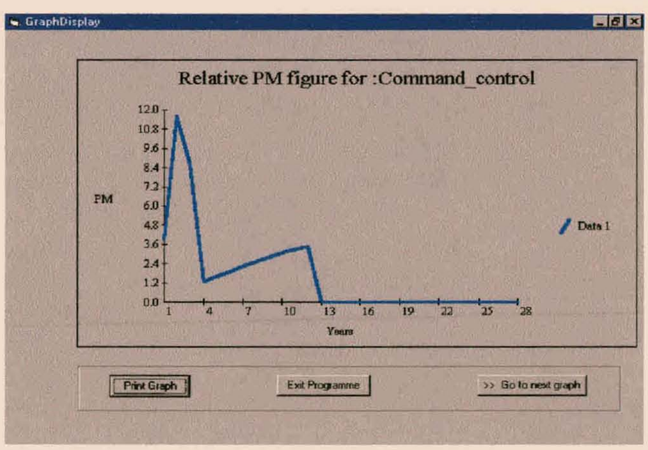


Figure 6.16: Relative programme manager figures for a function for run 4A.

6.5 Comparison of results

This paragraph considers the results in an integrated manner, i.e. by comparing all the runs with each other in order to highlight critical aspects when operating the model. It is done in three sections, namely Part 1: Pseudo results, Part 2: Actual results, and Part 3: Impact results.

Part 1: Pseudo results

The first aspect that was investigated, was the effect the initial project duration would have on the planning horizon. Two durations were considered, namely a minimum project duration and an average project duration.

	0% Growth and Escalation			
	Specific ordering (mixed priorities)		Original ordering (sequential priorities)	
	Minimum time	Average time	Minimum time	Average time
Computer run	1A	1C	1B	1D
Planning horizon in months	179	192	191	192
	+% Growth and Escalation			
	Specific ordering (mixed priorities)		Original ordering (sequential priorities)	
	Minimum time	Average time	Minimum time	Average time
Computer run	2A	2C	2B	2D
Planning horizon in months	264	255	257	252

Table 6.2: Planning horizon for minimum versus average project durations at initial pseudo scheduling.

If a zero percent growth rate in the budget and zero escalation are considered, the minimum duration gives a shorter planning horizon than for the average project duration. If a percentage growth rate in the budget and escalation are taken into consideration, the average duration tends to present planning horizons which are slightly less than those obtained if a minimum project duration is used. Planning horizons are extended to more than twenty years.

As the differences can be regarded as negligible over a long planning horizon, it is recommended that the minimum duration be used as the initial project duration during the initial pseudo scheduling. A further reason for this is explained in the next paragraph, namely Part 2: Actual results. See Table 6.2 for a summary of the results.

A further interesting result is the behaviour of the model at project level with regard to the final choice of a project's duration. In many instances the final project duration is either the minimum duration or the maximum duration. Only in a few instances, and for specific projects, the final project duration is something else than the minimum or maximum project duration. This can be useful for further research in order to reduce the number of computer computations in the searching process for a near optimal solution. See Appendix I for a summary of the comparison of results at project level.

The second aspect that was investigated, was the effect of sequential or original order versus a specific or mixed ordering of projects (also priorities). The important aspect here is that even the original ordering under escalation proves to give a shorter planning horizon than a specific or mixed ordering, the cumulative nominal values for the sequential ordering being far more than the values for specific or mixed ordering. It is therefore recommended to always search for a specific ordering which will result in a less cumulative nominal value.

This decision also confirms the recommendation made earlier with regard to using the minimum project duration during initial pseudo scheduling. Although a minimum project duration gives a slightly longer planning horizon than when the average project duration is used, the cumulative nominal values for a specific order are always less than the values obtained from sequential order. See Table 6.3 for a summary of the results.

	0% Growth and Escalation			
	Minimum time		Average time	
	Specific ordering	Original ordering	Specific ordering	Original ordering
Computer run	1A	1B	1C	1D
Planning horizon in months	179	192	191	192
Required cash flow R billion	7	7	7	7
Computer run	3A	3B		
Planning horizon in months	180	185		
Required cash flow R billion	7	7		
	+% Growth and Escalation			
	Specific ordering (mixed priorities)		Original ordering (sequential priorities)	
	Minimum time	Average time	Minimum time	Average time
Computer run	2A	2B	2C	2D
Planning horizon in months	264	257	255	252
Required cash flow R billion	17	21	17	20
Computer run	4A	4B		
Planning horizon in months	324	348		
Required cash flow R billion	20	30		

Table 6.3: Total required cash flow and planning horizon for specific order (mixed priorities) versus original order (sequential priorities) of projects.

The last aspect that was investigated under Part 1: Pseudo results, is the effect of a percentage growth in budget and escalation compared with results with zero growth in budget and no escalation. This is one of the most important results of this dissertation. If only one combination is analysed, i.e. specific ordering or mixed priorities with a minimum project duration for initial scheduling, it can be seen that the planning horizon increases from 179 months to 264 months, an increase of 47,5%, and that the cumulative nominal amount increases from R7 billion to approximately R17 billion, an increase of 142,9%. The effect of original order or sequential priorities is even worse. It is therefore clear that the effect of escalation due to inflation and changes in exchange rates plays a crucial role in the planning and scheduling of multiple capital projects. If there is a zero percent growth in the budget, and there is escalation due to inflation and changes in exchange rates, the final effect on the planning and overall scheduling will be even worse. See Table 6.4 for a summary of the results.

	Specific ordering i.e. mixed priorities			
	Minimum time		Average time	
	0%	+%	0%	+%
Computer run	1A	2A	1C	2C
Planning horizon in months	179	264	192	255
Required cash flow R billion	7	17	7	17
Computer run	3A	4A		
Planning horizon in months	180	324		
Required cash flow R billion	7	20		
	Original ordering i.e. sequential priorities			
	Minimum time		Average time	
	0%	+%	0%	+%
Computer run	1B	2B	1D	2D
Planning horizon in months	191	257	192	252
Required cash flow R billion	7	21	7	20
Computer run	3B	4B		
Planning horizon in months	185	348		
Required cash flow R billion	7	30		

Table 6.4: Total required cash flow and planning horizon for zero percent growth in budget with zero escalation versus a percentage growth in budget with escalation.

Part 2: Actual results

Two aspects are discussed in this part, namely the nominal actual cash flows versus the nominal pseudo cash flows, and the additional costs which are the differences between the requirement and the original cash flow values. (See Appendix H, pages 34 to 45)

For the first aspect it can be seen that in all runs with actual results, the actual nominal cash flows closely follow the final pseudo cash flows.

With regard to the second aspect it can be seen that the additional costs increase substantially as the planning horizon increases. This means that apart from the increase in the original makespans or completion times for all projects, the real requirement values also increase, which is the amount that should be budgeted in real terms in order to make provision for the required amounts in nominal terms in future.

Part 3: Impact results

It can be seen from Appendix H, pages 46 to 53, that any schedule that has been decided on may have a different impact on a selected impact parameter.

The same type of project information but other top level information can result in different cash flow scenarios for each impact parameter. Peaks and interrupted cash flows are clearly indicated.

One result that must be highlighted is the difference between the relative programme management figure and the cash flow of a specific engineering function. The examples in Appendix H, pages 49 and 53, show that there is no correlation between these two types of graphs. This is because the PM requirement is based on the default values per phase. More programme managers are required at the beginning stage, i.e. the development phase, than at the end stage, i.e. in the production phase. It is therefore incorrect to plan the human resources requirement according to cash flows that are predicted for a specific function. It can now be done according to a relative PM figure.

With all the information available after an impact analysis, data can be adjusted so that the results of the impact analysis can conform to the most suitable schedule of projects.

6.6 Summary of case study

Although it would have been possible to generate data for the case study in a random way, it was decided to use data that are used in practice. As a result some of the projects that were selected contain the same type of information. The data obtained nonetheless cover most of the aspects addressed by this model, thus giving results that can be related to practice. The results have proved to be acceptable and have pointed out that certain problems will occur in practice with regard to the planning of capital acquisition projects if there is no proper planning. The model also showed what the impact of any decision on a final schedule would be on selected parameters.

7. Conclusion and recommendations

7.1 Conclusion

A complex problem has been identified which exists in practice and which requires a very special solution due to its combinatorial complexity. A heuristic solution has been developed, taking into consideration the large number of parameters which apply.

The following aspects with regard to the solution can be highlighted:

* A total system approach is necessary to solve the complex research problem.
* The mathematical solution to the research problem proves to be practical as well.
* Uncertainty was excluded from the research, which eventually resulted in a deterministic model. A stochastic model would have added to the complexity of the problem. Although the budget could be fixed for some years to come, any (uncertain) changes due to political, financial or other reasons could be entered in the model to simulate the impact of those changes.
* Although the model does not allow for the effect of risk, any decisions that could be classified as risky could be assessed by making use of the model.
* The results prove to be acceptable, i.e. the cash flows for the actual analysis tend to follow the required cash flows as determined in the pseudo analysis.
* Strategic as well as tactical levels of the acquisition process are analysed.
* Inputs for the final decisions come not only from top management but also from the tactical or project level, thus forming an integral part of the model.
* Any decision made can be analysed by means of a sensitivity analysis in order to determine what impact it will have on selected parameters. Impacts are determined in money and a relative figure is provided of the human resources required.
* The relative human resources requirement of an engineering function is not directly proportional to the cash flow of that function.

* If the growth rate of the allocated budget is not the same as the growth rate of escalation due to inflation and changes in exchange rates, the effects of the latter must be taken into consideration in order to come up with a realistic, practical schedule. Even if these growth rates are the same and if products are acquired from foreign countries, the differences in inflation and exchange rates necessitate that each country's economic parameters be taken into consideration.
* Once an overall schedule has been determined for each project, each subproject and each phase of a subproject, other current methods can be used to schedule activities within each phase.
* It is advisable to execute a number of pseudo analyses before doing a specific impact analysis in order to save computer time. An impact analysis can be very time consuming.
* The number of impact analyses must be limited to the minimum due to the computer time problem. It is however an essential part of the model in order to determine the impact of a decision on selected parameters as part of a sensitivity analysis.
* The model can be used to look at the survival of strategic organisations in the local industry by predicting their cash flow.
* An impact analysis can be performed on all or on a group of selected projects, or on only a single selected project.
* Although the assumption was made that the budget is a given and that the projects are scheduled accordingly, it is also assumed, though not explicitly analysed, that an interactive converging process exists between the budgeting authority and the programme management in order to arrive at a final project budget that will be suitable for the requirement.
* The model may be used to support the portfolio management of a set of projects which are interrelated. The full implication of a specific schedule should thus be evaluated.

In conclusion, the fact that it is virtually impossible to do all the calculations by hand emphasises the importance of using a model such as the one proposed in this dissertation. Amounts running into billions are at stake and small mistakes or starting projects at the wrong time could cost any organisation dearly.

This heuristic integrated planning decision support model for large multiple capital projects proves to be a solution to a very complex research problem. The proposed model can indeed provide enormous support to all people involved, enabling them to make much better decisions. Yet the gut feeling of the decision makers should not be ignored in the decision-making process. In this regard, a what-if analysis may be conducted to support the decision-making.

It is difficult to translate the improvements effected by this model into money terms, but it is clear that billions could definitely be managed better in the long term.

7.2 Applications

Primary application

The primary application of this model is that of scheduling major capital projects within the South African Department of Defence and to determine the impact of the selected schedule on the programme management organisation and various other organisations. The schedule takes into account different inflation and exchange rates of different countries, and also recognises the difference between the growth rate of the allocated budget and the escalation of project costs over the planning horizon. Project escalation is due to inflation and weakening of the local currency against the currencies of supplier countries.

Once a schedule has been established for the acquisition of major capital projects, the following additional analyses can be conducted:

- a technology development plan
- a system operational plan (or life-cycle cost analysis)
- a corporate capital and operational financial plan
- a product system training plan
- a human resources plan

- a replacement or upgrade plan if it is not included in the schedule
- detailed project planning.

Other applications

A vast amount of money for capital expenditure is allocated annually to the different Government departments at national level, to provinces at provincial level, and at local government level, i.e. municipalities. These three levels of government are actually managing billions which have been allocated for capital expenditure.

The Department of Transport may be taken as an example. Various new units must be acquired for the railways, as well as new aircraft as additions to the existing fleet. Various supplier countries are involved. Some of the work in acquiring the said units and aircraft will be done locally but the majority will, in this instance, be handled by foreign suppliers.

Another example is that of the Department of Trade and Industry. It could be a requirement to determine the impact Government spending on capital items would have on the local industry. The model could be used to specify a particular industry and to eventually determine the impact of spending on that industry.

A national effort can be launched in order to determine the consolidated impact on industry. It could be possible to direct departmental plans in order to satisfy a national goal, such as the maintainability and survival of certain sectors of the industry.

The model can also be applied to organisations other than those linked to Government, for example mine companies or iron and steel manufacturers. Any organisation that spends money on capital items will benefit from using the proposed model.

7.3 Possible extensions

It is clear from the aforesaid applications that any organisation would benefit by using a model such as this as a decision support model in the strategic planning process. A national system could be developed to support the three levels of government separately, and even to consolidate the information into one central decision support service.

7.4 Further research

The scope of this research covered so many important aspects that it was impossible to investigate every significant factor down to the smallest detail. The main objective was to solve the research problem and to get a system going that would show results. It is obvious, therefore, that a number of aspects resulting from this research must be investigated further.

Eta profiles

Five basic profiles have been introduced. New profiles should be investigated that can describe the cash flow profile of a project as a whole. Mathematical profiles other than uniform, straight line, and parabolic can be investigated. The fit of actual project data onto a proposed known profile can also be investigated in order to determine the type of profile and the eta value. Other eta profiles could be researched such as combinations of the profiles proposed in this dissertation.

Initial pseudo scheduling

The whole concept of initial pseudo scheduling must be researched. As shown in the problem definition, optimisation takes place in nominal rands. It would have been easier if the optimisation could have been done in current or real terms, but for reasons mentioned earlier, such as the difference in growth rates of money supply and money demand, and differences in the inflation and exchange rates of the foreign countries, such an approach would not be suitable. Pseudo scheduling, as well as subsequent scheduling, will have to be done in nominal terms. Aspects such as the initial project duration, which lies between the maximum and the minimum project duration, and the initial absorption of nominal money per project, will play an important role in finding an effective initial pseudo schedule.

Final pseudo scheduling

The method of final scheduling is important because it will determine how close one could get to a real optimised schedule. Currently the project with the best reduction of deviation between the budget and overall cash flow is affected. The change (moves per operation) is also a maximum. It is unclear how shorter periods of a project change will affect the final optimised pseudo schedule. The six operations described, namely shift left or right, shrink left or right, and stretch left or right, will still be used as the basic operations. This method applies to an objective to minimise the deviation around a target budget.

Another objective could be to find a schedule where the cash flow of the projects is always less than the allocated budget in nominal terms. This means that where the present pseudo schedule presents a cash flow that can be higher or less than the target budget, the proposed objective will result in cash flows less than the budget. This would require a different optimisation approach and would perhaps result in more annual surplus money than is the case with the present proposed method.

Project optimisation with actual data

Even though the number of possible combinations has been reduced with the introduction of a pseudo schedule, the total number of combinations per project that has to be considered by the model was in certain circumstances unacceptable. With a maximum number of subprojects and a maximum number of phases per subproject, and with reasonable minimum and maximum duration estimates per phase, run time with the computer was too high. The number of possible combinations within a project was therefore reduced in order to get a practical use in computer time. This represents another research opportunity, namely to find a method to increase the number of possible combinations within a project to the maximum number of combinations that will be acceptable to the user. In other words, this should not be hard-coded, but rather a method should be made available to the user to adjust the sensitivity of the model if required.

Constrained optimisation

The current proposed method that is used for constrained optimisation can be improved. A method to link certain projects and then attempting to optimise their cash flows around the allocated budget would be an improvement on the existing method.

Annual inflation update

This aspect has not been covered by this research, although it is a definite requirement.

Planning for year 1 and onwards takes place in year 0. Once year 1 has been completed, it is possible that a certain amount of work planned for that year cannot be completed. An updating method must be researched to take account of the remainder of year 1 and the following years, based on year 1 actual inflation figures and predicted figures for the following years. Contractual escalation rates must be entered into the system for current projects or parts of projects that have been contracted.

Determination of the human resources default requirement

A fixed vs a variable component can be researched in the determination of the human resources required. The fixed component could be that part of the required human resources that must be provided irrespective of the quantity of work that should be done. The variable component is that part which is directly related to the amount of work which is required.

Industry human resources default requirement

Parameters must be researched to determine the impact on the industry in terms of system engineers, design engineers, programme managers, technicians and artisans in order to extend the current proposed model. It would then be possible to determine the specific human resources which are required by industry but from the client's point of view.

Verification of raw data

A method must be developed to check and verify the data so that a problem-free computer analysis can be executed.

Simulation of cash flow budgets for subprojects

The method of allocating a budget to a subproject from the allocated budget of the project can be investigated, in order to find a better solution.

Pseudo operations

The sequence in which and the range over which the pseudo operations are conducted can be investigated, in order to find a way to improve on the final pseudo schedule.

Search approaches

It should be further researched how the large number of possible combinations, in the various processes of searching for an optimised combination, could be reduced to find a quicker and reliable search routine.

Weighted optimisation

This research project optimises only the required cash flow relative to the available budget, and analyses the impact of a selected schedule on a number of impact parameters. Research should be conducted in order to find a method where these impact parameters could be weighted prior to the impact analysis so that the results then obtained would already have realised the impact of a selected schedule.

Near optimal *versus* suboptimal (approximate) solutions

A research may be conducted to assess the level of optimality of the solution, whether it is in fact near optimal or whether it is suboptimal (or an approximate solution).

Application of other modern heuristics

The application of some of the modern heuristics, such as tabu search, simulated annealing, genetic algorithms and neural networks, could be investigated and assessed in order to find better algorithms or even as a means of comparison.

7.5 Recommendations

It is recommended that the model be

* used as a baseline model to solve problems similar to the research problem
* improved by further research on aspects as mentioned
* used at national, provincial and local government levels
* used by all organisations with capital expenditure.

8. Software development

8.1 Introduction

This chapter describes the software and hardware that were used in developing the software model known as NOIDAPS (Near Optimal Integrated Defence Acquisition Planning System). Information with regard to the practical use of NOIDAPS is also given. Note that the software has been designed for academic purposes and not for commercial use. No time has been spent on developing the model as a user friendly model.

8.2 Hardware

The hardware configuration was as follows:

- CPU type : Pentium MMX
- CPU clock : 166 MHz
- Base memory : 640 K
- Extended memory : 31744 K
- Hard disk drive : 2 Gb
- Monitor type : EGA/VGA

8.3 Software

- Visual Basic 5, academic version.

8.4 Operating the model

<u>Menus</u>

The following gives a breakdown of the menus of the model (see Appendix J for menu printouts):

- Main menu for NOIDAPS (form 1)
- Default path (form 22)
- Model setup (form 2)
    - Inflation rates (form 12)
    - Exchange rates (form 8)
    - General information (form 2)
- High level data (form 3)
    - Project priorities (form 9)
    - Annual budget (form 11)
- Defaults (form 7)
    - Defaults per function
- Project data (form 4)
    - Project detail (form 13)
        - Number of subprojects (form 17)
        - Subprojects detail (form 14)
            - Phase detail (form 15)
- Printing menu (form 20)
    - Select projects
- Reports on impact analysis (form 6)
    - Selected projects
    - Selected impacts (form 15)
        - Select companies, functions and countries
- Processing (form 5)

Code

The code for the prototype model is available in certain issues of this dissertation. It is saved on a stiffy marked "NOIDAPS code". Note that the code is accessible and should not be altered.

Data

The corresponding data are saved on a separate stiffy marked "NOIDAPS data". The data on the stiffy are the starting data for the selected projects and must be copied before any changes are made. Some of the data are shown in the appendices. Data are organised by means of Visual Basic 5 own database.

Brief operating procedure

Model setup

- *General information*

  Number of projects that are considered (maximum 100).
  Number of planning horizon years (maximum 30).
  Ignore the Phi information (future research).
  Enter first year of planning. If it is for example 2000, then the final year for high-level data such as budget, inflation and exchange rates must be entered until 2030.

- *Inflation rates*

  Enter the applicable inflation rates per country. The user can modify his own database to suit his requirements. Rates are entered as a percentage.

- *Exchange rates*

Enter the applicable exchange rates per relevant country. The user can modify the database to suit requirements. The exchange rates for the local country chosen must be entered as 1. The other rates must be entered as local units per foreign unit.

- *Project breakdown*

Engineering functions:

Enter the names of all engineering functions that could be relevant to the model.

Companies:

List all organisations that could play a role as local supplier.

Countries:

List all foreign countries and their respective currencies.

Most of the tables have been designed for dynamic use. To make sure that data have been changed in the database, use the update commands on each form when exiting the form.

High-level data

- *Project priorities*

Enter the project numbers sequentially.

Enter a project description.

Enter a project priority. Each project must have a unique priority. Priorities do not have to be equal to the project number. The project with the highest priority (first to be completed) is given the number 1. The number of the project with the lowest priority must equal the total number of projects under consideration. No two projects may have the same priority.

Enter a required completion year for a project with its constraint "on" or "off". A "free" optimisation is nevertheless executed even if a number of projects have their completion time constraints "on". A "constrained" optimisation will be executed directly after the "free" optimisation.

It is optional to enter the estimated project cost (in current value). This high-level value is there to compare the final results with the input from lower levels.

- *Annual budget*

Nominal budget:

If the budget is entered as nominal values, the growth rates must be entered as 0 values. This means that the budget is already in nominal terms and will not be changed during run time.

Current budget:

If the budget is entered in current (real) terms, a growth rate must be entered. The growth rate is the expected rate at which the budget will increase. It is entered as a percentage. Negative rates are allowed.

Combination of nominal and current budget:

Certain annual budgets can be entered as nominal values with zero percent growth rate, while other annual budgets can be entered as current values with an appropriate growth rate.

Gompertz values:

For every year enter a discrete m_e value, where $1 < m_e < 12$, which describes the month within a financial year when the expected monthly cash flow is approximately equal to the average monthly cash flow. Also enter an eta value to describe the initial "steepness" of the cash flow curve. The Gompertz eta must be greater than -1 and less than 1.

Defaults

- Select an engineering function from the DBCombo box.
- For each engineering function in the DB Combo box complete the table for human resources defaults. All phases and all four rows must be completed.

Project data

- Select a project from the DB Combo box.
- For all projects in the DB Combo box complete all data as described in the following subsections.
- *Project detail*
    - Click on the command button in order to add, edit or delete subprojects.

- Click on the "status" text in order to choose from the Combo box whether the project is "current" or "future".

- Ignore "cash flow profile" and "eta value" as these parameters are calculated during run time.

- Click on any of the "update" commands.

- Choose a subproject and then choose the command to go to "subproject" level.

- *Subproject detail*

- Click on the radio buttons to select whether the subproject will be contracted locally or to a foreign supplier. If a foreign supplier has been selected, choose a foreign country and corresponding currency. Any combination is allowed: The supplier country may, for example, be Italy while the currency may be US dollars.

- Choose one of the phases and click on the command button to go to "phase detail". It is not necessary to complete all the phases. Ignore the maintenance phase (future research).

- *Phase detail*

- Enter the phase value in current rands. A zero phase value may be entered.

- Enter the minimum duration and the maximum duration to complete the phase. None of these two durations may be zero.

- Click on "engineering function" command. Two Combo boxes will appear. First select a percentage and then select an engineering function. The information will appear in a third Combo box. To delete specific information from the third Combo box, select the same engineering function again. The chosen engineering function will be replaced with a "null" entry. Maximum five entries are allowed. The total of the five entries must equal 100 percent. Click again on the "engineering function" command button and the Combo boxes will disappear.

- Click on "company" command. Two Combo boxes will appear. First select a percentage and then select an organisation. The information will appear in a third Combo box. To delete specific information from the third Combo box, select the same organisation again. The chosen organisation will be replaced with a "null" entry. Maximum five entries are allowed. The total of the five entries must equal 100 percent. Click again on the "company" command button and the Combo boxes will disappear.

- Ignore the "engineering discipline" (future research).

- If a foreign supplier has been selected, a countertrade frame will show. Enter the estimated percentages for direct, indirect and other countertrade. Click on "update".

- Click on the relevant radio button in order to describe the complexity of the project. A higher complexity will eventually need more human resources than for instance a phase with a low complexity value.

- Once completed, update the form and return to the main menu by following the same path as entered.

Select database path

Hard disk

If data are stored on hard disk, the default path must be :

"C:\program files\devstudio\vb\projectdata\noidapsdata1.mdb".

Stiffy drive

Use "a:\noidapsdata1.mdb".

Processing

Once all the data have been entered and checked, processing can commence.

- Macro : Free Optimisation

  Click first on the "Macro : free optimisation" command button to run the initial pseudo scheduling and final pseudo scheduling modules. Results are printed at the end of the two modules.

- Macro : Constrained Optimisation

  Click on the "Macro : constrained optimisation" command button to incorporate constraints that are "on" in the final pseudo schedule. This is optional and can be left out to be executed at a later stage. This optimisation can only take place after the "free" optimisation has been completed.

- Detailed project optimisation

  To execute the detailed project optimisation, either one of the macro optimisations must be completed.

Update database

Ignore for future research.

Reports on impact analysis

These reports can only be calculated after the actual detailed analysis has been completed.

- First select whether a local, foreign or a local and foreign impact analysis will be conducted.

- Select between graphs and tables, screen or printer, and annual or monthly results.

- Click the "Select projects..." command button to select a specific group of projects for which an impact analysis must be conducted.

- Click on selected projects and return to "Reports on Impact Analysis" menu.

- Click on "Continue with Impact Analysis" to select specific impact parameters.

- Choose (check boxes) impact parameters and functions, companies, countries, programme managers and QA human resource requirements as required.

- Click on "Continue with Impact Analysis".

- After a while, the final impact analysis per page will be available.

Print results

Ignore this menu as it will be developed at a later stage.

Bibliography

1. Alvarez-Valdes, R., Tamarit, J.M., "Heuristic algorithms for resource-constrained project scheduling: A review and an empirical analysis, advances in project scheduling", edited by R. Slowinski and J. Weglarz, Elsevier Science Publishers B.V., Amsterdam, 1989, pp 113-120.

2. ARMSCOR restricted document. "General policy for the management of category 1 matériel acquisition process", document number VB1000, issue 2, April 1994.

3. Bell, C.E., Han, J., "A new heuristic solution method in resource-constrained project scheduling", Naval Research Logistics, vol 38, 1991, pp 315-331.

4. Bell, C.E., Park, K., "Solving resource-constrained project scheduling problems by A^* search", Naval Research Logistics, vol 37, 1990, pp 61-84.

5 Bey, R.B., Doersch, R.H., Patterson, J.H., "The net present value criterion: Its impact on project scheduling", Project Management Quarterly, vol 12, no 2, 1981, pp 35-45.

6. Blaźewicz, J., Cellary, W., Slowinski, R., Weglarz, J., "Scheduling under resource constraints - deterministic models", Annals of Operations Research, vol 7, 1986, pp 1-8, pp 341-350.

7. Blaźewicz, J., Lenstra, J.K., Rinnooy Kan, A.H.G., "Scheduling subject to resource constraints: classification and complexity", Discrete Applied Mathematics, vol 5, 1983, pp 11-24.

8. Bock, D.B., Patterson, J.H., " A comparison of due date setting, resource assignment, and job preemption heuristics for the multi-project scheduling problem", Decision Sciences,

vol 21, 1990, pp 387-402.

9. Boctor, F.F., "Some efficient multi-heuristic procedures for resource-constrained project scheduling", European Journal of Operational Research, vol 29, no 1, November 1990, pp 3-13.

10. Boctor, F.F., "Heuristics for scheduling projects with resource restrictions and several resource-duration modes", International Journal of Production Research, vol 31, no 11, November 1993, pp 2547-2558.

11. Carlier, J., "Scheduling under financial constraints", Advances in Project Scheduling, edited by R. Slowinski and J. Weglarz, Elsevier Science Publishers, B.V., Amsterdam, 1989, pp 187-224.

12 Christofides, N., Alvarez-Valdes, R., Tamarit, J.M., "Project scheduling with resource constraints: A branch and bound approach", European Journal of Operational Research, vol 29, 1987, pp 262-273.

13. Combe, B., "Description of a resource allocation program ASTRA-DISC", Project Planning by Network Analysis, Proceedings of the Second International Congress, Amsterdam, The Netherlands, 6-10 October 1969, Editor: H.J.M. Lombaers, pp 243-248.

14. Cooper, D.F., "Heuristic for scheduling resource-constrained projects: An experimental investigation", Management Science, vol 22, no 11, July 1976, pp 1186-1194.

15. Daniels, R.L., "Resource allocation and multi-project scheduling", Advances in Project Scheduling, edited by R. Slowinski and J. Weglarz, Elsevier Science Publishers, B.V., Amsterdam, 1989, pp 87-112.

16. Davis, E.W., "Project scheduling under resource constraints - historical review and

categorization of procedures", AIIE Transactions, vol 5, no 4, December 1973, pp 297-313.

17. Davis, E.W., "Project network summary measures in constrained-resource scheduling", AIIE Transactions, vol 7, no 2, June 1975, pp 132-142.

18. Davis, E.W., "Resource allocation in project network models - a survey", Journal of Industrial Engineering, vol 17, no 4, April 1966, pp 177-188.

19. Davis, E.W., Heidorn, G.E., "An algorithm for optimal project scheduling under multiple resource constraints", Management Science, vol 27, no 12, August 1971, pp B803-B816.

20. Davis, E.W., Patterson, J.H., "A comparison of heuristic and optimum solutions in resource-constrained project scheduling", Management Science, vol 21, no 8, April 1975, pp 944-955.

21. Davis, K.R., " Resource constrained project scheduling with multiple objectives: A decision support approach", Computers and Operational Research, vol 19, no 7, October 1992, pp 657-669.

22. Dekro, R.F., "A decomposition approach to multi-project scheduling", European Journal of Operational Research, vol 51, no 1, March 1991, pp 110-118.

23. Demeulemeester, E., "Optimal algorithms for various classes of multiple resource-constrained project scheduling problems", Proefschrift voorgedragen tot het bekomen van de graad van Doctor in de Toegepaste economische Wetenschappen, Katholieke Universiteit Leuven, Belgium, 1992.

24. Demeulemeester, E., "Minimizing resource availability costs in time-limited project

networks", Management Science, vol 41, no 10, October 1995, pp 1590-1598.

25. Demeulemeester, E., Herroelen, W., "A branch-and-bound procedure for the multiple resource-constrained project scheduling problem", Management Science, vol 38, no 12, December 1992, pp 1803-1818.

26. De Wit, J., Herroelen, W., " An evaluation of microcomputer-based software packages for project management", European Journal of Operational Research, vol 49, 1990, pp 102-139.

27. Doersch, R.H., Patterson, J.H., "Scheduling a project to maximize its present value: A zero-one programming approach", Management Science, vol 23, no 8, 1977, pp 882-889.

28. Drexl, A., "Scheduling of project networks by job assignment", Management Science, vol 37, no 12, December 1991, pp 1590-1602

29. Drexl, A., Sprecher, A., "Resource- and time window-constraint production scheduling with alternative process plans: an artificial intelligence approach", Operations Research in Production Planning and Control, Proceedings of a Joint German/ US Conference, Hagen, Germany, June 1992, pp 307-320.

30. Dumond, J., "In a multi-resource environment, how much is enough?", International Journal of Production Research, vol 30, no 2, February 1992, pp 395-410.

31. Dumond, J., Mabert, V.A., "Evaluating project scheduling and due date assignment procedures: An experimental analysis", Management Science, vol 34, no 1, 1988, pp 101-118.

32. Fendly, L.G., "Toward the development of a complete multi-project scheduling system", Journal of Industrial Engineering, vol 19, no 10, October 1968, pp 475-486.

33. Fisher, M.L., "Optimal solution of scheduling problems using Lagrange multipliers : Part 1" , Operations Research, vol 21, no 5, 1973, pp 1114-1127.

34. Fox, G.E., Baker, N.R., Bryant, J.L., " Economic models for R and D project selection in the presence of project interactions", Management Science, vol 30, no 7, 1984, pp 890-902.

35. Gonguet, L., "Comparison of three heuristic procedures for allocating resources and producing schedule", Project Planning by Network Analysis, Proceedings of the Second International Congress, Amsterdam, The Netherlands, 6-10 October 1969, Editor:HJ.M. Lombaers, pp 249- 255.

36. Gorenstein, S., "An algorithm for project sequencing with resource-constraints", Operations Research, vol 20, no 4, 1972, pp 835-850.

37. Granot, D., Zuckerman, D., "Optimal sequencing and resource allocation in research and development projects", Management Science, vol 37, no 2, February 1991, pp 140-156.

38. Grinold, R.C., "The payment scheduling problem", Naval Research Logistics Quarterly, vol 9, no 1, 1972, pp 123-136.

39. Hamacher, H.W., Tufeci, S., "Algebraic flows and time-cost trade-off problems", Annals of Discrete Mathematics, vol 19, 1984, pp 165-182.

40. Herroelen, W.S., "Resource-constraint project scheduling - the state of the art", Operational Research Quarterly, vol 23, no 3, 1972, pp 261-275.

41. Hochbaum, D. S., Shamir, R., "Strongly polynomial algorithms for the high multiplicity scheduling problem", Operations Research, vol 39, no 4, August 1991, pp 648-653.

42. Icmeli, O., Erenguc, S.S.,Zappe, C.J., "Project scheduling problems: A survey", International Journal of Operations and Production Management, vol 13, 1993, pp 80-91.

43. Icmeli, O., Erenguc, S.S., "A branch and bound procedure for the resource-constrained project scheduling problem with discounted cash flows", Management Science, vol 42, no 10, October 1996, pp 1395-1408.

44. Icmeli, O., Rom, W.O., "Solving the resource constrained project scheduling problem with optimization subroutine library", Computers and Operations Research, vol 23, no 8, August 1996, pp 801-817.

45. Jaafari, A., "Time and priority allocation scheduling technique for projects", International Journal of Project Management, vol 14, no 5, October 1996, pp 289-299.

46. Khattab, M.M., Choobineh, F., "A new heuristic for project scheduling with a single resource constraint", Computers and Industrial Engineering, vol 19, 1990, pp 514-518.

47. Khattab, M.M., Choobineh, F., " A new approach for project scheduling with a limited resource", International Journal of Production Research, vol 29, no 1, 1991, pp 185-198.

48. Kolish, R., Drexl, A., "Adaptive search for solving hard project scheduling problems", Naval Research Logistics, vol 43, no 1, February 1996, pp 23-40.

49. Kolish, R., Sprecher, A., Drexl, A., "Characterization and generation of a general class of resource-constrained project scheduling problems", Management Science, vol 4, no 10, October 1995, pp 1693-1703.

50. Krzystof, D., Krzystof, S., " A note on sequencing jobs with deadlines problem", European Journal of Operational Research, vol 59, January 1992, pp 333-336.

51. Kurtulus, I. Davis, E.W., "Multi-project scheduling: Categorization of heuristic rules performance", Management Science, vol 28, no 2, February 1982, pp 161-172.

52. Kurtulus, I.S., Narula, S.C., "Multi-project scheduling: Analysis of project performance", IIE Transactions, vol 17, no 1, March 1985, pp58-66.

53. Leachman, R.C., Dincerler, A., Kim, S., " Resource-constrained scheduling of projects with variable-intensity activities", IEE Transactions, vol 22, 1990, pp 31-40.

54. Leachman, R.C., Kim, S., "A revised critical path method for networks including both overlap relationships and variable-duration activities", European Journal of Operational Research, vol 64, January 1993, pp 229-248.

55. Li, K.Y., Willis, R.J., "An iterative scheduling technique for resource-constrained project scheduling", European Journal of Operational Research, vol 56, no 3, February 1992, pp 370-379.

56. Liu, Z., Sanlaville, E., " Preemptive scheduling with variable profile, precedence constraints and due dates", Discrete Applied Mathematics, vol 58, no 3, April 1995, pp 253-280.

57. Lootsma, F.A., Mensch, T.C.A., Vos, F.A., "Multi-criteria analysis and budget reallocation in long-term research planning", European Journal of Operational Research, vol 47, 1990, pp 293-305.

58. Maggott, J., "Estimating the mean completion time of PERT networks with exponentially distributed duration of activities", European Journal of Operational Research, vol 71, no 1, November 1993, pp 70-79.

59. Mahhodi, F., Mosier, C.T., Guerin, R.E., "The effect of combining simple priority

heuristics in flow-dominant shops", International Journal of Production Research, vol 34, no 3, March 1996, pp 819-839.

60. Mandakovic, T., Souder, W.E., "An interactive decomposable heuristic for project selection", Management Science, vol 31, October 1985, pp 1257-1271.

61. Mason, A.T., Moodie, C.L., "A branch and bound algorithm for minimizing cost in project scheduling", Management Science, vol 11, no 4, Part I, December 1971, pp B158-B173.

62. McGee, A.A., and Markarian, M.D., "Optimum allocation of research/engineering manpower within a multi-project organizational structure," IEEE Transactions on Engineering Management, September 1962.

63. Nguyen, Q.C., Stone, R.E., "Multiperiod minimax resource allocation problem with substitutable resources", Management Science, vol 39, no 8, August 1993, pp 964-974.

64. Özdamar, L., Ulusoy, G., "A local constraint based analysis approach to project scheduling under general resource constraints", European Journal of Operational Research, vol 79, 1994, pp 287-298.

65. Özdamar, L., Ulusoy, G., "A survey on the resource-constrained project scheduling problem", IIE Transactions, vol 27, 1995, pp 574-586.

66. Özdamar, L., Ulusoy, G., "A note on an iterative forward/backward scheduling technique with reference to a procedure by Li and Willis", European Journal of Operational Research, vol 89, 1996, pp 400-407.

67. Padman, R., Smith-Daniels, D.E., "Early-tardy cost trade-offs in resource constrained projects with cash flows: An optimization-guided heuristic approach", European Journal

of Operational Research, vol 64, no 2, January 1993, pp 295-311.

68. Patterson, J.H., "Project scheduling: The effects of problem structure on heuristic performance", Naval Research Logistics Quarterly, vol 23, 1976, pp 95-123.

69. Patterson, J.H., "Comparison of exact approaches for solving the multiple constrained resource project scheduling problem", Management Science, vol 30, no 7, July 1984, pp 854-867.

70. Patterson, J.H., Huber, W.D., "A horizon varying, zero-one approach to project scheduling", Management Science, vol 20, no 6, February 1974, pp 990-998.

71. Patterson, J.H., Roth, G.W., "Scheduling a project under multiple resource constraints: A zero-one programming approach", AIIE Transactions, vol 8, no 4, May 1976, pp 449-455.

72. Patterson, J.H., Talbot, F.B., Slowinski, R., Weglarz, J., "Computational experience with a backtracking algorithm for solving a general class of precedence and resource constrained scheduling problems", European Journal of Operational Research, vol 49, 1990, pp 68-79.

73. PERT, Phase I Summary Report, Special Projects Office, Bureau of Ordnance Department of the Navy, Washington, July, 1958.

74. Plenert, G., " Optimizing theory of constraints when multiple constrained resources exist", European Journal of Operational Research, vol 70, no 1, October 1993, pp 126-133.

75. Pritsker, A.A.B., Happ, W.W., "GERT: Graphical Evaluation and Review technique. Part 1. Fundamentals", Journal of Industrial Engineering, vol 17, 1996, pp 267-274.

76. Pritsker, A.A.B., Watters, L.J., Wolfe, P.M.,"Multi-project scheduling with limited resources: A zero-one programming approach", Management Science, vol 16, no 1, September 1969, pp 93-108.

77. Radermacher, F.J., "Scheduling of Project Networks", Annals of Operations Research, vol 4, June 1985, pp 227-252.

78. Raman, N., Talbot, F.B., "The job shop tardiness problem : A decomposition approach", European Journal of Operational Research, vol 69, no 2, September 1993, pp 187-199.

79. Rodriques, A., Bowers, J., " System dynamics in project management: A comparative analysis with traditional methods", Systems Dynamics Review, vol 12, no 2, 1996, pp 121-139.

80. Russell, R.A., "Cash flows in networks", Management Science, vol 16, 1970, pp 357-373.

81. Russell, R.A., "A comparison of heuristics for scheduling projects with cash flows and resource restrictions", Management Science, vol 32, no 10, October 1986, pp 1291-1300.

82. Samuelson, P.A., Nordhaus, W.D., "Economics", Fifteenth Edition, 1995, McGraw-Hill, Inc.

83. Smith-Daniels, D.E., Aquilano, N.J., Using late-start resource-constrained project schedule to improve project net present value", vol 18, 1987, pp 617-630.

84. Smith-Daniels, D.E., Smith-Daniels, V.L., " Maximizing the net present value of a project subject to materials and capital constraints", Journal of Operations Management, vol 7, 1987, pp 33-45.

85. Spiegel, M.R., "Theory and problems of statistics", Schaum's Outline Series, 1972,

McGraw-Hill Book Company (UK) Limited.

86. Sprecher, A., "Resource-constrained project scheduling: exact methods for the multi-mode case", Springer-Verlag, Berlin Heidelberg, 1993.

87. Stinson, J.P., Davis, E.W., Khumawala, B.M., "Multiple resource-constrained scheduling using branch and bound", AIIE Transactions, vol 10, no 3, September 1978, pp 252-259.

88. Talbot, R.B., "Resource-constrained project scheduling with time-resource trade-offs: The non-preemptive case", Management Science, vol 28, no 10, October 1982, pp 1197-1210.

89. Talbot, F.B., Patterson, J.H., "An efficient integer programming algorithm with network cuts for solving resource-constraint scheduled problems", Management Science, vol 24, no 11, July 1978, pp 1163-1174.

90. Thesen, A., "Heuristic scheduling of activities under resource and precedence restrictions", Management Science, vol 23, 1976, pp 412-422.

91. Thesen, A., "Measures of restrictiveness of project networks", Networks, vol 7, 1977, pp 193-208.

92. Togsverd, T., "Resource allocation in decentralized organizations", Operational Research '78, Proceedings of the Eighth IFORS International Conference on Operational Research, Edited by Haley, K.B., 1978, pp 860-877.

93. Tsubakitani, S., Dekro, R.F., " A heuristic for multi-project scheduling with limited resources in the housing industry", European Journal of Operational Research, vol 49, no 1, November 1990, pp 80-91.

94. Ulusoy, G., Özdamar, L., "Heuristic performance and network resource characteristic in resource-constrained project scheduling", Journal of the Operational Research Society, vol 40, 1989, pp 1145-1152.

95. Ulusoy, G., Özdamar, L., "A constraint-based perspective in resource constrained project scheduling", International Journal of Production Research, vol 32, 1994, pp 693-705.

96. Ulusoy, G., Özdamar, L., "A heuristic algorithm for improving a project's duration and net present value", International Journal of Operations and Production Management, vol 15, 1995, pp 89-98.

97. Ulusoy, G., Özdamar, L., "Framework for an interactive project scheduling system under limited resources", European Journal of Operational Research, vol 90, 1996, pp 362-375.

98. Van Wassehove, L.N., Baker, K.R., "A bicriterion approach to time/cost trade-offs in sequencing", European Journal of Operational Research, vol 11, 1982, pp 48-54.

99. Valadares Tavares, L., "Optimal resource profiles for program scheduling", European Journal of Operational Research, vol 29, 1987, pp 83-90.

100. Viviers, F., "'n Projekbestuurstelsel vir kliëntorganisasies met spesifieke toepassing op gevorderde tegnologiese projekte", Proefskrif ingelewer vir die graad Doktor in die Wysbegeerte (Ingenieurswese) aan die Universiteit van Stellenbosch, Desember 1984, pp 46-64.

101. Weglarz, J., "Control in resource allocation systems", Foundations of Control Engineering, vol 5, 1980, pp 159-180.

102. Weglarz, J., "Project scheduling with continuously-divisible doubly constrained resources",

Management Science, vol 27, 1981, pp 1040-1053.

103. Weglarz, J., Blazewicz, J., Cellary, W., "An automated revised simplex method for constrained resource network scheduling", ACM Transactions on Mathematical Software, vol 3, no3, September 1977, pp 295-300.

104. Weiss. E.N., "An optimization based heuristic for scheduling parallel project networks with constrained renewable resources", IEE Transactions, vol 20, no 2, June 1988, pp 137-143.

105. Wiest, J.D., "Some properties of schedules for large projects with limited resources", Operations Research, vol 12, 1964, pp 395-418.

106. Wiest, J.D., "A heuristic model for scheduling large projects with limited resources", Management Science, vol 13, no 6, February 1967, pp 359-377.

107. Woodworth, B.M., Willie, C.J., "A heuristic algorithm for resource levelling in multi-project, multi-resource scheduling", Decision Sciences, vol 6, 1975, pp 525-540.

108. Yang, K.K., Talbot, F.B., Patterson, J.H., "Scheduling a project to maximize its net present value: An integer programming approach", European Journal of Operational Research, vol 64, 1993, pp 188-198.

109. Zahorik, A., Thomas, L.J., Trigeiro, W.W., "Network programming models for production scheduling in multi-stage, multi-item capacitated systems", Management Science, vol 30, no 3, March 1984, pp 308-325.

APPENDICES

Appendix A : Feasibility of $\frac{12}{(1-\eta)} = \sum_{m=1}^{12} [\frac{1}{(1-\eta)}]^{\frac{b^m - b}{b^{m_e}-b}}$

Appendix A:

Feasibility of $$\frac{12}{(1-\eta_g)} = \sum_{m=1}^{12} \left[\frac{1}{(1-\eta_g)}\right]^{\frac{b^m - b}{b^{m_e}-b}}$$

For this equation to be valid, $\eta \neq 1$ and .

$$b^{m_e} - b \neq 0$$

then

$$b\,(b^{m_e - 1} - 1) \neq 0$$

therefore, $b \neq 0$ and

$$b^{m_e - 1} \neq 1$$

The latter part implies that $(m_e - 1) \log b \neq \log 1$

$\therefore \quad (m_e - 1) \log b \neq 0$

Then, $(m_e - 1) \neq 0$ and $\log b \neq 0$

$\therefore \quad m_e \neq 1$ and $b \neq 1$

Result :

$b \neq 0$, $b \neq 1$, $m_e \neq 1$, and $\eta_g \neq 1$

Appendix B :

Algorithm to find constant b in Gompertz equation

Private Sub Gompertz(budgetintens As Double, etagompertz As Double, tegompertz As Double)

Given : Budget intensity = budgetintens
η_g -value = etagompertz
m_e = tegompertz

Algorithm:

```
lhs = 12 / (1 - etagompertz) "lefthand-side"
bstart = 2.0001
bend = 3.0001
continue1:
bmid = (bstart + bend) / 2
sumrhs = 0
sumrhe = 0
sumrhm = 0
For x = 1 To 12
        sumrhs = sumrhs + (1 / (1 - etagompertz)) ^ ((bstart ^ x - bstart) / (bstart ^
        tegompertz - bstart))
Next x
For x = 1 To 12
        sumrhe = sumrhe + (1 / (1 - etagompertz)) ^ ((bend ^ x - bend) / (bend ^
        tegompertz - bend))
Next x
For x = 1 To 12
        sumrhm = sumrhm + (1 / (1 - etagompertz)) ^ ((bmid ^ x - bmid) / (bmid ^
        tegompertz - bmid))
Next x
If (Abs((lhs - sumrhm) / lhs) <= 0.000001) Then
        GoTo continue2
End If
If (sumrhe < lhs) And (sumrhs < lhs) Then
        bstart = bend
        bend = 2 * bstart
        GoTo continue1
End If
If (sumrhs > lhs) And (sumrhe > lhs) Then
        bend = bstart
        bstart = 0.5 * bend
```

```
        GoTo continue1
End If
If sumrhm <= lhs Then
        bstart = bmid
        GoTo continue1
End If
If sumrhm > lhs Then
        bend = bmid
        GoTo continue1
End If
continue2:
b = bmid
q = (1 / (1 - etagompertz)) ^ (1 / (b ^ tegompertz - b))
p = (1 - etagompertz) * budgetintens / (q ^ b)
End Sub
```

Appendix C :

Theory development of eta cash flow profiles

1. Introduction

The aim of this appendix is to develop for each project real cash flow profiles from the given data, i.e. the eta-value, the duration and the total real cost of the project. These cash flow profiles are then used to determine the nominal cash flow for the project in a specific time slot and then to determine the overall nominal cash flow for all projects. These real cash flow profiles are developed as discrete values per time unit. The sequence in which the theory has been developed is uniform, straight line, semi-parabolic with zero slope at the end, semi-parabolic with zero slope at the beginning, and parabolic eta cash flow profiles.

2. Uniform profile

All projects are transformed into an initial pseudo project with a uniform profile. This uniform cash flow will be transformed into one of the four other types of cash flow profiles if the actual cash flow profile is predicted as different from that of the uniform profile. A profile will be chosen which suits the predicted cash flow the best. No η value is given to a uniform cash flow profile (default value of 0). The intensity I is defined as money/time unit. Although graphs are shown as continuous functions, values to be used in the model are treated as discrete.

Figure C1 : Uniform η-profile.

3. Straight line η-profile

Define η = intensity factor,
R = total real cost of the project,
$\bar{t}$ = the duration of the project, and
I = R/$\bar{t}$, the initial pseudo uniform intensity.

Let $f_t = \alpha t^2 + \beta t + \gamma$ where f_t defines a straight line function, t = discrete time units, and β and γ as constants obtained from boundary conditions. For the straight line profile, α=0.

Boundary conditions:

At t = 1, $f_t = I(1-\eta)$
then $I(1-\eta) = \beta + \gamma$. ...(C.1)

At $t = \bar{t}$ with $\bar{t}$ = total number of time periods, $f_t = I(1+\eta)$
then $I(1+\eta) = \beta\bar{t} + \gamma$. ...(C.2)

From C.1 $\gamma = I(1-\eta) - \beta$.

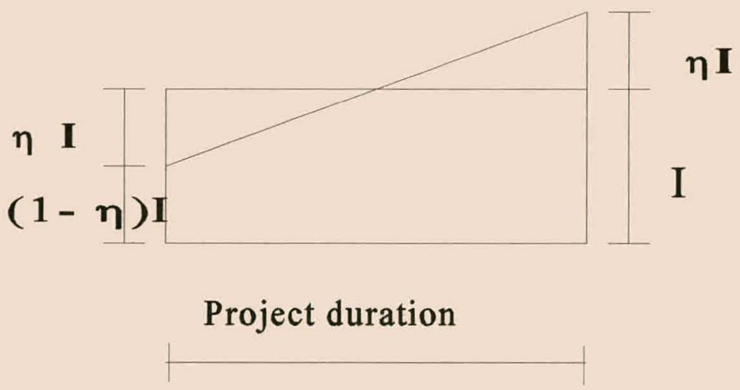


Figure C.2 : Straight line η-profile.

Substitute in C.2:

$I(1+\eta) = \beta\bar{t} + I(1-\eta) - \beta$

$\therefore \quad 2I\eta = \beta(\bar{t} - 1)$

$$\beta = \frac{2I\eta}{(\bar{t}-1)} \qquad \text{...(C.3)}$$

Substitute C.3 in C.1 :

$$I(1-\eta) = \frac{2I\eta}{(\bar{t}-1)} + \gamma$$

$$\therefore \quad \gamma = I(1-\eta) - \frac{2I\eta}{(\bar{t}-1)} \qquad \text{...(C.4)}$$

then

$$\therefore \quad f_t = \frac{2I\eta}{(\bar{t}-1)}(t-1) + I(1-\eta) \qquad \text{...(C.5)}$$

For C.5 to be feasible, $\bar{t} \geq 2$, $t \geq 1$, $-1 \leq \eta \leq 1$ where $\bar{t}, t \in \mathbb{N}$, $\eta \in \mathbb{R}$.

Check:

From C.4 and at $t = 1$ is $f_1 = I(1-\eta)$ and at $t = \bar{t}$ ...(C.6)

$$f_{\bar{t}} = \frac{2I\eta}{(\bar{t}-1)}(\bar{t}-1) + I(1-\eta)$$

$$= 2I\eta + I - I\eta$$

$$= I(1+\eta). \qquad \text{...(C.7)}$$

Both C.6 and C.7 satisfy boundary conditions.

If η is negative, then from C.6

$$f_1 = I(1+\eta) \qquad \text{...(C.6a)}$$

and from C.7 $f_{\bar{t}} = I(1-\eta)$ ...(C.7a)

which results in the following profile which has a negative slope:

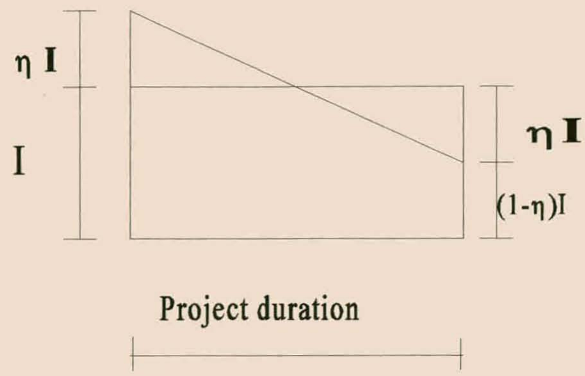


Figure C.3 : Straight line negative η-profile.

Let R = total amount of money to be spent on the total project over a period $\bar{t}$.

The average intensity I = R / $\bar{t}$

Substitute in C.5:

$$f_t = \frac{2R\eta}{\bar{t}\,(\bar{t}-1)}(t-1) + \frac{R}{\bar{t}}(1-\eta)$$

Arbitrary define $K_\alpha = (\bar{t} - 1)/2$. Then

$$= \frac{\eta\ R}{\bar{t}\ K_\alpha}\ t + \frac{R}{\bar{t}}(1-\eta-\frac{\eta}{K_\alpha})$$

$$Define\ \frac{\eta\ R}{\bar{t}\ K_\alpha} = \beta\ ,\ \frac{R}{\bar{t}}(1-\eta-\frac{\eta}{K_\alpha})\ as\ \gamma$$

then $f_t = \beta t + \gamma$ ...(C.8)

	Constants with $\bar{t} \neq 0,1$
K_α	$\frac{(\bar{t}-1)}{2}$
α	0
β	$\frac{\eta\ R}{\bar{t}\ K_\alpha}$
γ	$\frac{R}{\bar{t}}[1 - \eta - \frac{\eta}{K_\alpha}]$

Table C.1 : Summary of constants for straight line η-profile.

Example 1:
$R = 180$, $\bar{t} = 9$, $\eta = .5$, $I = R / \bar{t} = 180/9 = 20$
Substitute in equation C.8.
$f_1 = 10.0$, $f_2 = 12.5$, $f_3 = 15.0$, $f_4 = 17.5$, $f_5 = 20.0$,
$f_6 = 22.5$, $f_7 = 25.0$, $f_8 = 27.5$, $f_9 = 30.0$, $\sum f_t = 180$.

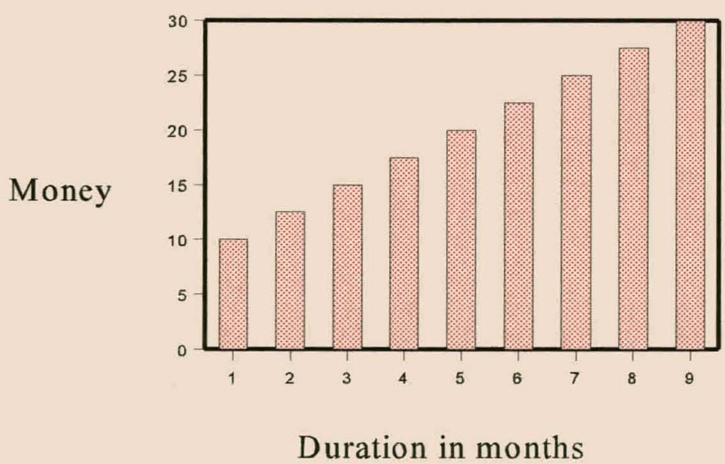


Figure C.4 : Straight line η-profile, example 1.

4. **Semi-parabolic η-profile with zero slope at end**

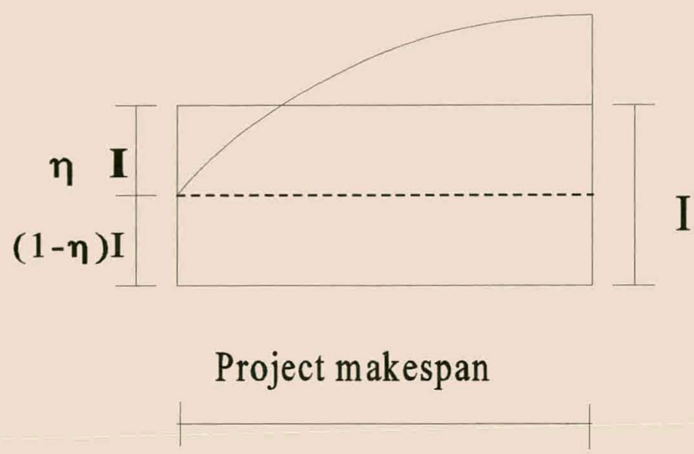


Figure C.5 : Semi-parabolic η-profile with zero slope at end.

With η as the intensity factor and I as the initial pseudo uniform intensity already defined, let $f_t = \alpha t^2 + \beta t + \gamma$ where f_t defines a parabolic convex function, t = discrete time units, and α, β and γ as constants obtained from boundary conditions.

Boundary conditions:

at t = 1 is $f_t = I(1-\eta)$

$$\therefore \quad \frac{R}{t}(1-\eta) = I(1-\eta) = \alpha + \beta + \gamma \qquad \text{...(C.9)}$$

$$f_t' = 2\alpha t + \beta$$

at $t = \bar{t}$ is $\quad f_t' = 0$

$$\therefore 0 = 2\alpha\bar{t} + \beta \qquad \text{...(C.10)}$$

One additional equation is needed.

For t=1 to $\bar{t}$ is $$\sum f_t = \bar{t} I = R$$

i.e., the summation of all periodic cash flow equals R, the total amount over period $\bar{t}$.

Develop a series from the original equation, $f_t = \alpha t^2 + \beta t + \gamma$.

$$\begin{array}{ll}
t=1: & f_1 = \alpha + \beta + \gamma \\
t=2: & f_2 = 4\alpha + 2\beta + \gamma \\
t=3: & f_3 = 9\alpha + 3\beta + \gamma \\
\vdots & \quad\ \vdots \quad\ \vdots \quad \vdots \\
t=\bar{t} & f_{\bar{t}} = \bar{t}^2\alpha + \bar{t}\beta + \gamma
\end{array}$$

Define series 1 as:

$\gamma + \gamma + \gamma + \ldots + \gamma \qquad \therefore S_\gamma = \bar{t}\,\gamma$

Define series 2 as:

$$1\beta + 2\beta + 3\beta + \ldots + \bar{t}\,\beta \qquad \therefore S_\beta = \frac{\bar{t}}{2}(\bar{t}+1)\beta$$

Define series 3 as:

$$1\alpha + 4\alpha + 9\alpha + \ldots + \bar{t}^{\,2}\alpha \qquad \therefore S_\alpha = \frac{\bar{t}\,(\bar{t}+1)(2\bar{t}+1)}{6}\alpha$$

Thus, the 3rd equation is:

$$S_{\bar{t}} = \frac{t(t+1)(2t+1)}{6}\alpha + \frac{t}{2}(\bar{t}+1)\beta + \bar{t}\,\gamma$$

But $S_{\bar{t}} = \bar{t}\,I = R$

$$\therefore \quad R = \bar{t}\,I = \frac{\bar{t}(\bar{t}+1)(2\bar{t}+1)}{6}\alpha + \frac{\bar{t}}{2}(\bar{t}+1)\beta + \bar{t}\,\gamma$$

Divide both sides with $\bar{t}$

Appendix C : Semi-parabolic eta profile with zero slope at end

$$\therefore \frac{R}{\bar{t}} = I = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha + \frac{1}{2}(\bar{t}+1)\beta + \gamma \qquad \text{...(C.11)}$$

From C.10, $\beta = -2\alpha\bar{t}$, then substitute in C.9 and C.11

$$\frac{R}{\bar{t}}(1-\eta) = I(1-\eta) = \alpha - 2\alpha\bar{t} + \gamma$$

$$= \alpha(1-2\bar{t}) + \gamma \qquad \text{...(C.9a)}$$

$$\therefore \frac{R}{\bar{t}} = I = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha - \frac{1}{2}(\bar{t}+1)(2\alpha\bar{t}) + \gamma$$

$$\therefore = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha - \bar{t}(\bar{t}+1)\alpha + \gamma$$

$$\therefore = \alpha(\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \bar{t}] + \gamma \qquad \text{...(C.11a)}$$

to summarise:

$$\frac{R}{\bar{t}}(1-\eta) = I(1-\eta) = \alpha(1-2\bar{t}) + \gamma \qquad \text{...(C.12)}$$

$$\therefore \frac{R}{\bar{t}} = I = \alpha(\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \bar{t}] + \gamma \qquad \text{...(C.13)}$$

From C.12, $\gamma = I(1-\eta) - \alpha(1-2\bar{t})$. Substitute in C.13.

$$I = \alpha(\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \bar{t}] + I(1-\eta) - \alpha(1-2\bar{t})$$

$$\eta I = \alpha \left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \bar{t}] - (1-2\bar{t}) \right\} \qquad \text{...(C.14)}$$

From C.14

$$\alpha = \frac{\eta I}{\left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \bar{t}\,] - (1-2\bar{t}) \right\}} \qquad \text{...(C.15)}$$

Define constant $K_\alpha = \left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \bar{t}\,] - (1-2\bar{t}) \right\}$

$$\alpha = \frac{\eta\, R}{\bar{t}\, K_\alpha} \qquad \text{...(C.15a)}$$

From C.12, $\gamma = I(1-\eta) - \alpha(1-2\bar{t})$

$$\therefore\ \gamma = \frac{R}{\bar{t}}(1-\eta) - \frac{\eta R(1-2\bar{t}\,)}{\bar{t}\, K_\alpha}$$

$$= \frac{R}{\bar{t}}[1 - \eta - \frac{\eta(1-2\bar{t}\,)}{K_\alpha}] \qquad \text{...(C.16)}$$

From C.10, $\beta = -2\alpha\,\bar{t}$

$$= -\frac{2\eta R}{K_\alpha} \qquad \text{...(C.17)}$$

Thus, all constants α, β, and γ are now known in order to equate

$$\therefore\ f_t = \alpha t^2 + \beta t + \gamma \qquad \text{...(C.18)}$$

	Constants with $\bar{t} \neq 0,1,5/4$
K_α	$\left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \bar{t}\,] - (1-2\bar{t}) \right\}$ $= -\frac{1}{6}(4\bar{t}^2 - 9\bar{t} + 5)$
α	$\frac{\eta R}{\bar{t} K_\alpha}$
β	$-\frac{2\eta R}{K_\alpha}$
γ	$\frac{R}{\bar{t}}[1 - \eta - \frac{\eta(1-2\bar{t})}{K_\alpha}]$

Table C.2 : Summary of constants for semi-parabolic η-profile with zero slope at the end.

Example 2: $R = 180$, $\bar{t} = 9$, $\eta = .5$, $I = R / \bar{t} = 180/9 = 20$. Substitute in equation C.18. $f_1 = 10.0$, $f_2 = 13.6$, $f_3 = 16.8$, $f_4 = 19.4$, $f_5 = 21.6$, $f_6 = 23.3$, $f_7 = 24.5$, $f_8 = 25.2$, $f_9 = 25.5$, $\sum f_t \approx 180$.

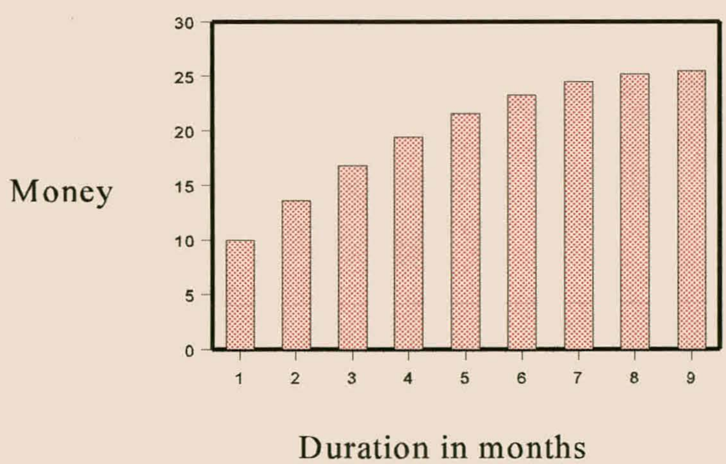


Figure C.6 : Semi-parabolic η-profile with zero slope at end, example 2.

5. **Semi-parabolic η-profile with zero slope at beginning**

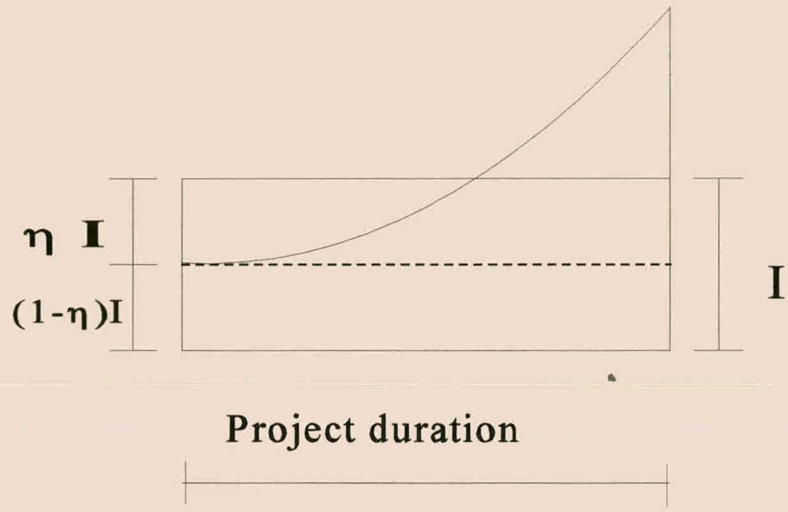


Figure C.7 : Semi-parabolic η-profile with zero slope at beginning.

As before, η = intensity factor and I = initial pseudo uniform intensity. Let $f_t = \alpha t^2 + \beta t + \gamma$ where f_t defines a parabolic convex function, t = discrete time units, and α, β and γ as constants obtained from boundary conditions.

Boundary conditions:

at t = 1 is $f_t = I(1-\eta)$

$$\therefore \quad \frac{R}{t}(1-\eta) = I(1-\eta) = \alpha + \beta + \gamma \qquad \text{...(C.19)}$$

$$f_t^{'} = 2\alpha t + \beta$$

at t = 1 is $\quad f_t^{'} = 0$

$$\therefore 0 = 2\alpha + \beta \qquad \text{..(C.20)}$$

As before, one additional equation is required.

Thus, the 3rd equation is:

$$\therefore \frac{R}{\bar{t}} = I = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha + \frac{1}{2}(\bar{t}+1)\beta + \gamma \qquad \text{...(C.21)}$$

From C.20, $\beta = -2\alpha$, then substitute in C.19 and C.21

$$\frac{R}{\bar{t}}(1-\eta) = I(1-\eta) = \alpha - 2\alpha + \gamma$$

$$= -\alpha + \gamma \qquad \text{...(C.19a)}$$

$$\therefore \frac{R}{\bar{t}} = I = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha + \frac{1}{2}(\bar{t}+1)\beta + \gamma$$

$$\therefore \quad = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha - (\bar{t}+1)\alpha + \gamma$$

$$\therefore \quad = \alpha(\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - 1\ ] + \gamma \qquad \text{...(C.21a)}$$

to summarise:

$$\frac{R}{\bar{t}}(1-\eta) = I(1-\eta) = -\alpha + \gamma \qquad \text{...(C.22)}$$

$$\therefore \frac{R}{\bar{t}} = I = \alpha(\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - 1\ ] + \gamma \qquad \text{...(C.23)}$$

From C.22, $\gamma = I(1-\eta) + \alpha$. Substitute in C.23

$$\eta I = \alpha \left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - 1\ ] + 1 \right\} \qquad \text{...(C.24)}$$

From C.24

$$\alpha = \frac{\eta I}{\left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - 1\ ] + 1 \right\}} \qquad \text{...(C.25)}$$

$$\textit{Define constant } K_\alpha = \left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - 1\ ] + 1 \right\} \qquad \text{...(C.25a)}$$

$$\alpha = \frac{\eta\ R}{\bar{t}\ K_\alpha}$$

From C.22, $\gamma = I(1-\eta) + \alpha$

$$\begin{aligned} \therefore\ \gamma &= \frac{R}{\bar{t}}(1-\eta) + \frac{\eta R}{\bar{t}\ K_\alpha} \\ &= \frac{R}{\bar{t}}(1 - \eta + \frac{\eta}{K_\alpha}) \end{aligned} \qquad \text{...(C.26)}$$

From C.20,

$$\begin{aligned} \beta &= -2\alpha \\ &= -\frac{2\eta R}{\bar{t}\ K_\alpha} \end{aligned} \qquad \text{...(C.27)}$$

Thus, all constants α, β, and γ are now known in order to equate

$$\therefore\ f_t = \alpha t^2 + \beta t + \gamma \qquad \text{...(C.28)}$$

	Constants with $\bar{t} \neq 0,1/2,1$
K_α	$\left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - 1\ ] + 1 \right\}$ $= \frac{1}{6}(2\bar{t}^2 - 3\bar{t} + 1)$
α	$\frac{\eta\ R}{\bar{t}\ K_\alpha}$
β	$-\frac{2\eta R}{\bar{t}\ K_\alpha}$
γ	$\frac{R}{\bar{t}}(1 - \eta + \frac{\eta}{K_\alpha})$

Table C.3 : Summary of constants for semi-parabolic η-profile with zero slope at beginning.

Example 3:

$R = 180$, $\bar{t} = 9$, $\eta = .5$, $I = R / \bar{t} = 180/9 = 20$. Substitute in equation C.28.
$f_1 = 10.0$, $f_2 = 10.4$, $f_3 = 11.8$, $f_4 = 14.0$, $f_5 = 17.1$,
$f_6 = 21.0$, $f_7 = 25.9$, $f_8 = 31.6$, $f_9 = 38.2$, $\sum f_t \approx 180$.

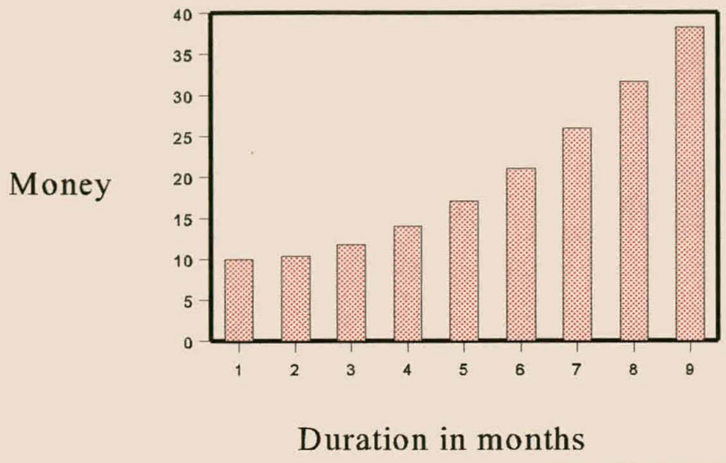


Figure C.8 : Semi-parabolic η-profile with zero slope at beginning, example 3.

6. **Parabolic η-profile**

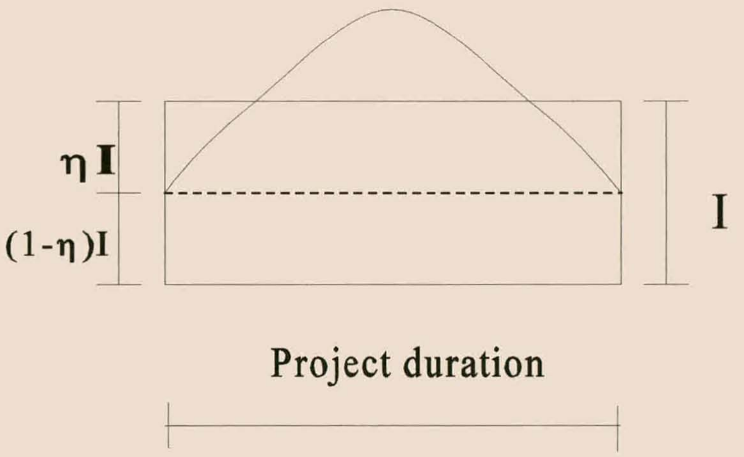


Figure C.9 : Parabolic η-profile.

As before, η = intensity factor and I = initial pseudo uniform intensity. Let $f_t = \alpha t^2 + \beta t + \gamma$ where f_t defines a parabolic convex function, t = discrete time units, and α, β and γ as constants obtained from boundary conditions.

Boundary conditions: at $t = 1$ is $f_t = I(1\text{-}\eta)$

$$\therefore \ \frac{K}{t}(1-\eta) = I(1-\eta) = \alpha + \beta + \gamma \qquad ...(C.29)$$

$$f_t' = 2\alpha t + \beta$$

$$at\ t = \frac{(\bar{t}+1)}{2}$$

$$f_t' = 0$$

$$\therefore \ 0 = (\bar{t}+1)\alpha + \beta \qquad ...(C.30)$$

As before, a 3rd equation is needed.

$$\therefore \frac{R}{\bar{t}} = I = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha + \frac{1}{2}(\bar{t}+1)\beta + \gamma \qquad ...(C.31)$$

From C.30, $\beta = -\alpha(\bar{t} + 1)$, then substitute in C.29 and C.31

$$\frac{R}{\bar{t}}(1-\eta) = I(1-\eta) = \alpha - \alpha(\bar{t}+1) + \gamma$$

$$= -\alpha\bar{t} + \gamma \qquad ...(C.29a)$$

$$\therefore \frac{R}{\bar{t}} = I = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha - \frac{1}{2}(\bar{t}+1)(\bar{t}+1)\alpha + \gamma$$

$$\therefore \ = \frac{(\bar{t}+1)(2\bar{t}+1)}{6}\alpha - \frac{1}{2}(\bar{t}+1)^2\alpha + \gamma$$

$$\therefore \ = \alpha(\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \frac{1}{2}(\bar{t}+1)] + \gamma \qquad ...(C.31a)$$

to summarise:

$$\frac{R}{\bar{t}}(1-\eta) = I(1-\eta) = -\alpha\bar{t} + \gamma \qquad \text{...(C.32)}$$

$$\therefore \frac{R}{\bar{t}} = I = \alpha(\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \frac{1}{2}(\bar{t}+1)] + \gamma \qquad \text{...(C.33)}$$

From C.32, $\gamma = I(1-\eta) + \alpha\bar{t}$. Substitute in C.33.

$$\eta I = \alpha \left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \frac{1}{2}(\bar{t}+1)] + \bar{t} \right\} \qquad \text{...(C.34)}$$

From C.34

$$\alpha = \frac{\eta I}{\left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \frac{1}{2}(\bar{t}+1)] + \bar{t} \right\}} \qquad \text{...(C.35)}$$

Define constant $K_\alpha = \left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \frac{1}{2}(\bar{t}+1)] + \bar{t} \right\}$

$$\alpha = \frac{\eta\ K}{\bar{t}\, K_\alpha} \qquad \text{...(C.35a)}$$

From C.32, $\gamma = I(1-\eta) + \alpha\bar{t}$

$$\therefore\ \gamma = \frac{R}{\bar{t}}(1-\eta) + \frac{\eta R \bar{t}}{\bar{t}\, K_\alpha}$$

$$= \frac{R}{\bar{t}}[1 - \eta + \frac{\eta\bar{t}}{K_\alpha}] \qquad \text{...(C.36)}$$

From C.30,

$\beta = -\alpha(\bar{t}+1)$

$$= -\frac{\eta R(\bar{t}+1)}{\bar{t}\,K_\alpha} \qquad \text{...(C.37)}$$

Thus, all constants α, β, and γ are now known in order to equate

$$\therefore\ f_t = \alpha t^2 + \beta t + \gamma \qquad \text{...(C.38)}$$

	Constants with $\bar{t} \neq 0,1,2$
K_α	$\left\{ (\bar{t}+1)[\frac{(2\bar{t}+1)}{6} - \frac{1}{2}(\bar{t}+1)] + \bar{t} \right\}$ $= -\frac{1}{6}(\bar{t}^2 - 3\bar{t} + 2)$
α	$\frac{\eta R}{\bar{t}\,K_\alpha}$
β	$-\frac{\eta R(\bar{t}+1)}{\bar{t}\,K_\alpha}$
γ	$\frac{R}{\bar{t}}[1 - \eta + \frac{\eta \bar{t}}{K_\alpha}]$

Table C.4 : Summary of constants for parabolic η-profile.

Example 4:

R = 180, $\bar{t} = 9$, $\eta = .5$, $I = R / \bar{t} = 180/9 = 20$. Substitute in equation C.38.
$f_1 = 10.0$, $f_2 = 17.5$, $f_3 = 22.9$, $f_4 = 26.1$, $f_5 = 27.1$,
$f_6 = 26.1$, $f_7 = 22.9$, $f_8 = 17.5$, $f_9 = 10.0$, $\sum f_t \approx 180$.

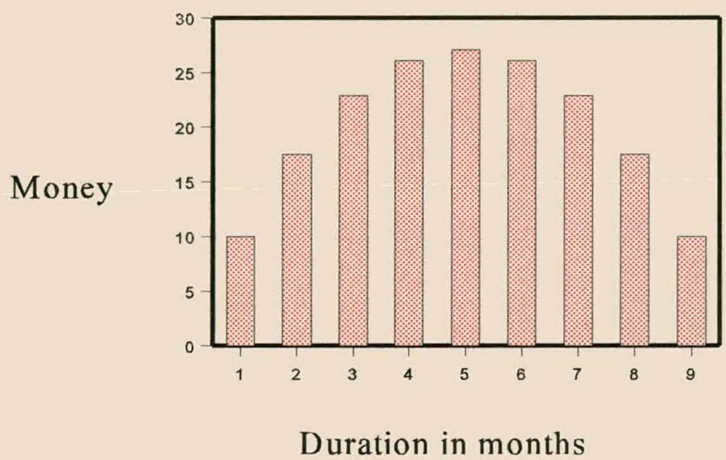


Figure C.10 : Parabolic η-profile, example 4.

Appendix D:

Project detail

Project 1

Estimated value	:	R16,622 m
Project status	:	Future
Due date	:	2000

Subproject 1.1

Local Supply

Contract currency : ZAR

Phase 1.1.9

Description	:	Production
Phase value	:	R16 622 000
Minimum time	:	36 months
Maximum time	:	40 months
Engineering functions:		
Radar	:	100%
Possible organisation	:	
Plessey	:	100%

Project 2

Estimated value	:	R75 m
Project status	:	Future
Due date	:	2000

Subproject 2.1

Local Supply

Contract currency : ZAR

Phase 2.1.9

Description	:	Production
Phase value	:	R75 000 000
Minimum time	:	30 months
Maximum time	:	36 months
Engineering functions:		
Command & control	:	85 %
Log A&M	:	5%
Radar	:	10%
Possible organisation	:	
ADS	:	60%
Avitronics	:	35%
Other	:	5%

Project 3

Estimated value	:	R332 m
Project status	:	Future
Due date	:	2003

Subproject 3.1

Local Supply

Contract currency	:	ZAR

Phase 3.1.9

Description	:	Production
Phase value	:	R332 000 000
Minimum time	:	65 months
Maximum time	:	73 months
Engineering functions:		
Support vehicles	:	100 %
Possible organisation	:	
FAF Engineering	:	60%
Steelcor Engineering	:	20%
Reumech OMC	:	20%

Project 4

Estimated value	:	R 168 m
Project status	:	Future
Due date	:	2004

Subproject 4.1

Foreign Supply

Country	:	UK
Contract currency	:	GBP

Phase 4.1.9

Description	:	Production
Phase value	:	GBP20 709 834
Minimum time	:	69 months
Maximum time	:	75 months
Engineering functions:		
Aircraft	:	70 %
Quality	:	10%
Radar	:	10%
Other	:	10%
Countertrade:		
Direct	:	25%
Indirect	:	25%
Total	:	50%

Project 5

Estimated value	:	R662 m
Project status	:	Future
Due date	:	2015

Subproject 5.1

Local Supply

Contract currency	:	ZAR

Phase 5.1.6

Description	:	Engineering development model (EDM)
Phase value	:	R810 743
Minimum time	:	4 months
Maximum time	:	7 months
Engineering functions:		
Air weapons	:	100 %
Possible organisation	:	

	Epsilon	:	35%
	RDI	:	65%
<u>Phase 5.1.7</u>			
	Description	:	EDM test and evaluation
	Phase value	:	R4 766 191
	Minimum time	:	10 months
	Maximum time	:	12 months
	Engineering functions:		
	Air weapons	:	100 %
	Possible organisation	:	
	Epsilon	:	35%
	RDI	:	65%
<u>Phase 5.1.8</u>			
	Description	:	System test and evaluation
	Phase value	:	R4 700 000
	Minimum time	:	12 months
	Maximum time	:	24 months
	Engineering functions:		
	Air weapons	:	100 %
	Possible organisation	:	
	Naschem	:	15%
	Somchem	:	20%
	RDI	:	25%
	Epsilon	:	40%
<u>Phase 5.1.9</u>			
	Description	:	Production
	Phase value	:	R132 885 000
	Minimum time	:	90 months
	Maximum time	:	102 months
	Engineering functions:		
	Air weapons	:	100 %
	Possible organisation	:	
	Naschem	:	25%
	Somchem	:	40%
	RDI	:	25%
	Other	:	10%

<u>Subproject 5.2</u>

Local Supply

Contract currency : ZAR

<u>Phase 5.2.6</u>			
	Description	:	Engineering development model (EDM)
	Phase value	:	R3 088 494
	Minimum time	:	11 months
	Maximum time	:	14 months
	Engineering functions:		
	Air weapons	:	100 %
	Possible organisation	:	
	Epsilon	:	20%
	RDI	:	80%
<u>Phase 5.2.7</u>			
	Description	:	EDM test and evaluation
	Phase value	:	R8 500 000
	Minimum time	:	24 months

Maximum time	:	30 months
Engineering functions:		
Air weapons	:	100 %
Possible organisation	:	
Epsilon	:	25%
RDI	:	75%

<u>Phase 5.2.8</u>

Description	:	System test and evaluation
Phase value	:	R10 000 000
Minimum time	:	30 months
Maximum time	:	36 months
Engineering functions:		
Air weapons	:	100 %
Possible organisation	:	
Naschem	:	20%
Somchem	:	15%
RDI	:	35%
Epsilon	:	30%

<u>Phase 5.2.9</u>

Description	:	Production
Phase value	:	R184 037 500
Minimum time	:	32 months
Maximum time	:	38 months
Engineering functions:		
Air weapons	:	100 %
Possible organisation	:	
Naschem	:	15%
Somchem	:	25%
RDI	:	55%
Other	:	5%

<u>Subproject 5.3</u>

Local Supply

Contract currency : ZAR

<u>Phase 5.3.8</u>

Description	:	System test and evaluation
Phase value	:	R4 912 265
Minimum time	:	12 months
Maximum time	:	24 months
Engineering functions:		
Air weapons	:	100 %
Possible organisation	:	
Naschem	:	10%
RDI	:	60%
Epsilon	:	30%

<u>Phase 5.3.9</u>

Description	:	Production
Phase value	:	R126 750 000
Minimum time	:	72 months
Maximum time	:	84 months
Engineering functions:		
Air weapons	:	100 %
Possible organisation	:	
Naschem	:	20%

RDI : 75%
Other : 5%

Subproject 5.4

Local Supply
Contract currency : ZAR

Phase 5.4.8

Description : System test and evaluation
Phase value : R6 500 000
Minimum time : 12 months
Maximum time : 18 months
Engineering functions:
Air weapons : 100 %
Possible organisation :
Other : 5%
RDI : 70%
Epsilon : 25%

Phase 5.4.9

Description : Production
Phase value : R83 780 000
Minimum time : 84 months
Maximum time : 96 months
Engineering functions:
Air weapons : 100 %
Possible organisation :
Naschem : 25%
RDI : 70%
Other : 5%

Subproject 5.5

Local Supply
Contract currency : ZAR

Phase 5.5.8

Description : System test and evaluation
Phase value : R4 500 000
Minimum time : 24 months
Maximum time : 48 months
Engineering functions:
Air weapons : 100 %
Possible organisation :
Naschem : 10%
RDI : 60%
Epsilon : 30%

Phase 5.5.9

Description : Production
Phase value : R86 740 000
Minimum time : 114 months
Maximum time : 120 months
Engineering functions:
Air weapons : 100 %
Possible organisation :
Naschem : 40%
RDI : 50%
Other : 10%

Project 6

Estimated value : R45 m
Project status : Future
Due date : 2008

Subproject 6.1

Local Supply
Contract currency : ZAR

Phase 6.1.8

Description : System test and evaluation
Phase value : R4 730 000
Minimum time : 10 months
Maximum time : 14 months
Engineering functions:
Infantry weapons : 100 %
Possible organisation :
Vektor : 100%

Phase 6.1.9

Description : Production
Phase value : R40 270 000
Minimum time : 90 months
Maximum time : 100 months
Engineering functions:
Infantry weapons : 100%
Possible organisation :
Vektor : 30%
Swartklip : 70%

Project 7

Estimated value : R210 m
Project status : Future
Due date : 2011

Subproject 7.1

Foreign Supply
Foreign country : EU
Contract currency : USD

Phase 7.1.1

Description : Concept/definition
Phase value : $ nil
Minimum time : 10 months
Maximum time : 14 months
Engineering functions:
Not applicable
Possible organisation :
Not applicable

Phase 7.1.2

Description : Experimental development model
Phase value : $ nil
Minimum time : 2 months
Maximum time : 4 months
Engineering functions:
Not applicable

Possible organisation	:	
Not applicable		

Phase 7.1.6

Description	:	Engineering development model
Phase value	:	\$10 372 000
Minimum time	:	9 months
Maximum time	:	12 months
Engineering functions:		
Not applicable		
Possible organisation	:	
Not applicable		
Countertrade	:	30% direct

Phase 7.1.8

Description	:	System test and evaluation
Phase value	:	\$3 000 000
Minimum time	:	15 months
Maximum time	:	24 months
Engineering functions:		
Not applicable		
Possible organisation	:	
Not applicable		
Countertrade	:	30% direct

Phase 7.1.9

Description	:	Production
Phase value	:	\$30 000 000
Minimum time	:	28 months
Maximum time	:	32 months
Engineering functions:		
Not applicable		
Possible organisation	:	
Not applicable		
Countertrade	:	30% direct

Subproject 7.2

Local Supply

Contract currency : ZAR

Phase 7.2.1

Description	:	Concept/definition
Phase value	:	R9 400 000
Minimum time	:	10 months
Maximum time	:	14 months
Engineering functions:		
GMS	:	90%
Aircraft	:	5%
Other	:	5%
Possible organisation	:	
Kentron	:	80%
Somchem	:	5%
Denel Aviation	:	5%
OTR	:	5%
Other	:	5%

Phase 7.2.2

Description	:	Experimental development model
Phase value	:	R1 880 000

Minimum time	:	2 months
Maximum time	:	4 months
Engineering functions:		
GMS	:	80%
Aircraft	:	10%
Other	:	10%
Possible organisation	:	
Kentron	:	75%
Somchem	:	10%
Denel Aviation	:	5%
OTR	:	5%
Other	:	5%

Phase 7.2.6

Description	:	Engineering development model
Phase value	:	R13 000 000
Minimum time	:	9 months
Maximum time	:	12 months
Engineering functions:		
GMS	:	80%
Aircraft	:	10%
Other	:	10%
Possible organisation	:	
Kentron	:	80%
Somchem	:	10%
Denel Aviation	:	5%
OTR	:	5%

Phase 7.2.8

Description	:	System test and evaluation
Phase value	:	R49 500 000
Minimum time	:	15 months
Maximum time	:	24 months
Engineering functions:		
GMS	:	80%
Aircraft	:	10%
Other	:	10%
Possible organisation	:	
Kentron	:	65%
Somchem	:	5%
Denel Aviation	:	5%
OTR	:	20%
Other	:	5%

Phase 7.2.9

Description	:	Production
Phase value	:	R nil
Minimum time	:	28 months
Maximum time	:	32 months
Engineering functions:		
Not applicable		
Possible organisation	:	
Not applicable		

Project 8

Estimated value	:	R139,5 m
Project status	:	Future
Due date	:	2004

<u>Subproject 8.1</u>

Local Supply

Contract currency : ZAR

<u>Phase 8.1.9</u>

Description	:	Production
Phase value	:	R139 454 000
Minimum time	:	55 months
Maximum time	:	65 months
Engineering functions:		
Telecommunications	:	100%
Possible organisation	:	
RDI	:	40%
Grintek	:	60%

Project 9

Estimated value	:	R20,7 m
Project status	:	Future
Due date	:	2001

<u>Subproject 9.1</u>

Local Supply

Contract currency : ZAR

<u>Phase 9.1.9</u>

Description	:	Production
Phase value	:	R9 820 883
Minimum time	:	30 months
Maximum time	:	36 months
Engineering functions:		
Telecommunications	:	10%
Artillery	:	70%
Quality	:	10%
Possible organisation	:	
LIW	:	80%
ADS	:	20%

<u>Subproject 9.2</u>

Local Supply

Contract currency : ZAR

<u>Phase 9.2.9</u>

Description	:	Production
Phase value	:	R526 995
Minimum time	:	10 months
Maximum time	:	14 months
Engineering functions:		
Artillery	:	80%
Quality	:	20%
Possible organisation	:	
LIW	:	100%

Subproject 9.3

Local Supply		
Contract currency	:	ZAR

Phase 9.3.9

Description	:	Production
Phase value	:	R1 632 838
Minimum time	:	21 months
Maximum time	:	27 months
Engineering functions:		
Artillery	:	80%
Quality	:	20%
Possible organisation	:	
LIW	:	90%
Other	:	10%

Subproject 9.4

Local Supply		
Contract currency	:	ZAR

Phase 9.4.9

Description	:	Production
Phase value	:	R8 764 912
Minimum time	:	33 months
Maximum time	:	39 months
Engineering functions:		
Telecommunications	:	10%
Artillery	:	70%
Quality	:	20%
Possible organisation	:	
Other	:	100%

Project 10

Estimated value	:	R1 609 m
Project status	:	Future
Due date	:	2016

Subproject 10.1

Foreign Supply		
Foreign country	:	EU
Contract currency	:	USD

Phase 10.1.1

Description	:	Concept/definition
Phase value	:	$2 000 000
Minimum time	:	12 months
Maximum time	:	18 months
Engineering functions:		
Command & control	:	80%
Other	:	20%
Possible organisation	:	
Other	:	80%
Reutech OMC	:	20%

Phase 10.1.8

Description	:	System test and evaluation
Phase value	:	$20 000 000
Minimum time	:	18 months

Maximum time	:	24 months
Engineering functions:		
Command & control	:	80%
Other	:	20%
Possible organisation	:	
OTR	:	15%
Kentron	:	10%
Reutech OMC	:	10%
Other	:	55%

Phase 10.1.9

Description	:	Production
Phase value	:	$370 000 000
Minimum time	:	108 months
Maximum time	:	132 months
Engineering functions:		
Command & control	:	80%
Other	:	15%
Possible organisation	:	
LIW	:	15%
Kentron	:	15%
Reutech OMC	:	10%
Other	:	60%
Countertrade	:	30% direct 20% indirect 30% commercial
Total	:	80%

Project 11

Estimated value	:	R3 000 m
Project status	:	Future
Due date	:	2011

Subproject 11.1

Local Supply

Contract currency : ZAR

Phase 11.1.1

Description	:	Concept phase
Phase value	:	R4 490 000
Minimum time	:	12 months
Maximum time	:	18 months
Engineering functions:		
Mech Infantry	:	90 %
Other	:	10%
Possible organisation	:	
Propenta	:	60%
Reumech OMC	:	25%
LIW	:	15%

Phase 11.1.5

Description	:	ADM test and evaluation
Phase value	:	R100 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		

Mech Infantry	:	90 %
Other	:	10%
Possible organisation	:	
Propenta	:	10%
Reumech OMC	:	50%
LIW	:	30%
Other	:	10%

<u>Phase 11.1.6</u>

Description	:	Engineering development model (EDM)
Phase value	:	R12 000 000
Minimum time	:	24 months
Maximum time	:	36 months
Engineering functions:		
Mech Infantry	:	90 %
Other	:	10%
Possible organisation	:	
Propenta	:	10%
Reumech OMC	:	50%
LIW	:	30%
Other	:	10%

<u>Phase 11.1.7</u>

Description	:	EDM test and evaluation
Phase value	:	R100 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	90 %
Other	:	10%
Possible organisation	:	
Propenta	:	10%
Reumech OMC	:	50%
LIW	:	30%
Other	:	10%

<u>Phase 11.1.8</u>

Description	:	Total system and evaluation
Phase value	:	R100 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	90 %
Other	:	10%
Possible organisation	:	
Propenta	:	10%
Reumech OMC	:	50%
LIW	:	30%
Other	:	10%

<u>Phase 11.1.9</u>

Description	:	Production
Phase value	:	R28 000 000
Minimum time	:	60 months
Maximum time	:	84 months
Engineering functions:		
Mech Infantry	:	90 %

Other	:	10%
Possible organisation	:	
Propenta	:	10%
Reumech OMC	:	50%
LIW	:	30%
Other	:	10%

<u>Subproject 11.2</u>

Local Supply

Contract currency : ZAR

<u>Phase 11.2.1</u>

Description	:	Concept phase
Phase value	:	R nil
Minimum time	:	12 months
Maximum time	:	18 months
Engineering functions:		
Not applicable		
Possible organisation	:	
Not applicable		

<u>Phase 11.2.4</u>

Description	:	Advanced development model (ADM)
Phase value	:	R24 010 000
Minimum time	:	24 months
Maximum time	:	36 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

<u>Phase 11.2.5</u>

Description	:	ADM test and evaluation
Phase value	:	R1 800 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

<u>Phase 11.2.6</u>

Description	:	Engineering development model (EDM)
Phase value	:	R14 402 000
Minimum time	:	24 months
Maximum time	:	36 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%

Other	:	20%

Phase 11.2.7

Description	:	EDM test and evaluation
Phase value	:	R3 800 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

Phase 11.2.8

Description	:	Total system and evaluation
Phase value	:	R9 800 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

Phase 11.2.9

Description	:	Production
Phase value	:	R2 259 560 000
Minimum time	:	60 months
Maximum time	:	84 months
Engineering functions:		
Mech Infantry	:	90 %
Other	:	10%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

Subproject 11.3

Local Supply

Contract currency : ZAR

Phase 11.3.1

Description	:	Concept phase
Phase value	:	R nil
Minimum time	:	12 months
Maximum time	:	18 months
Engineering functions:		
Not applicable		
Possible organisation	:	
Not applicable		

Phase 11.3.4

Description	:	Advanced development model (ADM)
Phase value	:	R5 000 000
Minimum time	:	24 months

Maximum time	:	36 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

<u>Phase 11.3.5</u>

Description	:	ADM test and evaluation
Phase value	:	R100 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

<u>Phase 11.3.6</u>

Description	:	Engineering development model (EDM)
Phase value	:	R20 000 000
Minimum time	:	24 months
Maximum time	:	36 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

<u>Phase 11.3.7</u>

Description	:	EDM test and evaluation
Phase value	:	R100 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

<u>Phase 11.3.8</u>

Description	:	Total system and evaluation
Phase value	:	R100 000
Minimum time	:	4 months
Maximum time	:	8 months
Engineering functions:		
Mech Infantry	:	80 %
Other	:	20%
Possible organisation	:	

Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

Phase 11.3.9

Description	:	Production
Phase value	:	R800 000 000
Minimum time	:	60 months
Maximum time	:	84 months
Engineering functions:		
Mech Infantry	:	90 %
Other	:	10%
Possible organisation	:	
Reumech OMC	:	50%
LIW	:	30%
Other	:	20%

Appendix E:

Macro information

Inflation rates (%):

Year	South Africa	UK	EU
1999	9.033	2.951	2.303
2000	7.875	2.914	2.277
2001	9.000	2.626	2.343
2002	9.040	2.378	2.300
2003	8.940	2.241	2.300
2004	8.590	2.156	2.300
2005	8.250	2.081	2.300
2006	7.920	2.059	2.300
2007	8.830	2.124	2.300
2008	8.030	2.124	2.300
2009	7.800	2.134	2.300
2010	7.460	2.166	2.300
2011	7.310	2.185	2.300
2012	7.010	2.225	2.300
2013	6.780	2.299	2.300
2014	6.520	2.373	2.300
2015	6.121	2.450	2.300
2016	6.500	2.450	2.300
2017	6.500	2.450	2.300
2018	6.500	2.450	2.300
2019	6.500	2.450	2.300
2020	6.500	2.450	2.300
2021	6.500	2.450	2.300
2022	6.500	2.450	2.300
2023	6.500	2.450	2.300
2024	6.500	2.450	2.300
2025	6.500	2.450	2.300
2026	6.500	2.450	2.300
2027	6.500	2.450	2.300
2028	6.500	2.450	2.300
2029	6.500	2.450	2.300
2030	6.500	2.450	2.300

Notes :

Option 1 = Apply inflation rates.
Option 2 = 0% inflation rates.

Exchange rates:

Year	ZAR/USD	ZAR/GBP	ZAR/ZAR
1999	5.542	8.134	1
2000	5.813	8.441	1
2001	6.115	8.891	1
2002	6.453	9.399	1
2003	6.830	9.971	1
2004	7.251	10.615	1
2005	7.681	11.284	1
2006	8.109	11.963	1
2007	8.525	12.639	1
2008	8.930	13.306	1
2009	9.324	13.964	1
2010	9.707	14.613	1
2011	10.080	15.252	1
2012	10.468	15.878	1
2013	10.876	16.496	1
2014	11.278	17.105	1
2015	11.673	17.705	1
2016	12.000	18.300	1
2017	12.500	18.900	1
2018	13.000	19.600	1
2019	13.500	20.400	1
2020	14.000	21.300	1
2021	14.500	22.000	1
2022	15.000	23.000	1
2023	15.500	24.000	1
2024	16.000	25.000	1
2025	16.500	26.000	1
2026	17.000	27.000	1
2027	17.500	28.000	1
2028	18.000	29.000	1
2029	18.500	30.000	1
2030	19.000	31.000	1

Notes:

Option 1 = Consider changes in exchange rates.

Option 2 = Exchange rates are seen as constant over period, i.e. 0% change.

Annual budgets: (in R million)

	OPTION						
Year	1	2	3	4	5	6	7
Run	1A 1C	1B 1D	2A 2C	2B 2D	3A 3A1 3F 4A 4F	3B 3B1	4B
1999	656	450	700	800	251	193	193
2000	656	450	700	800	316	233	233
2001	656	450	700	800	378	244	244
2002	618	450	700	800	402	288	288
2003	618	450	700	800	451	302	302
2004	588	450	700	800	457	300	300
2005	450	450	700	800	394	355	355
2006	450	450	700	800	455	430	430
2007	450	450	700	800	514	509	509
2008	445	450	700	800	576	588	588
2009	445	450	700	800	642	658	658
2010	445	450	700	800	577	731	731
2011	445	450	700	800	516	800	800
2012	275	450	700	800	592	839	839
2013	450	450	700	800	615	521	521
2014	450	450	700	800	900	900	950
2015	450	450	700	800	900	900	950
2016	450	450	700	800	900	900	950
2017	450	450	700	800	900	900	950
2018	450	450	700	800	900	900	950
2019	450	450	700	800	900	900	950
2020	450	450	700	800	900	900	950
2021	450	450	700	800	900	900	950
2022	450	450	700	800	900	900	950
2023	450	450	700	800	900	900	950
2024	450	450	700	800	900	900	950
2025	450	450	700	800	900	900	950
2026	450	450	700	800	900	900	950
2027	450	450	700	800	900	900	950
2028	450	450	700	800	900	900	950
2029	450	450	700	800	900	900	950
2030	450	450	700	800	900	900	950

Notes:

Option 1 = Apply a budget growth rate of 2% per year.
Option 2 = Apply a 0% budget growth rate per year.
Eta Gompertz is constant at .15 in a year.
Te Gompertz is constant at 8 months in a year.

Project priorities

Project Number	Option 1 Priorities	Option 2 Priorities
1	1	3
2	2	1
3	3	5
4	4	6
5	5	11
6	6	8
7	7	7
8	8	4
9	9	2
10	10	9
11	11	10

Completion date constraints

Notes:

Option 1 = All completion date constraints are "off".
Option 2 = Only completion date constraint for project 11 is "on".

Initial pseudo project duration

Notes:

Option 1 = The initial pseudo project duration is taken as the minimum duration of the project.
Option 2 = The initial pseudo project duration is taken as the average of the minimum and the maximum duration of the project.

Method for actual scheduling

Notes:

Option 1 = The scheduling is based on a weighted value of sector time.
Option 2 = The scheduling is based on a required sector time.

Appendix F:

Default data

System default	**Average Amount of Phase**	**Average Months of Phase**	**Average Number of PM**	**Average Number of QA**
Concept/definition	200 000	1	1	.3
XDM	950 000	1	1	.3
XDM T&E	425 000	1	1	.4
ADM	900 000	1	1	.3
ADM T&E	300 000	1	1	.4
EDM	1 000 000	1	1	.5
EDM T&E	375 000	1	1	.5
System T&E Qualification	400 000	1	1	.6
Production	8 800 000	1	1	.9
Other	**Average Amount of Phase**	**Average Months of Phase**	**Average Number of PM**	**Average Number of QA**
Concept/definition	200 000	1	1	.3
XDM	950 000	1	1	.3
XDM T&E	425 000	1	1	.4
ADM	900 000	1	1	.3
ADM T&E	300 000	1	1	.4
EDM	1 000 000	1	1	.5
EDM T&E	375 000	1	1	.5
System T&E Qualification	400 000	1	1	.6
Production	8 800 000	1	1	.9

Aircraft	**Average Amount of Phase**	**Average Months of Phase**	**Average Number of PM**	**Average Number of QA**
Concept/definition	500 000	6	1.5	.2
XDM	200 000 000	23	2	.5
XDM T&E	16 000 000	5	2	.5
ADM	200 000 000	18	3	1
ADM T&E	20 000 000	9	3	1
EDM	200 000 000	18	4	1.5
EDM T&E	20 000 000	6	4	2
System T&E Qualification	40 000 000	24	3	2
Production	2 100 000 000	39	2	2

GMS	**Average Amount of Phase**	**Average Months of Phase**	**Average Number of PM**	**Average Number of QA**
Concept/definition	15 000 000	24	1.5	.3
XDM	46 000 000	21	2.5	.75
XDM T&E	8 000 000	5	2.5	1
ADM	85 000 000	24	3	1
ADM T&E	15 000 000	6	3	1
EDM	95 000 000	27	3.5	1.5
EDM T&E	20 000 000	6	3.5	1.5
System T&E Qualification	30 000 000	12	3	1.5
Production	400 000 000	60	1.6	1

Mech Infantry	Average Amount of Phase	Average Months of Phase	Average Number of PM	Average Number of QA
Concept/definition	4 490 000	15	1	.5
XDM	10 000 000	24	1	1
XDM T&E	3 000 000	4	1	1
ADM	44 000 000	30	3	1
ADM T&E	2 000 000	6	2	1
EDM	176 000 000	30	4	2
EDM T&E	4 000 000	6	2	1
System T&E Qualification	10 000 000	6	4	2
Production	8 770 000 000	228	6	3

Radar	Average Amount of Phase	Average Months of Phase	Average Number of PM	Average Number of QA
Concept/definition	5 000 000	24	1.5	.5
XDM	60 000 000	36	2	.75
XDM T&E	6 000 000	6	2.5	1
ADM	40 000 000	24	2.5	1
ADM T&E	6 000 000	6	2.5	1
EDM	60 000 000	20	4	1
EDM T&E	8 000 000	6	2.5	1
System T&E Qualification	10 000 000	6	2.5	.75
Production	600 000 000	60	1.5	.75

Support Vehicles	**Average Amount of Phase**	**Average Months of Phase**	**Average Number of PM**	**Average Number of QA**
Concept/definition	1 400 000	12	1	.5
XDM	5 000 000	12	1	1.4
XDM T&E	100 000	6	.5	.7
ADM	3 200 000	8	.8	.4
ADM T&E	100 000	3	.5	.7
EDM	3 200 000	8	.8	.4
EDM T&E	80 000	3	.5	.7
System T&E Qualification	500 000	6	.8	.4
Production	24 000 000	12	.5	1

Telecommunications	**Average Amount of Phase**	**Average Months of Phase**	**Average Number of PM**	**Average Number of QA**
Concept/definition	500 000	8	1	0
XDM	400 000	10	.8	.1
XDM T&E	100 000	2	.3	.1
ADM	1 000 000	16	.5	.2
ADM T&E	400 000	6	.2	.2
EDM	2 000 000	15	.5	.2
EDM T&E	400 000	4	.2	.2
System T&E Qualification	100 000	3	.3	.3
Production	15 000 000	24	.1	.3

Appendix G:

Description of results of computer model run of combinations

Introduction

All computer model combinations are discussed in two parts, namely Part 1: Pseudo analysis and Part 2: Actual analysis. The results of the impact analyses are not described in this appendix as it is dealt with in the latter part of Chapter 6. The graphs of these results, including those for the impact analyses, are shown in Appendix H.

Although runs 3A and 4A are discussed in Chapter 6, these descriptions are repeated here for the sake of completeness.

Part 1 : Pseudo analysis

The pseudo analysis is done to quickly obtain an overall schedule at project level before a final and actual schedule is determined at phase level. Each pseudo run is discussed separately.

<u>Run 1A</u>: Appendix H pages 2 and 3

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	1	Specific amount and R450 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Budget and pseudo cash flow

Although the priorities were selected so that the projects with the shortest durations can be completed before those with longer durations, it is clear from the graph that there will be a surplus of final funds during the initial years and a shortage of funds during the last number of years. This means that, although more money is available during the first part of the planning horizon, it cannot be utilised. Consequently the budget allocation cannot be considered without looking at the corresponding cash flow projection.

Cumulative cash flow: Total R7 130 million

Although there are huge differences between the annual nominal budget and the final annual nominal cash flow, the cumulative amounts of the budget and final cash flow are approximately the same, proving that in this case with zero inflation and escalation, the initial and final scheduling techniques which are used are mathematically acceptable.

Project scheduling: Ending month 179

The schedule shows that if the project priorities are carefully chosen, the initial and final schedule for each project will be approximately the same.

Run 1C: Appendix H pages 4 and 5

Data

	Option	
Priorities	2	Mixed
Initial project time	2	Average
Constraints	1	Off
Budget	1	Specific amount and R450 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Budget and pseudo cash flow

This run is exactly the same as run 1A except that the initial pseudo project scheduling time is based on the average between the minimum and maximum time, and not on the minimum time alone. The comments on run 1A also apply to run 1C.

Cumulative cash flow: Total R7 130 million

The comments on run 1A also apply to run 1C.

Project scheduling: Ending month 192

The comments on run 1A also apply to run 1C except that the planning horizon has increased from 179 to 192 months.

Run 3A: Appendix H pages 6 and 7

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Budget and pseudo cash flow

Although runs 1A and 1C show that huge annual surpluses and shortages can occur if the budget is allocated without taking the project's cash flow predictions into account, this run 3A shows that if the budget allocation is more or less the same as the nominal cash flow predictions, the huge differences between budget and cash flow are reduced. This means that after only one pseudo analysis the results of that analysis can be used to determine the budget that should be allocated.

Cumulative cash flow: Total R7 130 million

The cumulative nominal budget and cumulative nominal cash flow are virtually the same, which means that run 3A has reached a near optimal solution for a pseudo analysis.

Project scheduling: Ending month 180

The schedule shows that if the project priorities are carefully chosen, the initial and final schedule for each project will be approximately the same.

Run 3A1: Appendix H pages 8 and 9

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R 900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The only difference between this run 3A1 and run 3A is that run 3A1 takes account of the effect of changes in exchange rates while in run 3A the exchange rate is constant. The comments on run 3A apply to run 3A1.

Cumulative cash flow: Total R8 070 million

Once again it is shown that the cumulative difference between the nominal budget and the nominal cash flow is small. However, a major difference is the fact that this run 3A1 ends with a cumulative value of approximately R8 000 million, R900 million more than 3A.

Project scheduling: Ending month 192

It should be noted that although there has been a slight increase in months in the planning horizon, the schedule still ends in year 16, i.e. month 192. The main difference in the schedule of run 3A1 and that of run 3A is the right shifting of some of the projects in order to accommodate the effect of changes in exchange rates.

Run 3F: Appendix H pages 10 and 11

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum

Constraints	2	Project 11 on
Budget	5	Specific amount and R900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The aim of run 3F is to show the effect of a project completion date constraint, i.e. that the constraint for priority 10 (project 11) is "on". The final nominal pseudo cash flow shows that - for almost the full planning horizon - it is more than the allocated nominal budget, except for the last year or so when the effect of project 11 is no longer active.

Cumulative cash flow: Total R8 030 million

Since the annual nominal cash flows are higher than the cash flows of the budget, the cumulative cash flow follows the same trend.

Project scheduling: Ending month 192

The required completion date for project 11 is month 156. It can be seen from the schedule that the model constrained the completion date of project 11 to this required completion date. The other projects are rescheduled in such a way that the overall negative effect of this constraint is minimised.

Run 2A: Appendix H pages 12 and 13

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	3	Average of R700 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

Although the budget available at the beginning of the planning horizon is sufficient, it still has unwanted allocated funds that cannot be absorbed by the scheduled projects due to the low budget requirements of the priorities at the beginning of the planning horizon. The fact that some of the later projects require huge amounts of money results in a shortage of funds at the end of the planning horizon. The project's nominal cash flow requirements are nevertheless optimised around the nominal budget.

Cumulative cash flow: Total R16 600 million

The cumulative nominal cash flow at the end of the planning horizon has increased from R7 130 million to R16 600 million. This is due to the effects of inflation and changes in exchange rates.

Project scheduling: Ending month 264

A crucial effect of inflation and changes in exchange rates is the fact that the planning horizon has increased from 179 months to 264 months, which could have been worse if the allocated budget was not increased. This increase in the planning horizon is unacceptable in practice as technologies become old and obsolete. One way to reduce the planning horizon is to increase the budget substantially so that the planning horizon can be reduced to the original 179 months. In many cases this is not possible however, due to budgetary constraints.

<u>Run 2C</u>: Appendix H pages 14 and 15

Data

	Option	
Priorities	2	Mixed
Initial project time	2	Average
Constraints	1	Off
Budget	3	Average of R700 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The only difference between this run and run 2A is that the initial project duration is taken as the average between the minimum and the maximum duration, instead of the minimum duration. As can be seen from the graph, the nominal cash flow profile is similar to that of run 2A.

Cumulative cash flow: Total R16 480 million

The cumulative nominal cash flow of R16 480 million total at the end of the planning horizon is approximately the same as the total of R16 600 million of run 2A.

Project scheduling: Ending month 255

Although there is a slight decrease in the planning horizon, it can be seen as negligible if a total duration of 21 years is considered.

<u>Run 4A</u>: Appendix H pages 16 and 17

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The difference between this run and run 2A is that a specific budget has been allocated for a number of years, after which an average of R900 million is allocated per annum. This graph clearly shows the pseudo optimisation from the initial to the final phase. The initial cash flow deviates further from the budget than the final cash flow, which is 'closer' to the budget. The large deviations during the last 10 years are due to the fact that, because of the escalation of cost due to inflation and changes in exchange rates, projects 5, 10 and 11 have been shifted to the right. Projects 10 and 11 in turn contribute approximately R4 000 million only for their production phases. Of these two, project 11 is causing the peak in the cash flow.

Cumulative cash flow: Total R20 480 million

From the cumulative nominal curve the optimising effect of the model, from the initial to the final phase, can again be seen.

Project scheduling: Ending month 324

The increase in the planning horizon from month 264 to month 324 is due to the fact that the cumulative amount of the budget has been reduced during the first number of years, resulting in a right shift of the first number of projects and the eventual shifting of the last number of projects to the right. This proves that the final schedule is sensitive to budget allocation.

<u>Run 4F</u>: Appendix H pages 18 and 19

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	2	Project 11 on
Budget	3	Specific amount and R900 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The difference between this run and run 4A is the effect the completion date constraint of project 11 has on the results. The peak, which could be noticed in run 4A, has clearly shifted from the right to the centre of the planning horizon. The graph further shows a shortage of funds from years 5 to 13 and a surplus from year 14 onwards.

Cumulative cash flow: Total R15 520 million

There is a large decrease in the final cumulative nominal cash flow from R20 480 million to R15 520 million, mainly owing to savings on escalation due to inflation and changes in exchange rates. But this kind of saving requires a higher allocated budget, as shown in the previous paragraph. Nevertheless, the effort of the model to optimise the cash flow around the budget is again noticeable.

Project scheduling: Ending month 324

No change in the planning horizon occurs as expected. The optimisation with the constraints "on" only takes place after the 'free' optimisation and then captures the final planning horizon.

Note : The following results deal with runs that show the effect of sequential priorities.

Run 1B Appendix H pages 20 and 21

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum
Constraints	1	Off
Budget	2	An average of R450 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Budget and pseudo cash flow

An average budget of R450 million per year has been allocated. This results in a surplus of funds during the first half of the planning horizon and a shortage during the second half. Again it can be emphasised that the predicted cash flow requirements of the various projects must be taken into account in budget allocation.

Cumulative cash flow: Total R7 130 million

It is clear that the model cannot get to such an optimised result that the final cumulative values are close to the budget. The reason is that with the sequential priorities, project 5 requires more time and is actually shifting subsequent projects to the right.

Project scheduling: Ending month 191

For reasons mentioned in the foregoing two paragraphs, the planning horizon has also increased, from about 179 months to 191 months.

<u>Run 1D</u>: Appendix H pages 22 and 23

Data

	Option	
Priorities	1	Sequential
Initial project time	2	Average
Constraints	1	Off
Budget	1	An average of R450 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Budget and pseudo cash flow

The difference between this run and run 1B is that the initial project duration is taken as the average between the minimum and the maximum duration of the projects, instead of the minimum duration. The initial and final cash flow are similar to the cash flows of run 1B.

Cumulative cash flow: Total R1 130 million

No noticeable differences exist between this run and run 1B.

Project scheduling: Ending month 192

The increase in the planning horizon from 191 to 192 months is negligible.

<u>Run 3B</u>: Appendix H pages 24 and 25

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum

Constraints	1	Off
Budget	6	New specific amount and R 900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Budget and pseudo cash flow

This run can be compared with run 3A, except that run 3A uses mixed priorities. The final cash flow is well optimised around the budget. Compared with run 1B it shows a better annual cash flow. This is the result of better allocation of the annual budget.

Cumulative cash flow: Total R7 130 million

The final cumulative cash flow shows an improvement over the initial cumulative cash flow. Again, the reason that it cannot be optimised closer to the budget is that project 5 is governing the cash flow of the subsequent projects due to its long duration. It also shows a better cumulative result if it is compared with run 1B.

Project scheduling: Ending month 185

Compared with run 3A, the planning horizon has increased from 180 months to 185 months. This is expected due to the effect of sequential priorities. If it is compared with run 1B, the planning horizon has decreased from 191 months to 185 months, which can be ascribed to the better allocation of the annual budget.

<u>Run 3B1</u>: Appendix H pages 26 and 27

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R 900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The difference between this run and run 3B is the effect of changes in exchange rates. It can be seen that with the same allocated budget as run 3B, projects have shifted to the right, resulting in surpluses during the first half of the planning horizon and shortages of funds during the second half.

If compared with run 3A, which used sequential priorities, the surpluses and shortages as described in the previous paragraph increase around the allocated budget. This can be ascribed directly to the fact that sequential priorities have been used in this run instead of mixed priorities as in run 3A1.

Cumulative cash flow: Total R8 720 million

The comments made in the preceding two paragraphs apply to the cumulative cash flow. Compared with 3A1 it can be seen that the final cumulative cash flow of this run is worse than that of run 3A1.

Project scheduling: Ending month 209

Compared with runs 3A1 and 3B, the planning horizon has increased from 192 and 185 months respectively to 209 months, which can be expected due to the effects of sequential priorities and changes in exchange rates.

<u>Run 2B</u> : Appendix H pages 28 and 29

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum
Constraints	2	Off
Budget	4	Average of R800 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The difference between this run and run 1B is that the effects of inflation and changes in exchange rates are taken into account. Both runs take an average allocated annual budget into account, but with the annual budget of this run taken as R 800 million compared with R450 million for run 1B. The reason for the annual budget increase is that the R450 million was not enough to cope with the effects of inflation and changes in exchange rates. It was also necessary to use an average amount so as to compare it with run 1B.

The surpluses and shortages for run 2B are much higher than before, again showing that sequential priorities cannot be optimised in the same way as mixed priorities.

Cumulative cash flow: Total R21 140 million

Compared with 1B, the final cumulative value of R21 140 million for this run is so much higher than the cumulative value of R7 130 million of run 1B. This is expected, but with sequential priorities the nominal values have increased substantially.

Project scheduling: Ending month 257

What is not good to see, is the increase in the planning horizon from 191 months to 257 months when compared with run 1B. This, again, is unacceptable in practice as such an increase would definitely impact on the technologies that are required.

<u>Run 2D</u> : Appendix H pages 30 and 31

Data

	Option	
Priorities	4	Sequential
Initial project time	2	Average
Constraints	1	Off
Budget	4	Average of R800 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The difference between this run and run 2B is that an average duration of project time has been used. No noticeable differences can be seen between the cash flows of these two runs.

Cumulative cash flow: Total R19 810 million

The cumulative cash flow of R19 810 million for this run proves to be slightly less than that of run 2B, which was R21 140 million.

Project scheduling: Ending month 252

The planning horizon of 252 months for this run proves to be slightly less than that of run 2B, which was 257 months.

Run 4B: Appendix H pages 32 and 33

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum
Constraints	1	Off
Budget	7	Specific amount and R950 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Budget and pseudo cash flow

The difference between this run and run 3B is the effect of inflation and changes in exchange rates. This effect shifts the projects to the right and eventually worsens the nominal cash flow around the allocated budget towards the end of the planning horizon.

Cumulative cash flow: Total R30 400 million

The final cumulative cash flow increases substantially from R7 130 million for run 3B to R30 400 million for this run due to the effects of inflation and changes in exchange rates.

Project scheduling: Ending month 348

The planning horizon increases substantially from 185 months for run 3B to 348 months for this run due to the effects of inflation and changes in exchange rates.

Part 2 : Actual analysis

The subsequent paragraphs describe the results of the actual analyses that have been executed. Only certain runs are taken to demonstrate the results. The first section of the results of each run, i.e. the final nominal pseudo *versus* actual cash flows, shows how the actual nominal results tend to follow the required pseudo cash flows. The second section, i.e. the real original *versus* requirement value, shows the final actual required values relative to the original values. The difference between the required and the original values gives the additional costs that should be added to the original values due to inflation and changes in exchange rates. Runs 3A, 3A1 and 4A are executed with mixed priorities, while runs 3B, 3B1 and 4B are executed with sequential priorities.

Run 3A : Appendix H pages 34 and 35

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Final nominal pseudo (R7 130 million) versus actual (R7 130 million) cash flows

This graph shows the trend of the actual cash flow to follow the pseudo cash flow curve. It should also be noted that as these graphs are based on only a small number of selected projects, the actual values may differ from the pseudo values. It nevertheless demonstrates the original assumption that if the actual cash flow values are close to the pseudo cash flow values of each project, the total actual cash flow values for all projects will also be close to the total pseudo cash flow values.

The cumulative cash flow curves for both the actual and pseudo cash flows show that they are close to each other. The fact that the actual value is the same as the total pseudo value (R7 130 million) is because no escalation is taken into consideration.

Real original (R7 130 million) versus requirement (R7 130 million) value

The real requirement is determined by de-escalating the nominal requirement with a factor derived from the budget growth. The real original value is the cost of the project based on the original real values which were used as input data.

The differences between the real original and requirement values represent the additional costs in real money terms to complete the projects and should be budgeted so that the correct amount of money will be available when the project is executed.

The reason why the cumulative real original and requirement values are the same for this run, is that no escalation was taken into consideration.

<u>Run 3A1</u> : Appendix H pages 36 and 37

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	1	As for applicable countries

Final nominal pseudo (R8 075 million) versus actual (R8 110 million) cash flows

The difference between this run and run 3A is that changes in exchange rates are taken into account. The cumulative final nominal actual value has increased from R7 130 million to R8 110 million, which is due only to changes in exchange rates.

Real original versus requirement value

The real requirement value of R8 110 million is also the same as the actual value of R8 110 million. The reason is that there is a zero percent growth rate in the budget, which resulted in a de-escalation factor of 1.

<u>Run 4A</u> : Appendix H pages 38 and 39

Data

	Option	
Priorities	2	Mixed
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R900 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Final nominal pseudo (R20 477 million) versus actual (R21 189 million) cash flows

The difference between this run and run 3A is that in this run the full escalation due to inflation and changes in exchange rates is taken into consideration. The cumulative nominal actual value increases from R7 130 million to R21 189 million.

Real original (R7 130 million) versus requirement (R15 546 million) value

When the actual cash flows are de-escalated to real terms, a cumulative real requirement value of R15 546 million results, which is R8 416 million more than the original planned cash flow of R7 130 million for all the projects. This additional cost is due to inflation and changes in exchange rates.

<u>Run 3B</u> : Appendix H pages 40 and 41

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum

Constraints	1	Off
Budget	6	New specific amount and R900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	2	Constant

Final nominal pseudo (R7 130 million) versus actual (R7 130 million) cash flows

The difference between this run and run 3A is that this run deals with sequential priorities whereas run 3A deals with mixed priorities. There is no difference in the final nominal pseudo and actual values.

Real original (R7 130 million) versus requirement (R7 130 million) value

It can be noted that the cumulative real original and requirement values are the same as those for run 3A. This is also because no escalation due to inflation and changes in exchange rates is taken into consideration.

Run 3B1 : Appendix H pages 42 and 43

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum
Constraints	1	Off
Budget	5	Specific amount and R 900 million per year
Budget growth	2	0 %
Inflation rates	2	0 %
Exchange rates	1	As for applicable countries

Final nominal pseudo (R8178 million) versus actual (R8 815 million) cash flows

The difference between this run and run 3B is that changes in exchange rates only are taken into consideration. As the planning horizon for sequential priorities is greater than the planning horizon for mixed priorities, the cumulative nominal actual value has increased when compared with the R8 110 million of run 3A1. It should further be noted that the actual curves are close to the pseudo curves.

Real original (R7 130 million) versus requirement (R8 742 million) value

The cumulative difference between the real requirement and original values is R1 612 million, which is also the cumulative additional cost due to inflation and changes in exchange rates. It is also R632 million more than the cumulative real requirement value of R8 110 million of run 3A1.

Run 4B : Appendix H pages 44 and 45

Data

	Option	
Priorities	1	Sequential
Initial project time	1	Minimum
Constraints	1	Off
Budget	7	Specific amount and R950 million per year
Budget growth	1	2 %
Inflation rates	1	As for applicable countries
Exchange rates	1	As for applicable countries

Final nominal pseudo (R30 397 million) versus actual (R31 373 million) cash flows

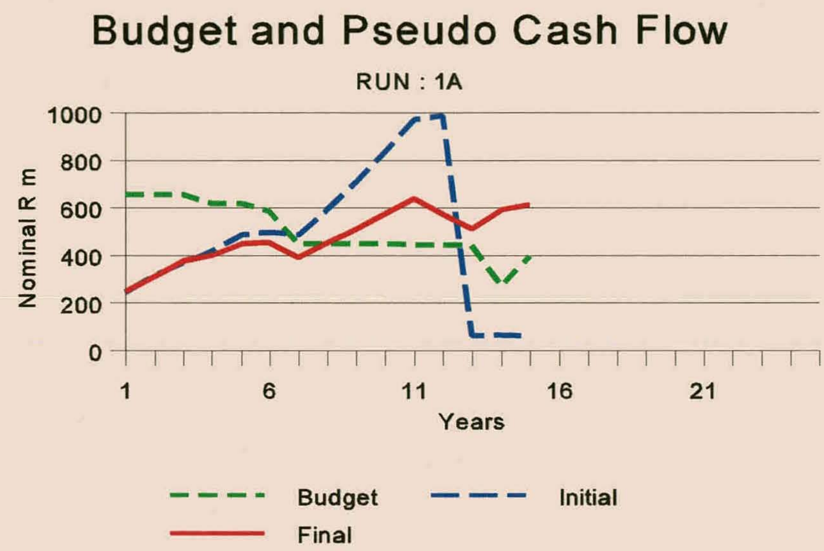
If compared with run 4A, the cumulative final nominal pseudo value increased from R21 189 million to R31 373 million. Again it can be seen that the final nominal actual cash flows are close to the final nominal pseudo cash flows.

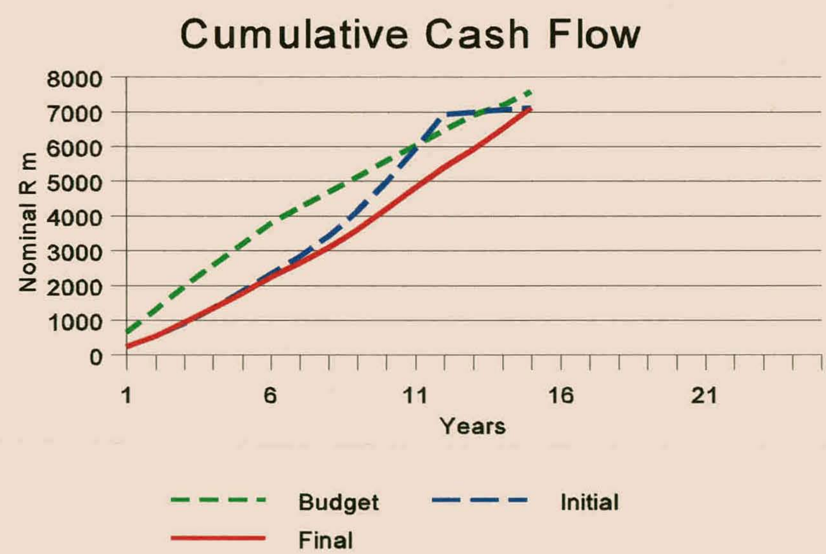
Real original (R7 130 million) versus requirement (R20 204 million) value

If the final nominal actual cash flow of R31 373 million is de-escalated to real terms, a real requirement value of R20 204 million results, which is R13 074 million more than the original input value of R7 130 million.

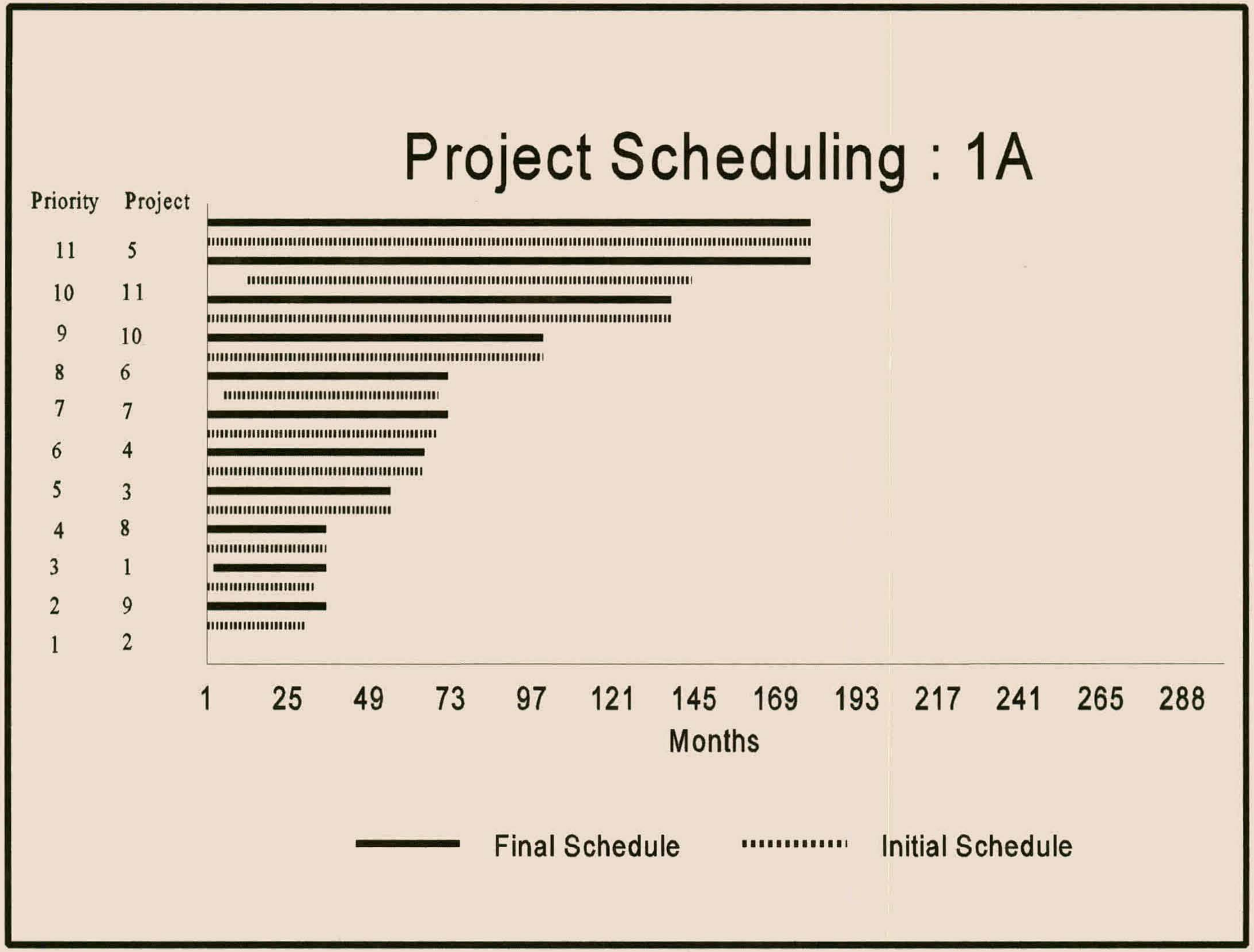
Appendix H:

Results of model computer run combinations

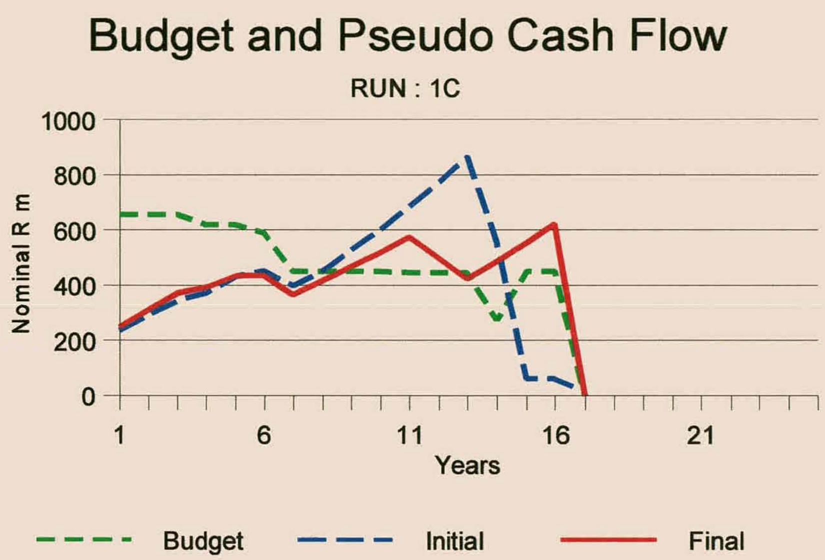

Budget and Pseudo Cash Flow
RUN : 1A
Nominal R m
1000
800
600
400
200
0
1
6
11
16
21
Years
Budget
Initial
Final

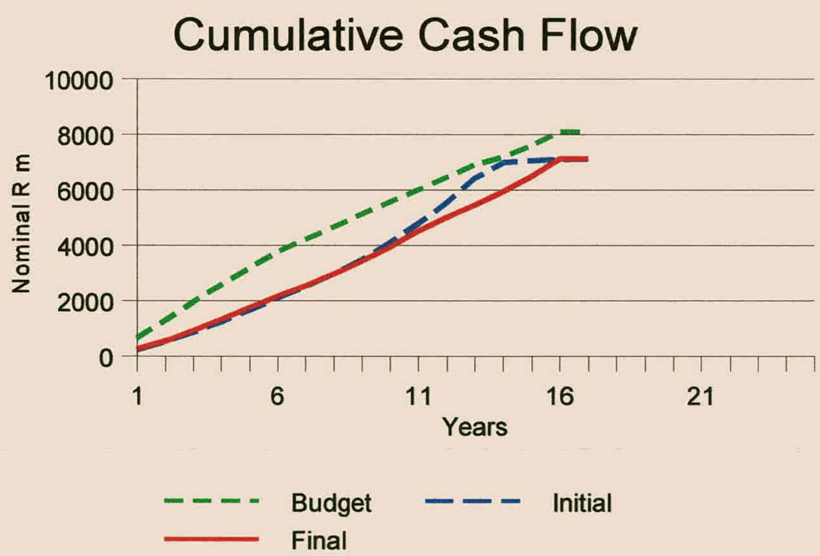

Cumulative Cash Flow
Nominal R m
8000
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
Years
Budget
Initial
Final

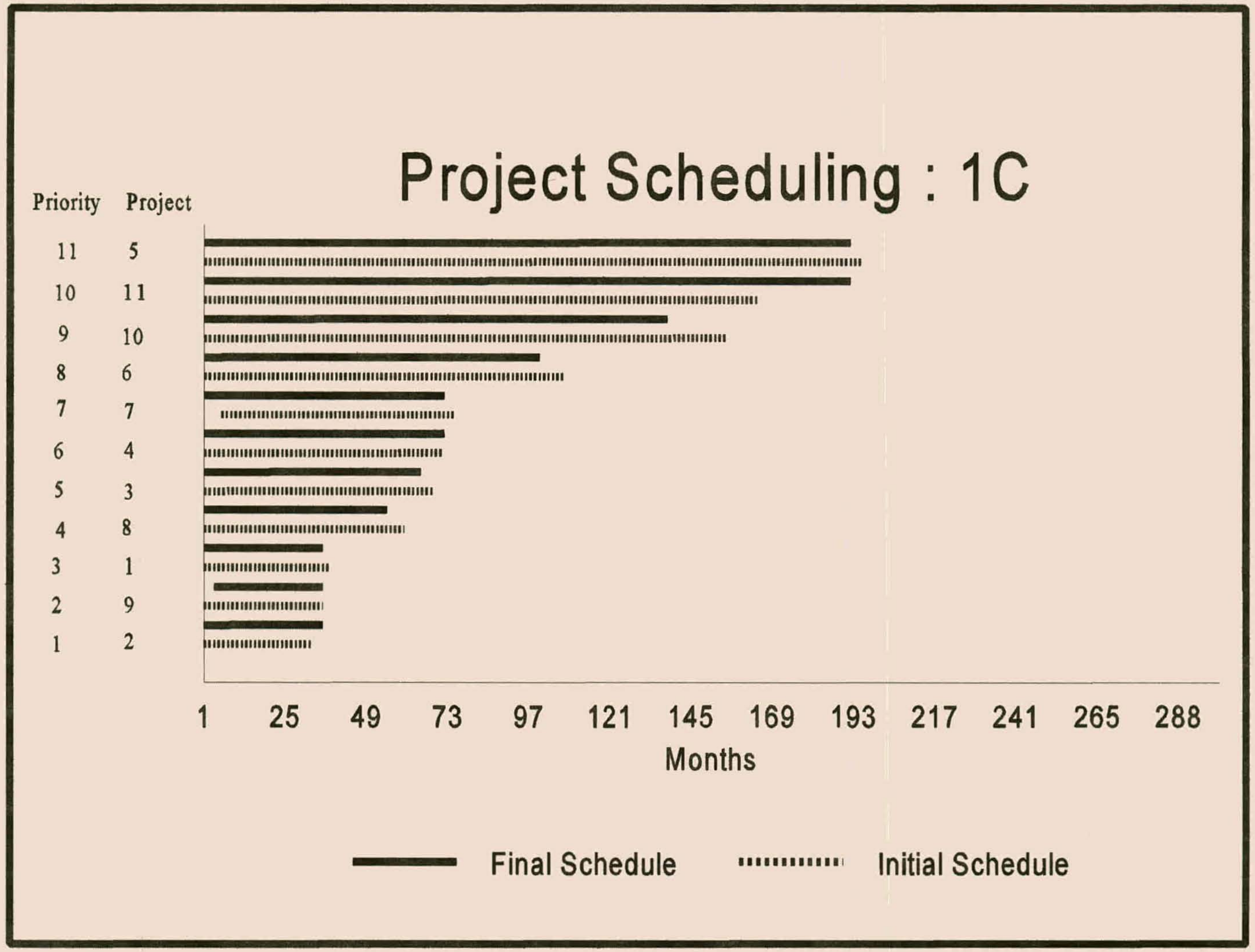
Appendix H

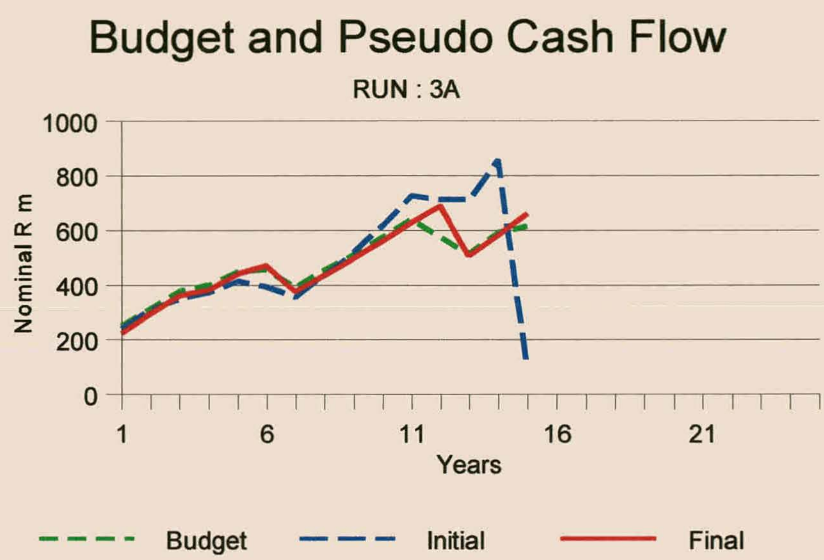


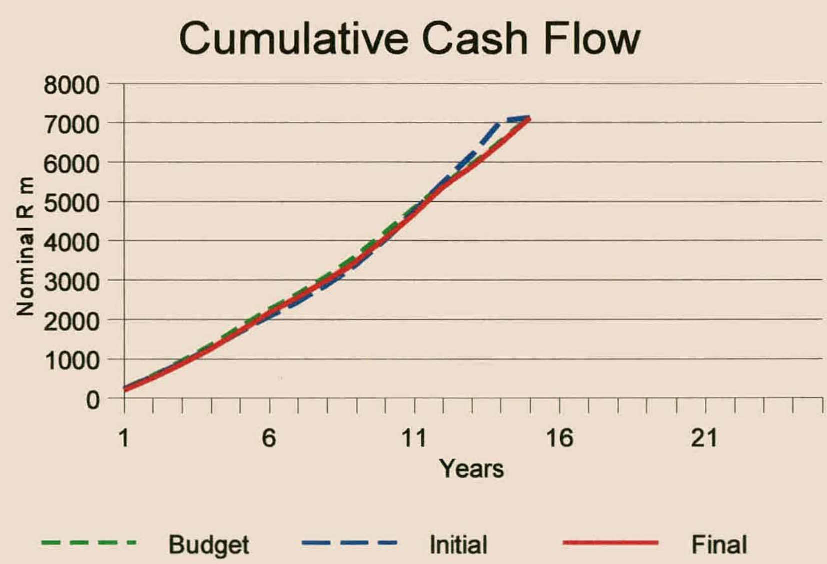
Project Scheduling : 1A
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule


Budget and Pseudo Cash Flow
RUN : 1C
Nominal R m
1000
800
600
400
200
0
1
6
11
16
21
Years
Budget
Initial
Final

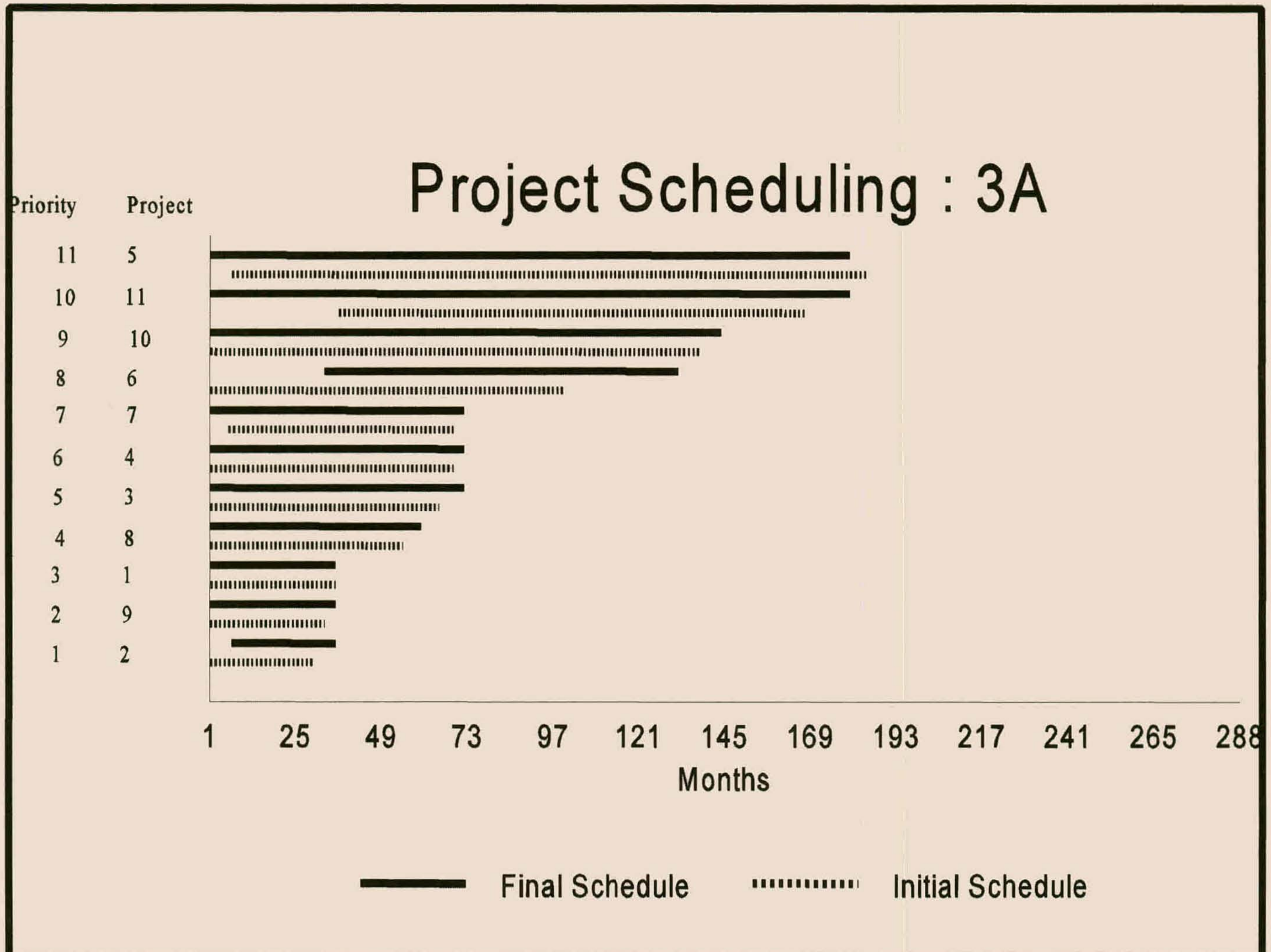

Cumulative Cash Flow
Nominal R m
10000
8000
6000
4000
2000
0
1
6
11
16
21
Years
Budget
Initial
Final


Project Scheduling : 1C
Priority
Project
11
5
10
11
9
10
8
6
7
7
6
4
5
3
4
8
3
1
2
9
1
2
1
25
49
73
97
121
145
169
193
217
241
265
288
Months
Final Schedule
Initial Schedule

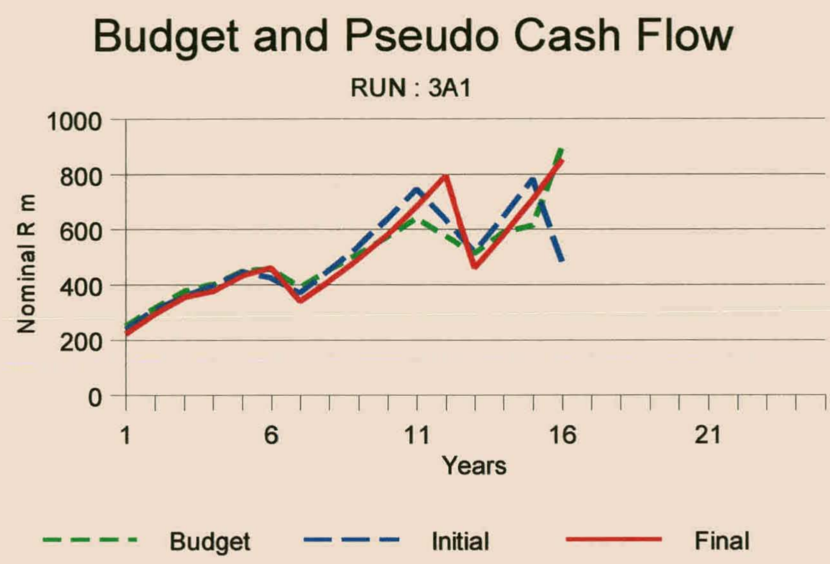

Budget and Pseudo Cash Flow
RUN : 3A
Nominal R m
1000
800
600
400
200
0
1
6
11
16
21
Years
Budget
Initial
Final

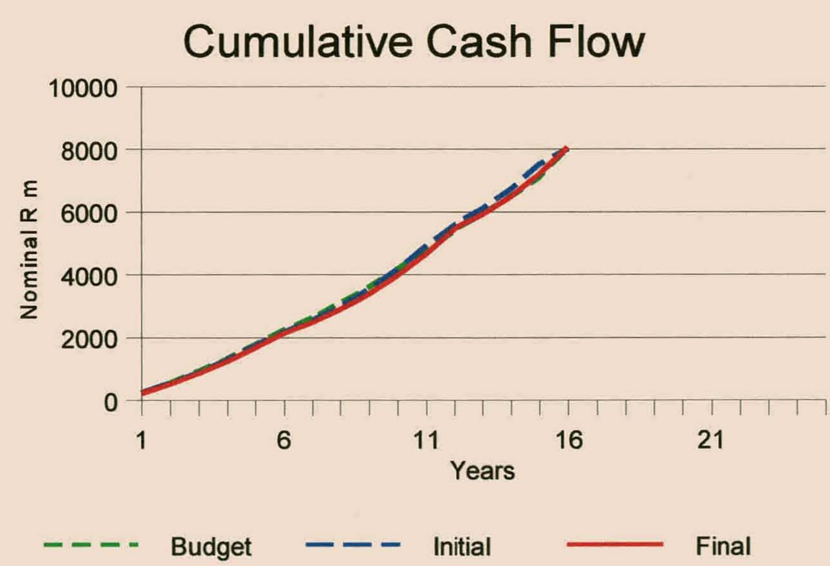

Cumulative Cash Flow
Nominal R m
8000
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
Years
Budget
Initial
Final

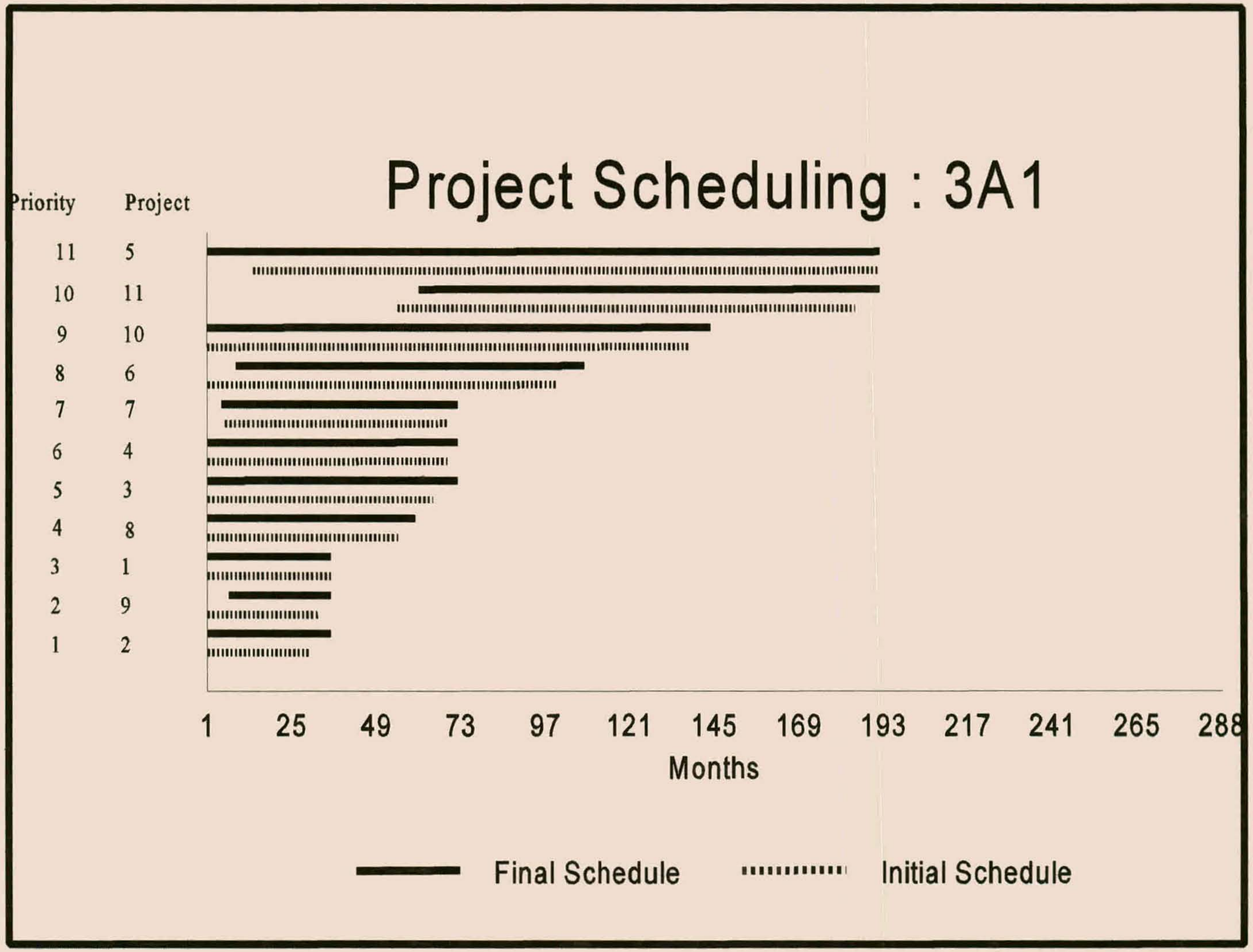
Appendix H

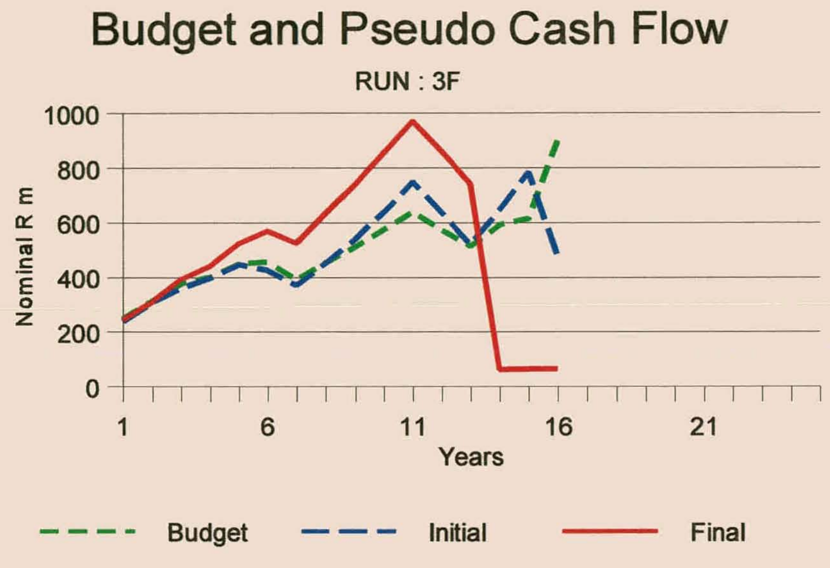


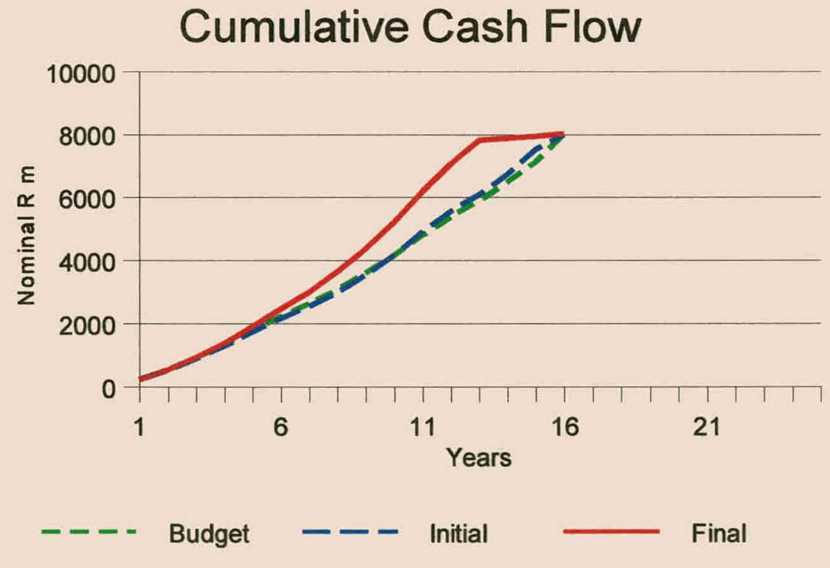
Project Scheduling : 3A
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

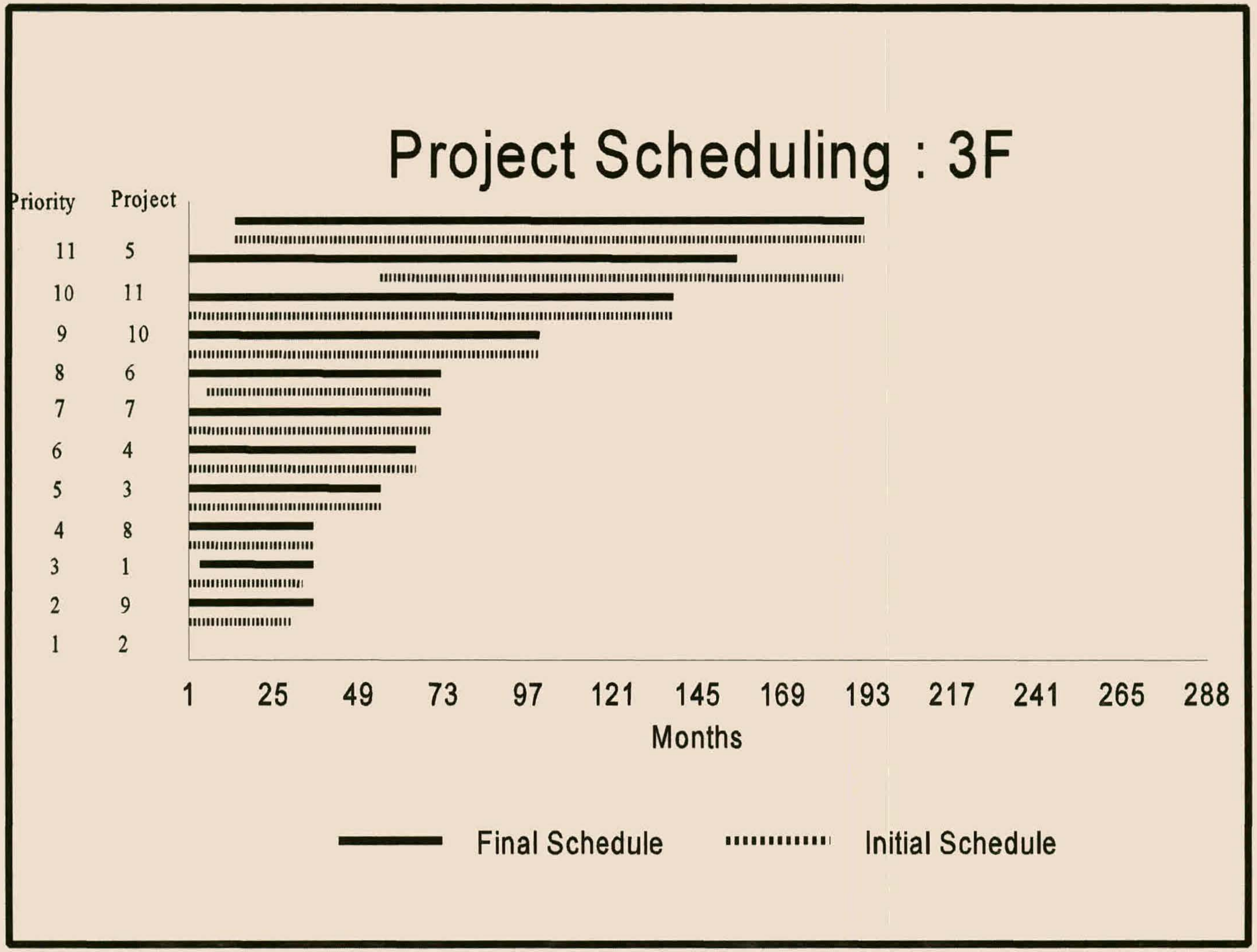

Budget and Pseudo Cash Flow
RUN : 3A1
1000
800
600
400
200
0
Nominal R m
1
6
11
16
21
Years
Budget
Initial
Final

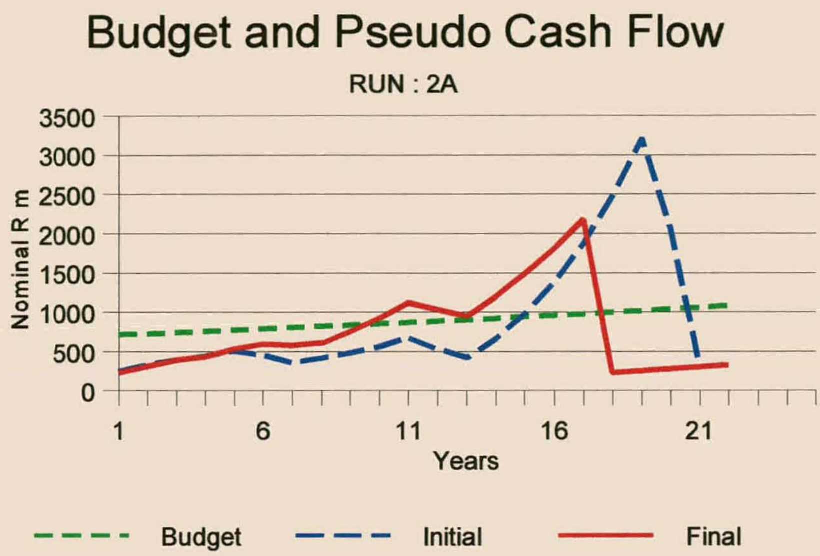

Cumulative Cash Flow
10000
8000
6000
4000
2000
0
Nominal R m
1
6
11
16
21
Years
Budget
Initial
Final

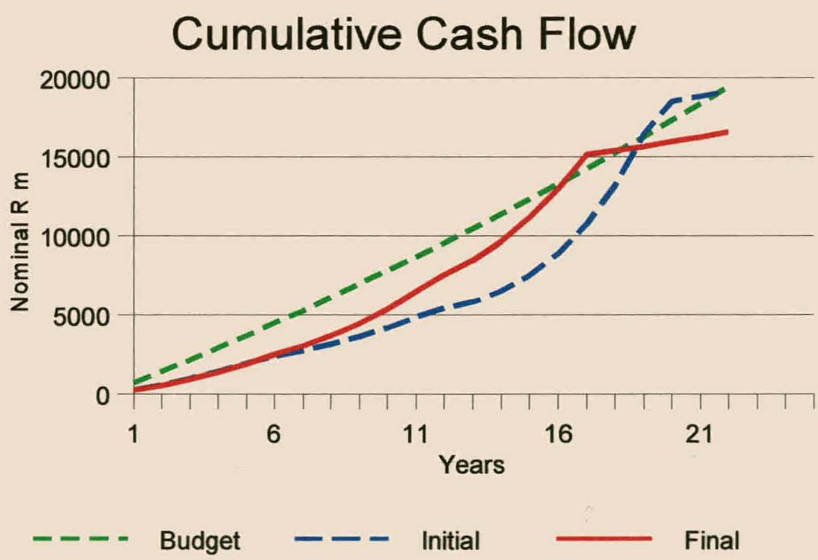

Project Scheduling : 3A1
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

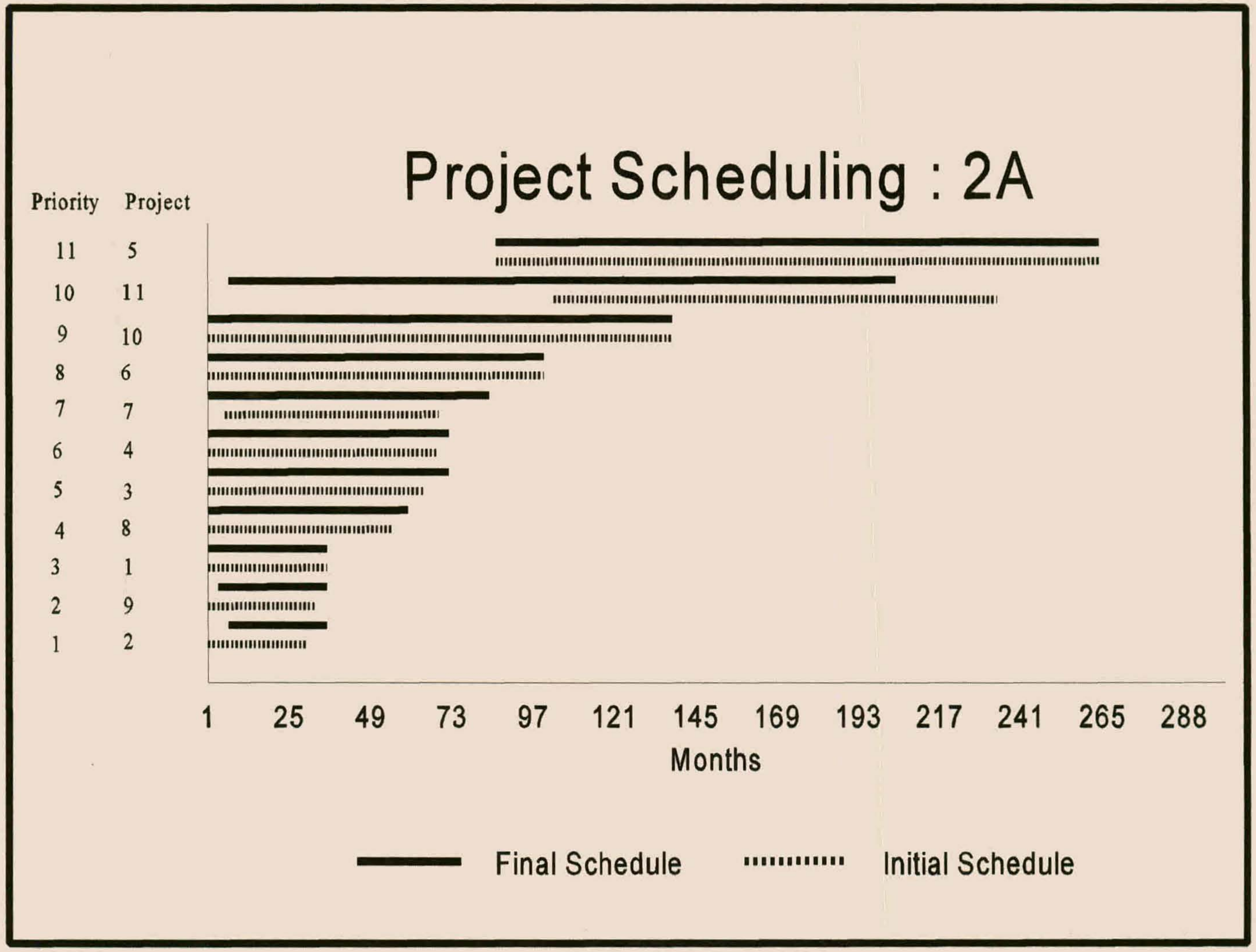

Budget and Pseudo Cash Flow
RUN : 3F
Nominal R m
1000
800
600
400
200
0
1
6
11
16
21
Years
Budget
Initial
Final


Cumulative Cash Flow
Nominal R m
10000
8000
6000
4000
2000
0
1
6
11
16
21
Years
Budget
Initial
Final

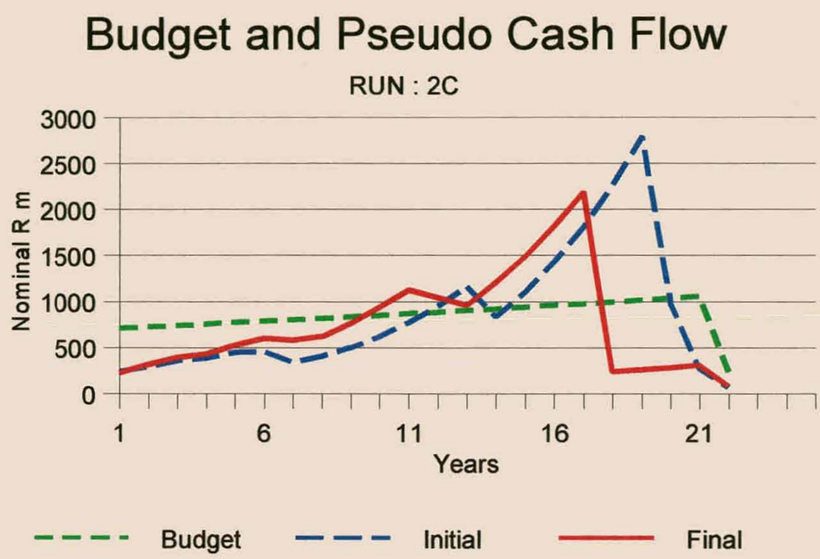

Project Scheduling : 3F
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1
25
49
73
97
121
145
169
193
217
241
265
288
Months
Final Schedule
Initial Schedule

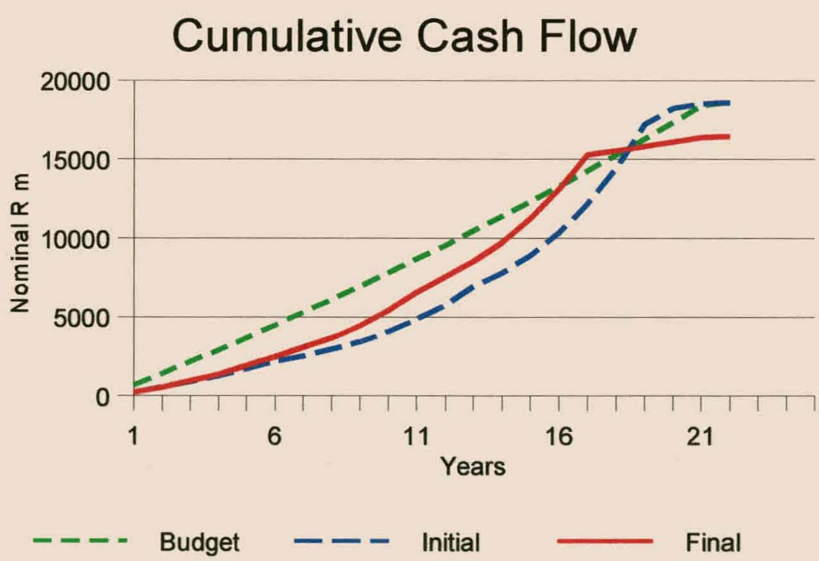

Budget and Pseudo Cash Flow
RUN : 2A
Nominal R m
3500
3000
2500
2000
1500
1000
500
0
1
6
11
16
21
Years
Budget
Initial
Final

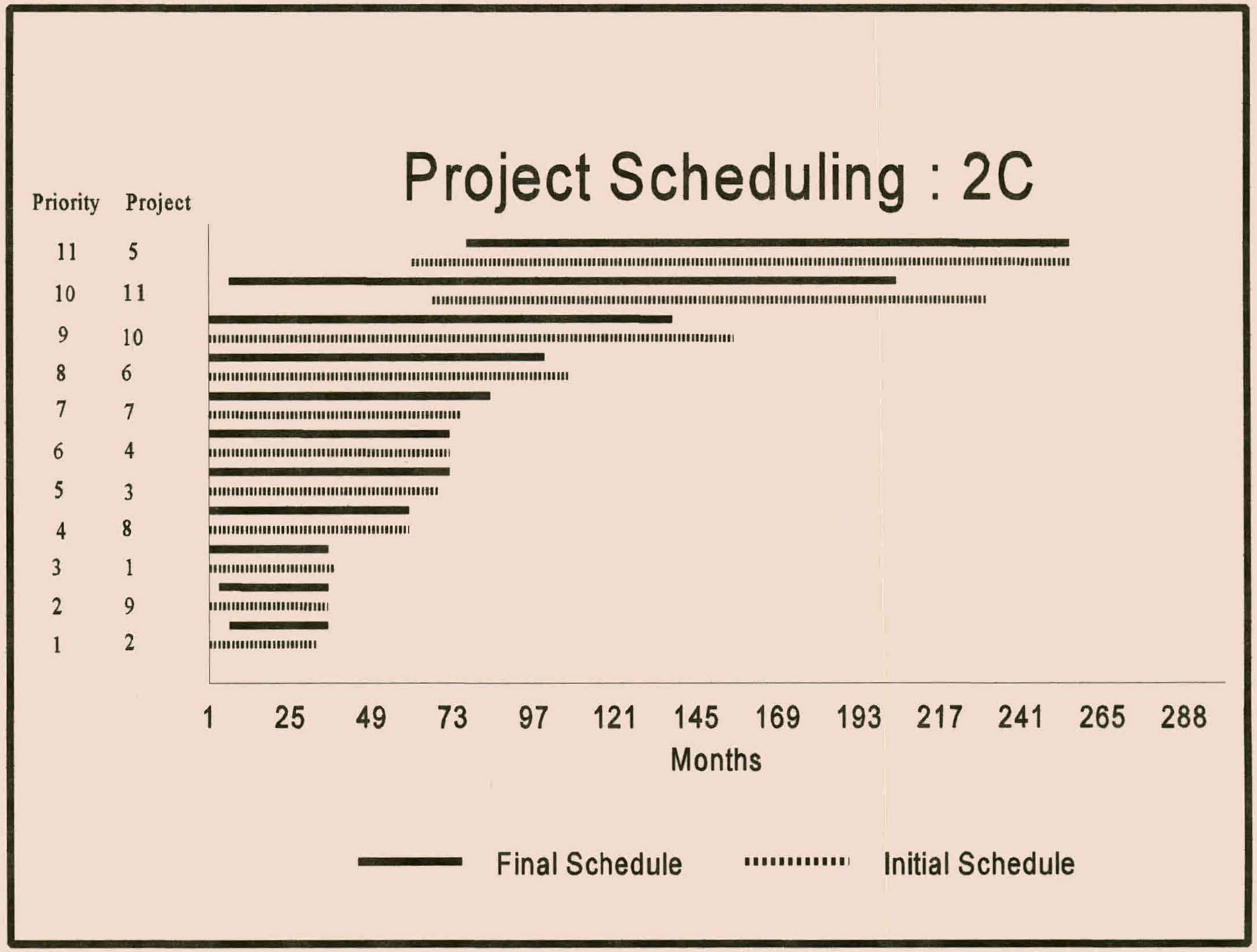

Cumulative Cash Flow
Nominal R m
20000
15000
10000
5000
0
1
6
11
16
21
Years
Budget
Initial
Final

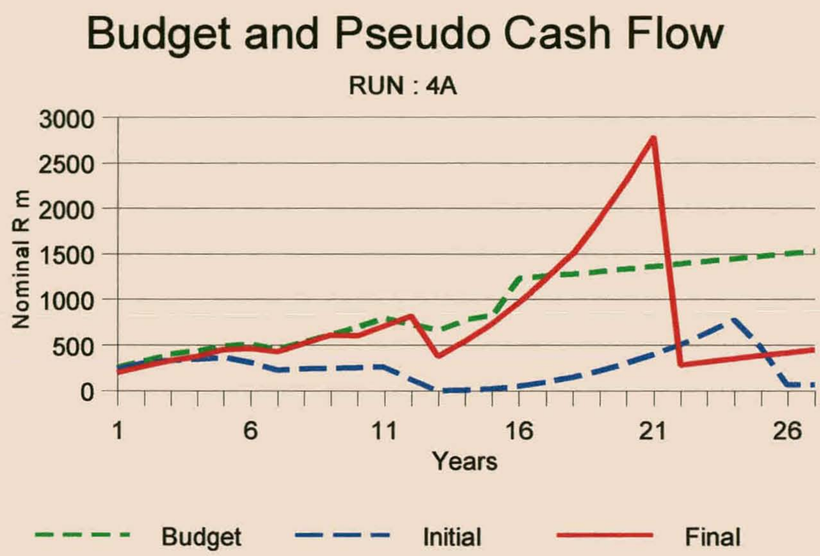


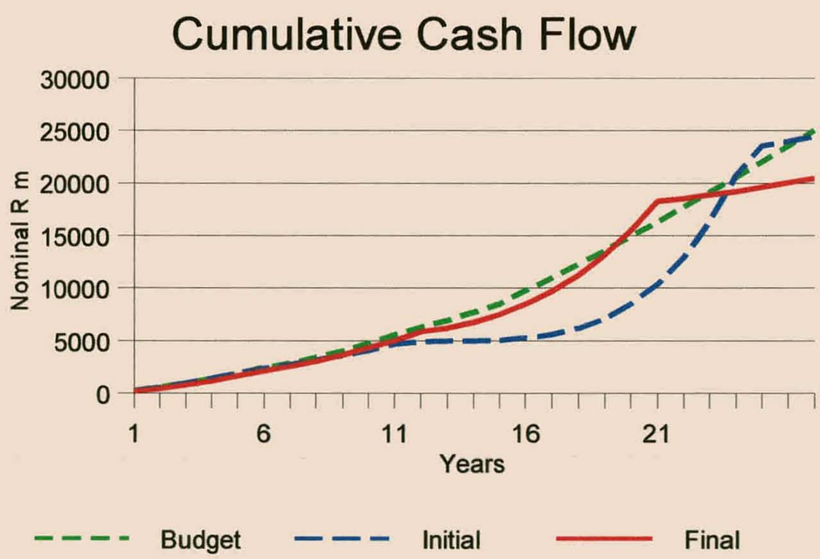
Project Scheduling : 2A
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

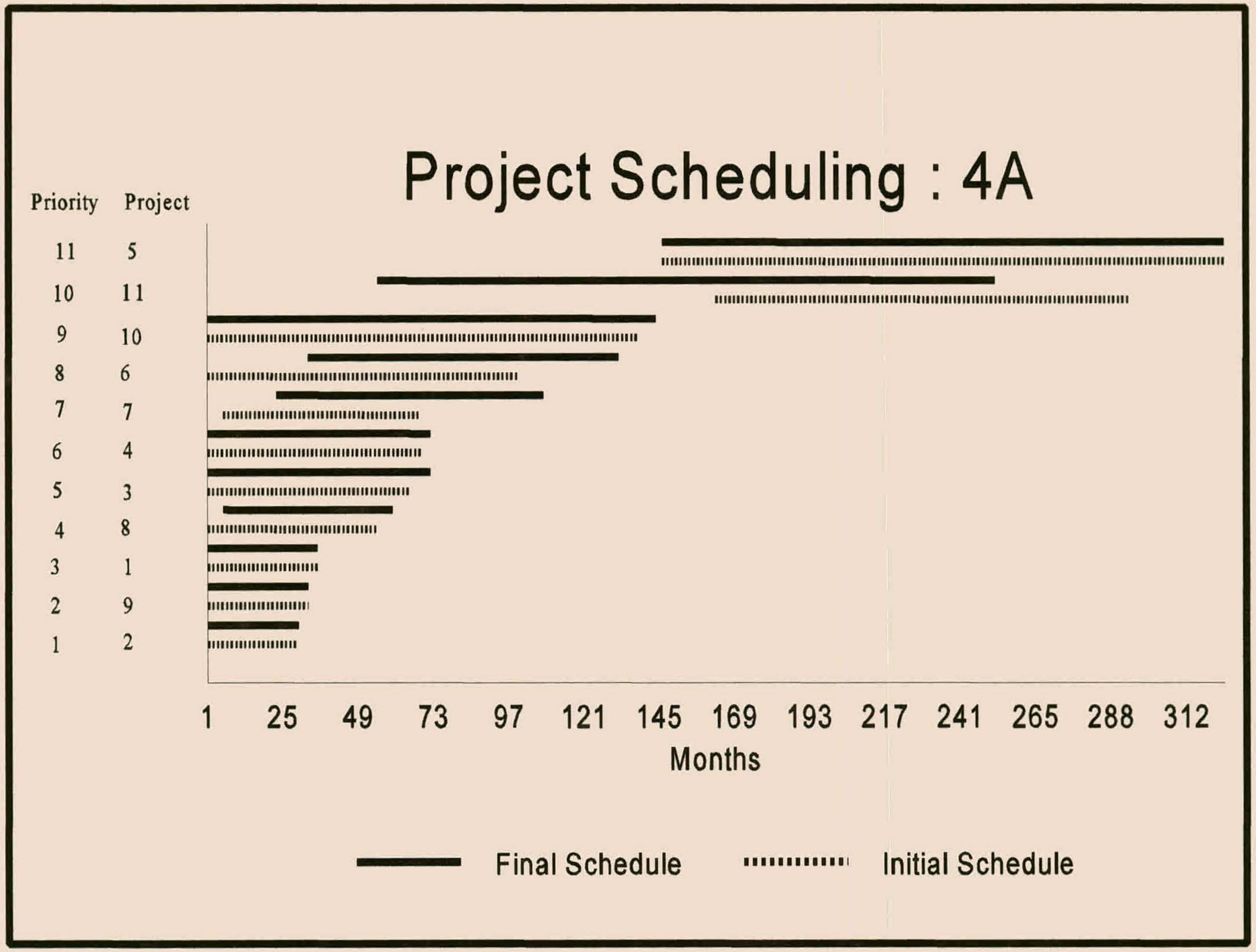

Budget and Pseudo Cash Flow
RUN : 2C
3000
2500
2000
1500
1000
500
0
Nominal R m
1
6
11
16
21
Years
Budget
Initial
Final

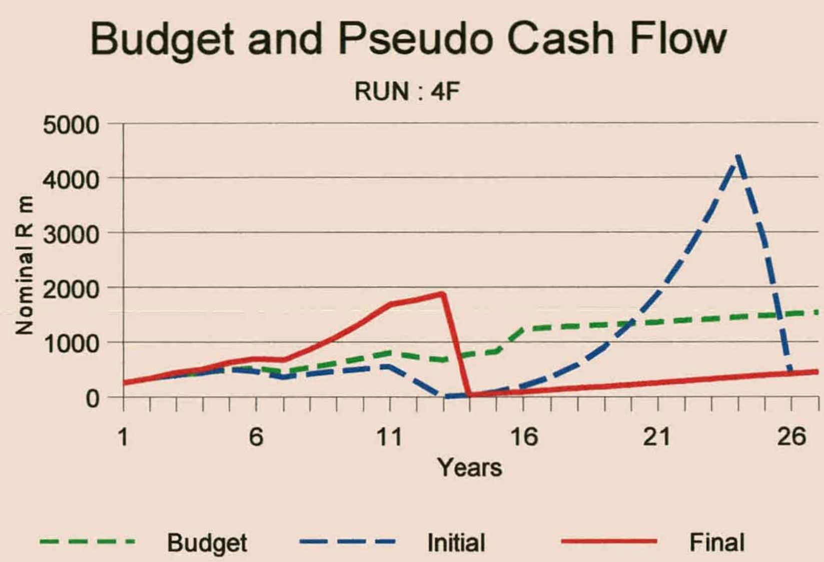

Cumulative Cash Flow
20000
15000
10000
5000
0
Nominal R m
1
6
11
16
21
Years
Budget
Initial
Final

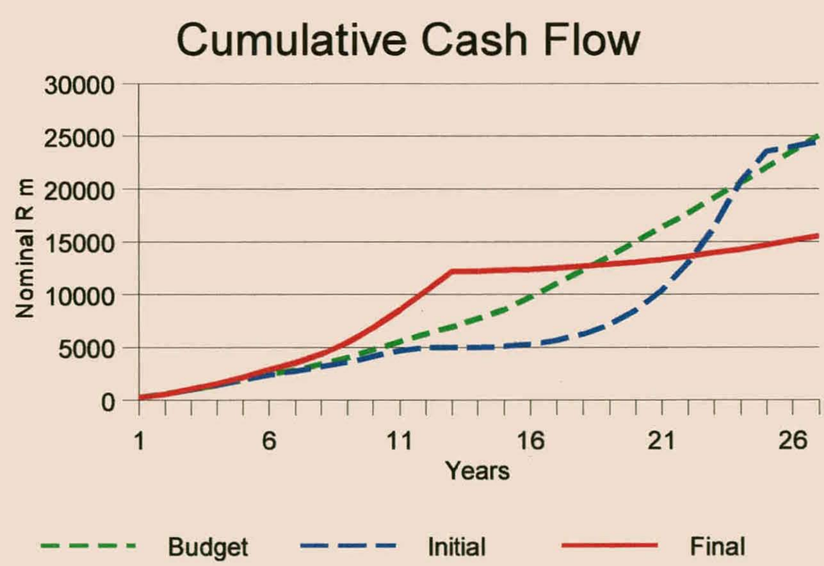

Project Scheduling : 2C
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

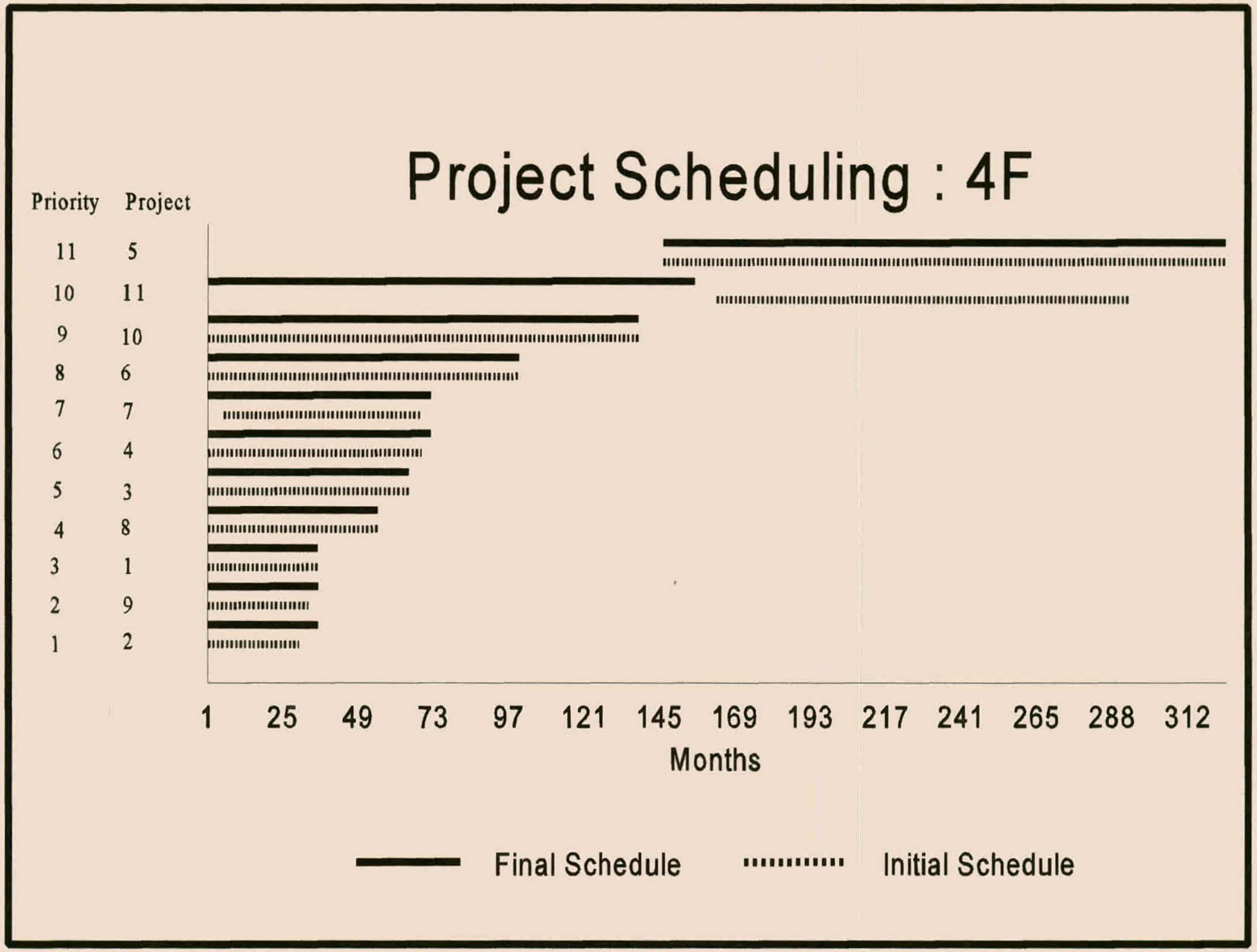

Budget and Pseudo Cash Flow
RUN : 4A
3000
2500
2000
1500
1000
500
0
Nominal R m
1
6
11
16
21
26
Years
Budget
Initial
Final

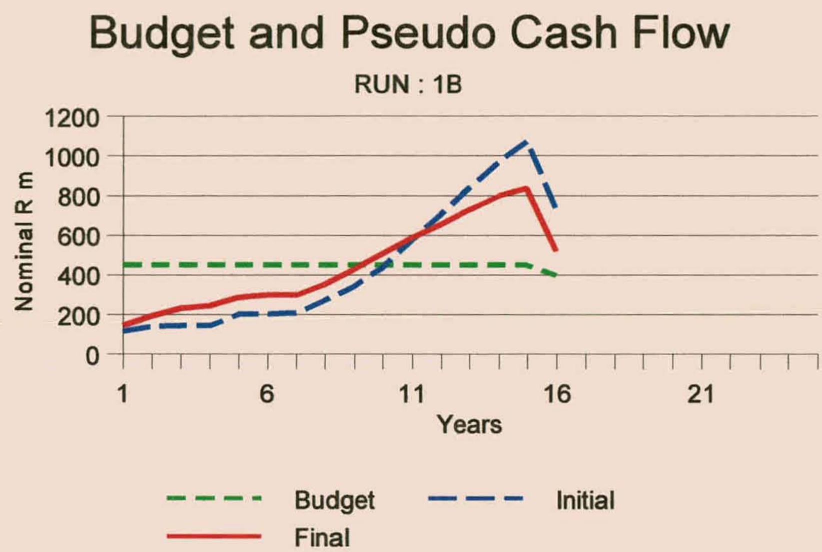

Cumulative Cash Flow
30000
25000
20000
15000
10000
5000
0
Nominal R m
1
6
11
16
21
Years
Budget
Initial
Final

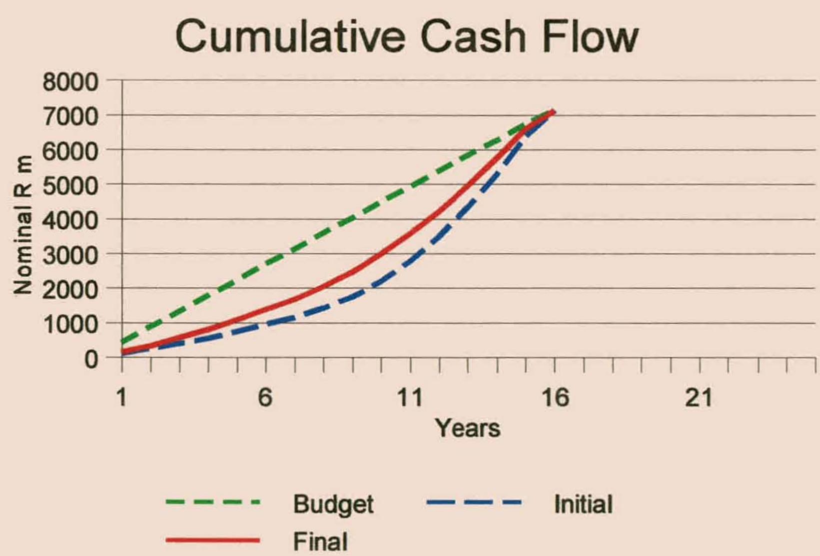

Project Scheduling : 4A
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1 25 49 73 97 121 145 169 193 217 241 265 288 312
Months
Final Schedule
Initial Schedule

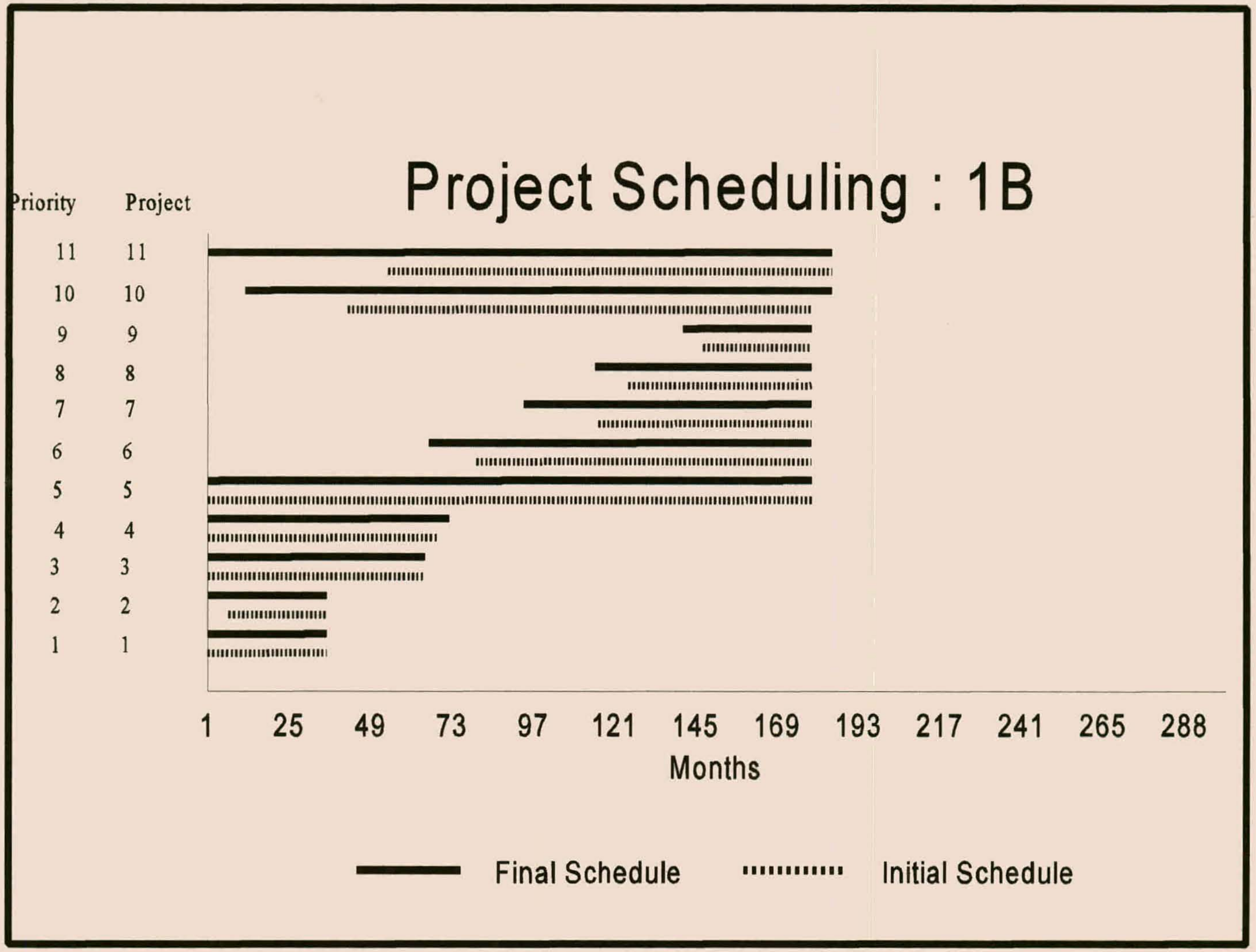

Budget and Pseudo Cash Flow
RUN : 4F
5000
4000
3000
2000
1000
0
Nominal R m
1
6
11
16
21
26
Years
Budget
Initial
Final

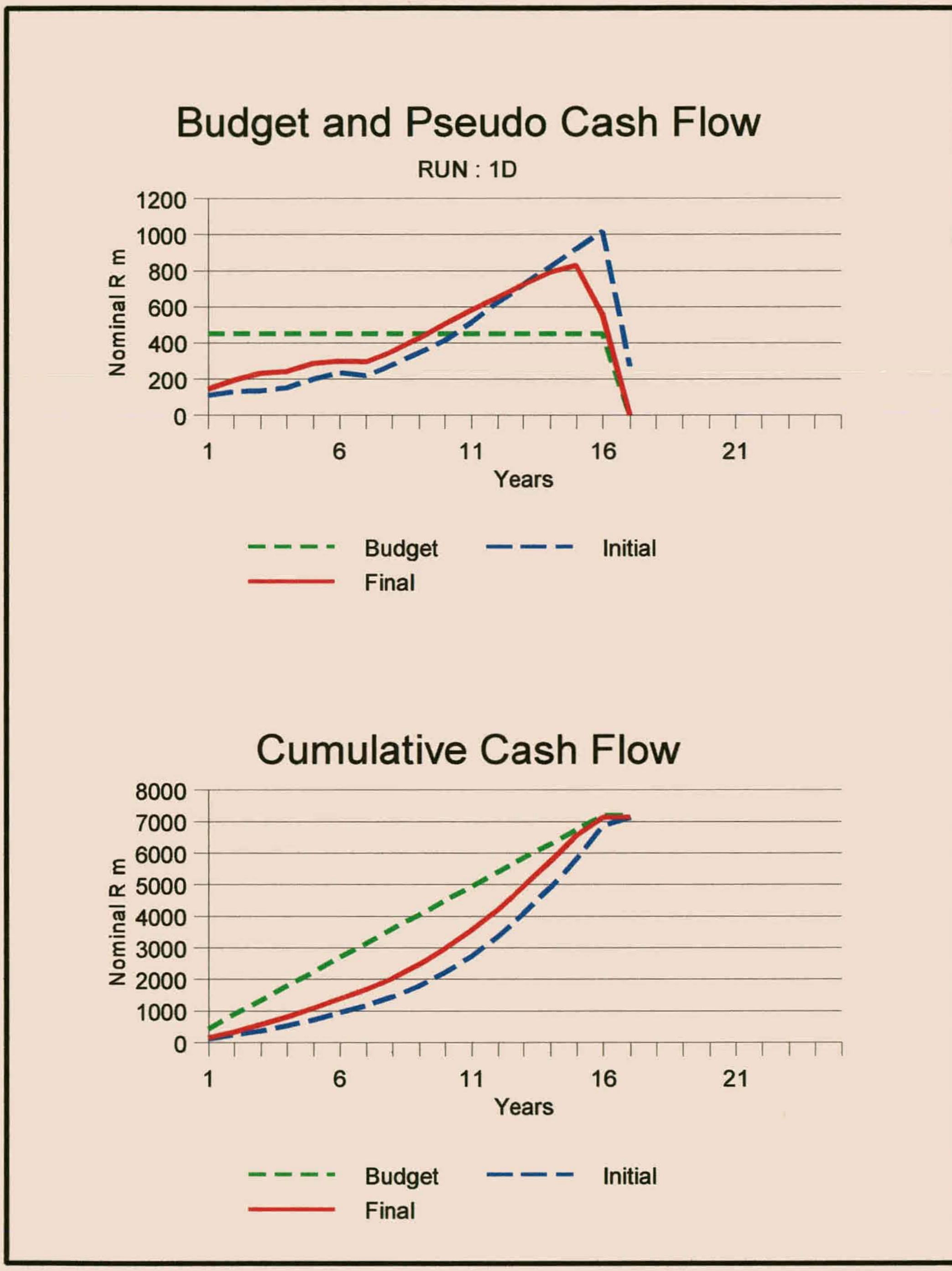

Cumulative Cash Flow
30000
25000
20000
15000
10000
5000
0
Nominal R m
1
6
11
16
21
26
Years
Budget
Initial
Final

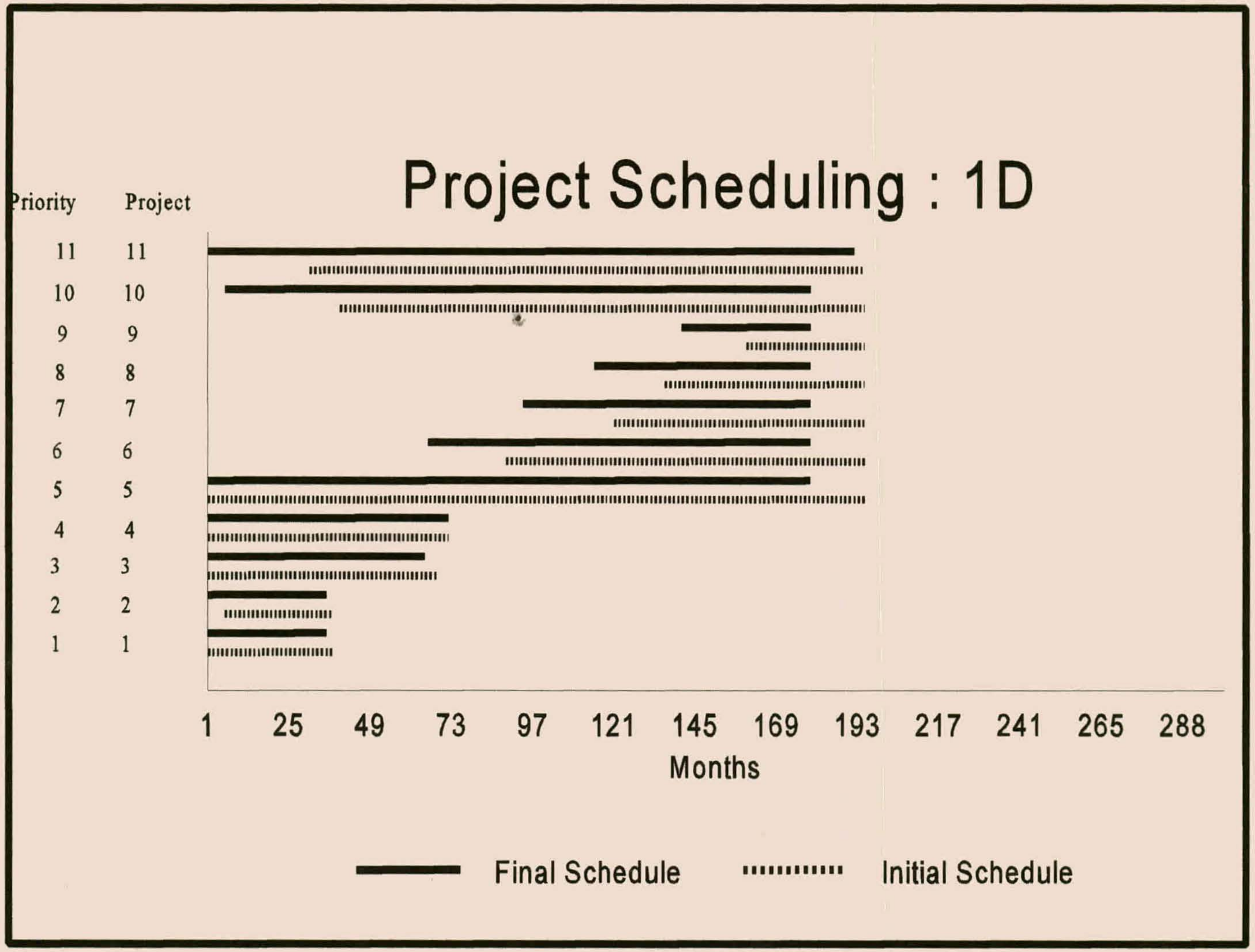

Project Scheduling : 4F
Priority
Project
11 5
10 11
9 10
8 6
7 7
6 4
5 3
4 8
3 1
2 9
1 2
1 25 49 73 97 121 145 169 193 217 241 265 288 312
Months
Final Schedule
Initial Schedule

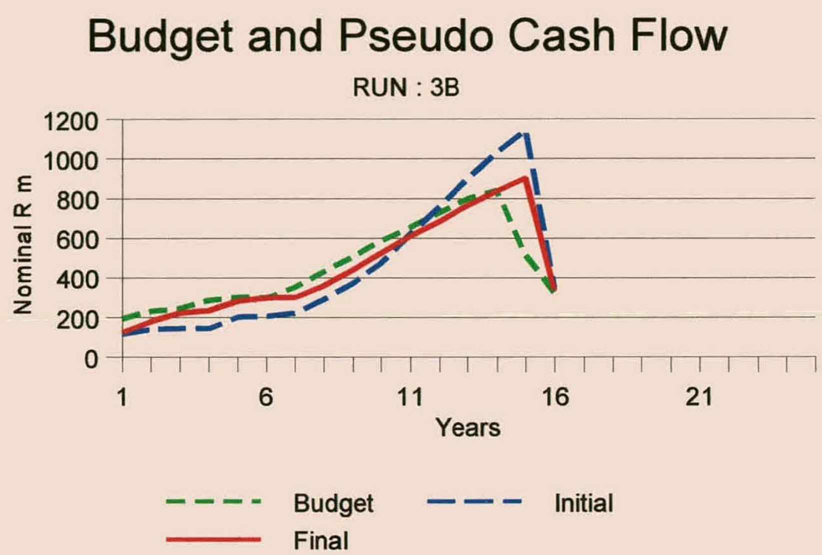

Budget and Pseudo Cash Flow
RUN : 1B
1200
1000
800
600
400
200
0
Nominal R m
1
6
11
16
21
Years
Budget
Initial
Final

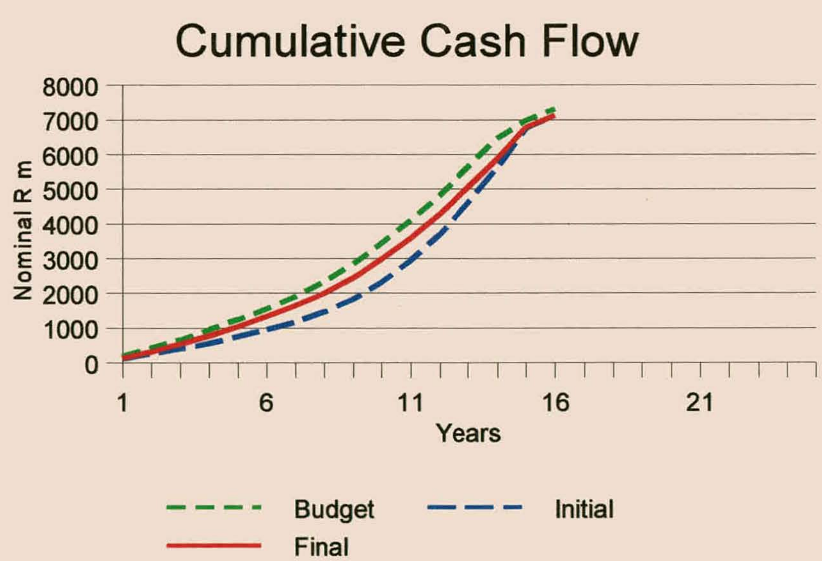

Cumulative Cash Flow
8000
7000
6000
5000
4000
3000
2000
1000
0
Nominal R m
1
6
11
16
21
Years
Budget
Initial
Final

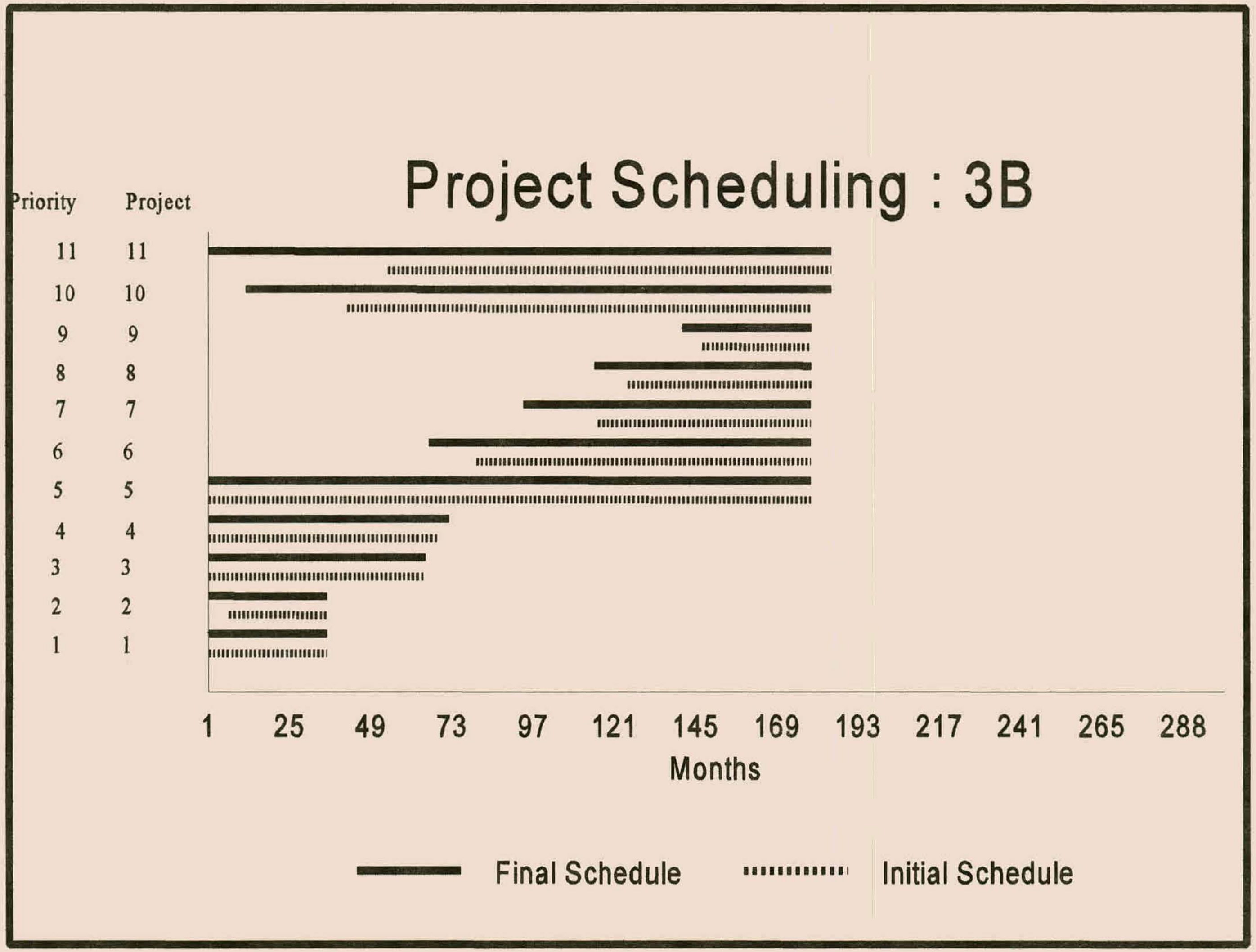

Project Scheduling : 1B
Priority
Project
11 11
10 10
9 9
8 8
7 7
6 6
5 5
4 4
3 3
2 2
1 1
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

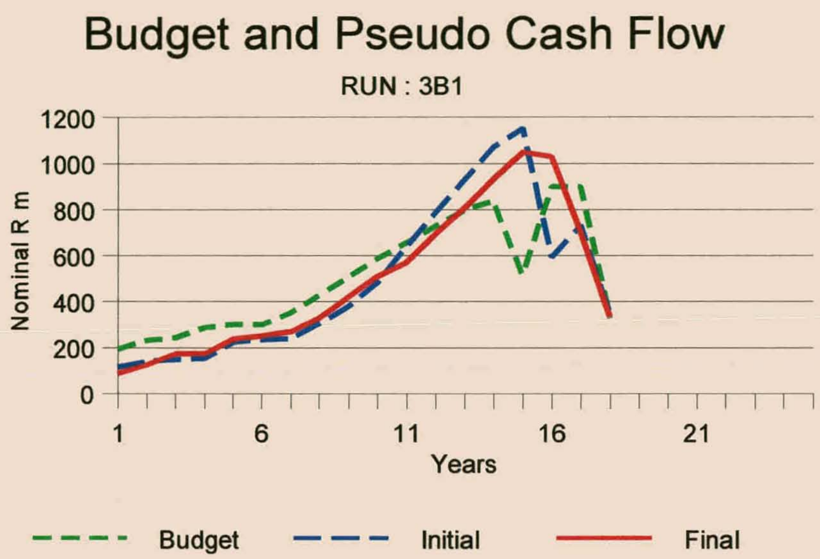

Budget and Pseudo Cash Flow
RUN : 1D
Nominal R m
1200
1000
800
600
400
200
0
1
6
11
16
21
Years
Budget
Initial
Final
Cumulative Cash Flow
Nominal R m
8000
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
Years
Budget
Initial
Final


Project Scheduling : 1D
Priority
Project
11 11
10 10
9 9
8 8
7 7
6 6
5 5
4 4
3 3
2 2
1 1
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

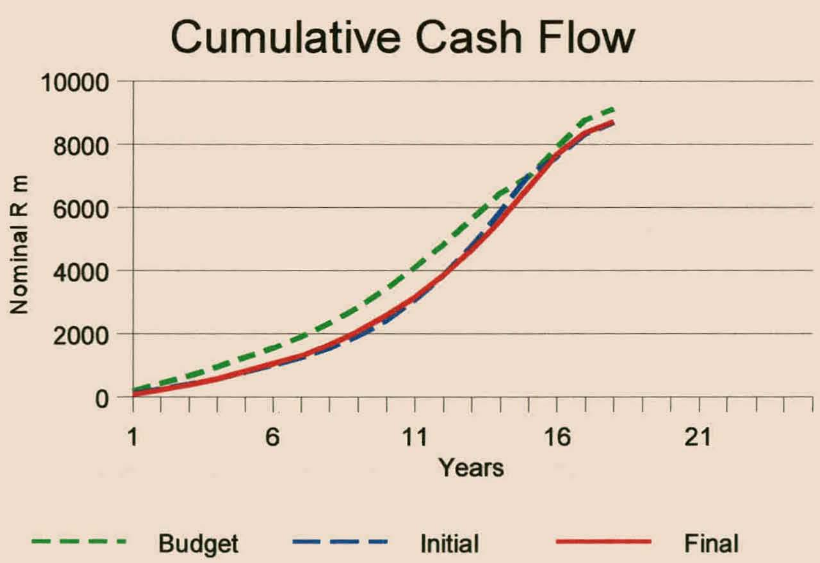

Budget and Pseudo Cash Flow
RUN : 3B
Nominal R m
1200
1000
800
600
400
200
0
1
6
11
16
21
Years
Budget
Initial
Final


Cumulative Cash Flow
Nominal R m
8000
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
Years
Budget
Initial
Final


Project Scheduling : 3B
Priority
Project
11 11
10 10
9 9
8 8
7 7
6 6
5 5
4 4
3 3
2 2
1 1
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

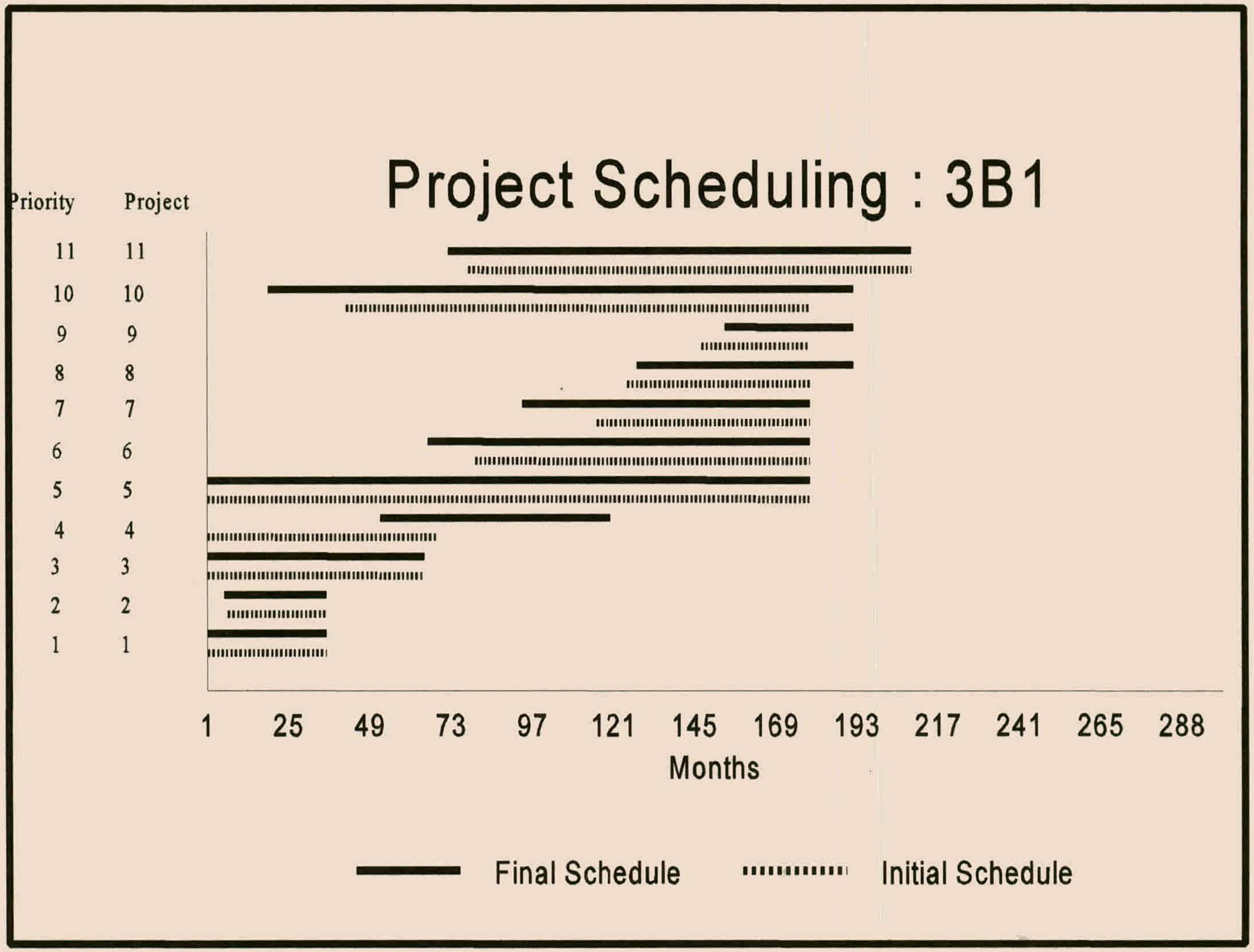


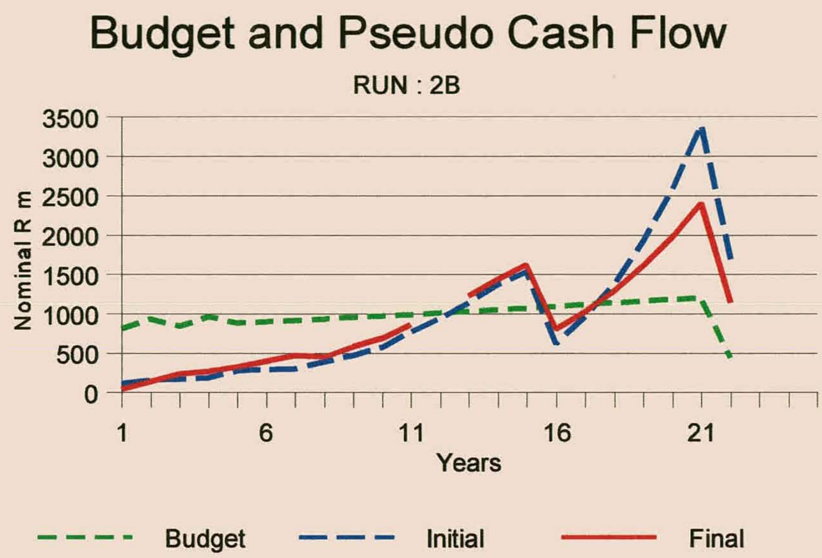
Budget and Pseudo Cash Flow
RUN : 3B1
Nominal R m
1200
1000
800
600
400
200
0
1
6
11
16
21
Years
Budget
Initial
Final



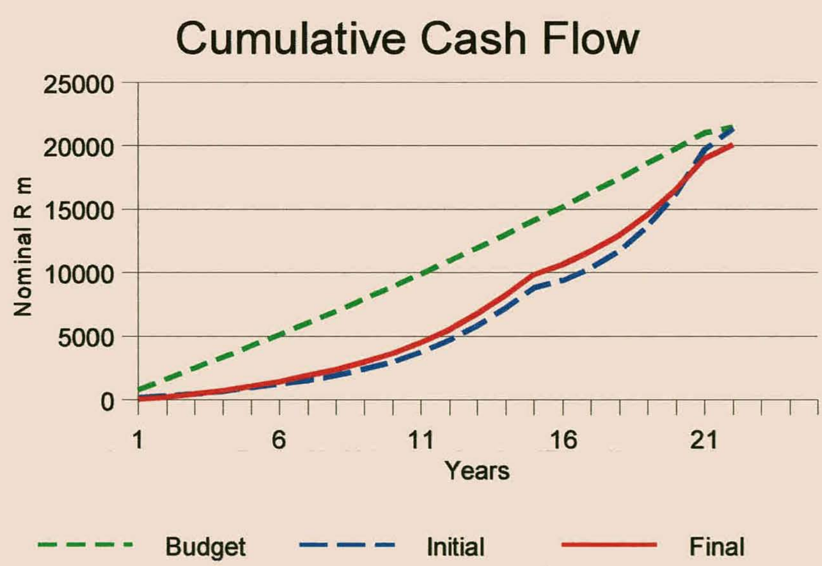
Cumulative Cash Flow
Nominal R m
10000
8000
6000
4000
2000
0
1
6
11
16
21
Years
Budget
Initial
Final

Appendix H

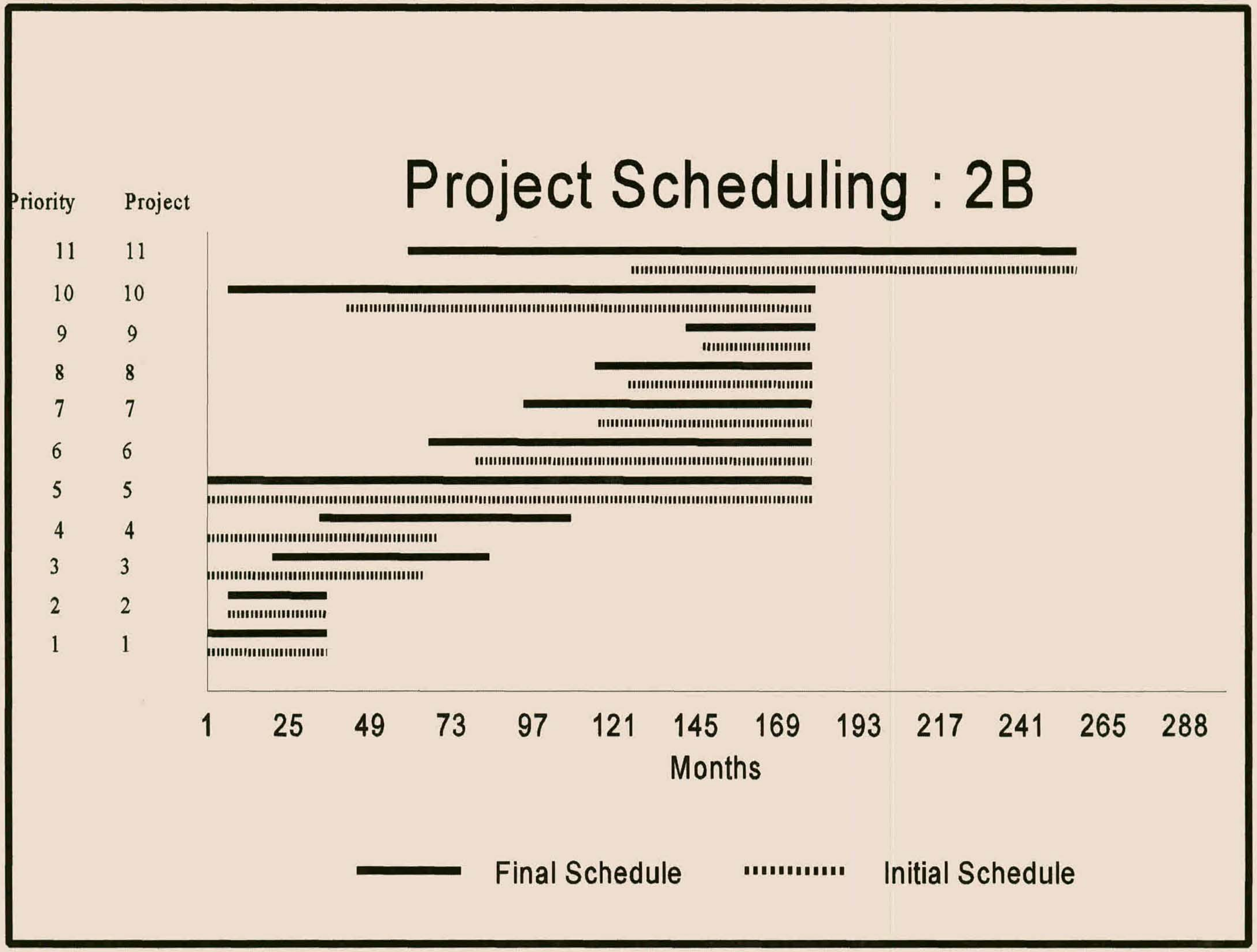

Project Scheduling : 3B1
Priority
Project
11 11
10 10
9 9
8 8
7 7
6 6
5 5
4 4
3 3
2 2
1 1
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

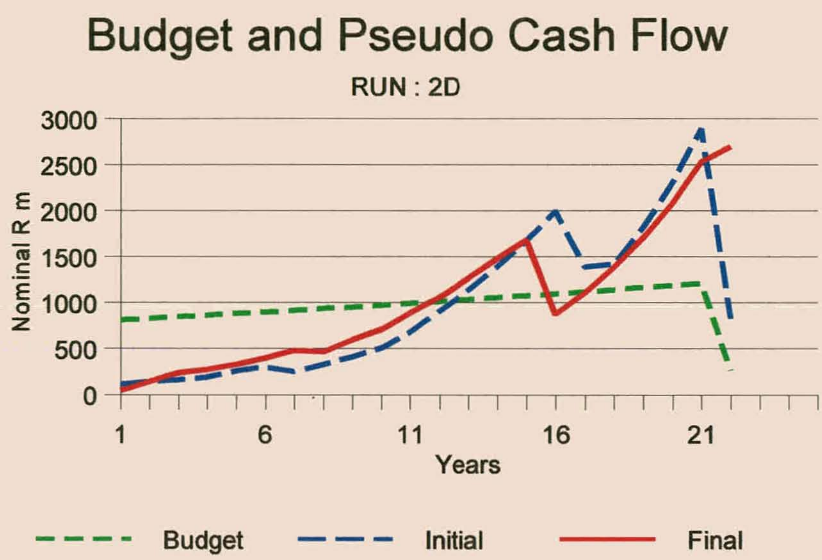


Budget and Pseudo Cash Flow
RUN : 2B
Nominal R m
3500
3000
2500
2000
1500
1000
500
0
1
6
11
16
21
Years
Budget
Initial
Final

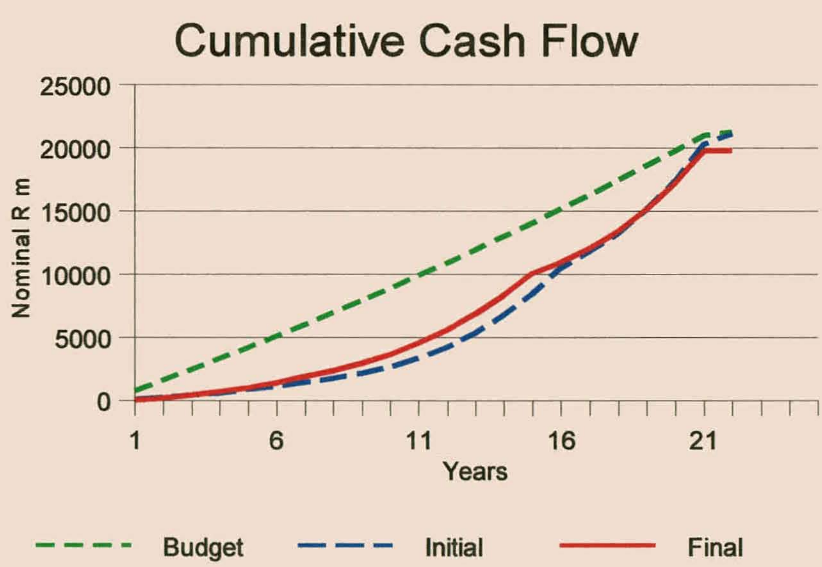


Cumulative Cash Flow
Nominal R m
25000
20000
15000
10000
5000
0
1
6
11
16
21
Years
Budget
Initial
Final

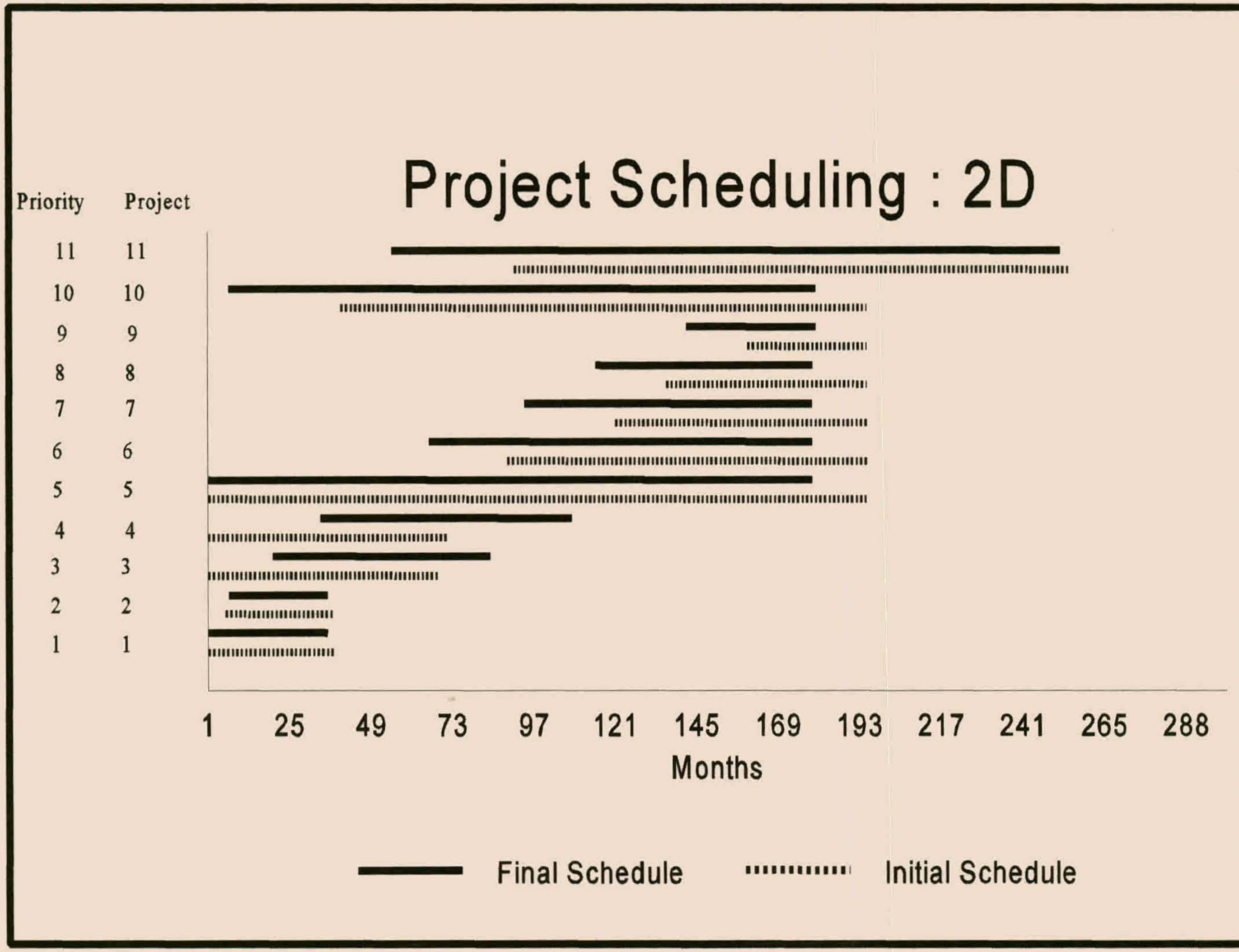

Project Scheduling : 2B
Priority
Project
11 11
10 10
9 9
8 8
7 7
6 6
5 5
4 4
3 3
2 2
1 1
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

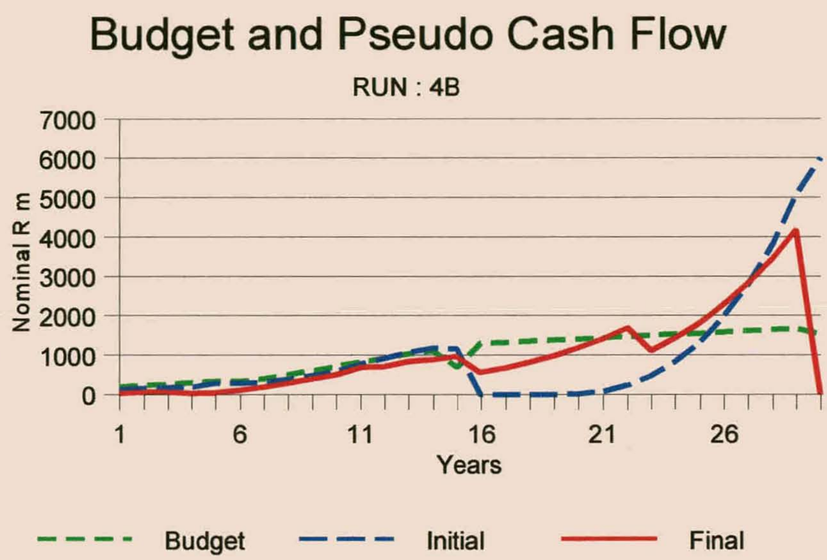


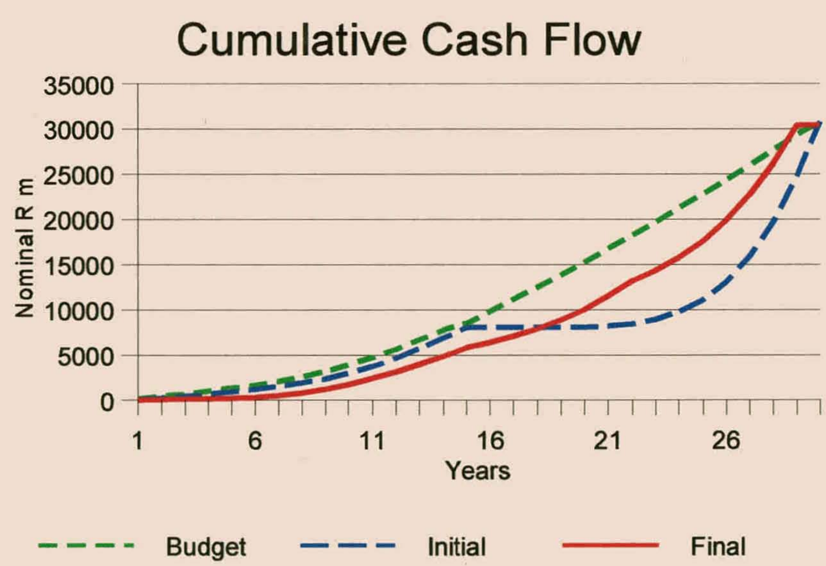
Budget and Pseudo Cash Flow
RUN : 2D
Nominal R m
3000
2500
2000
1500
1000
500
0
1
6
11
16
21
Years
Budget
Initial
Final



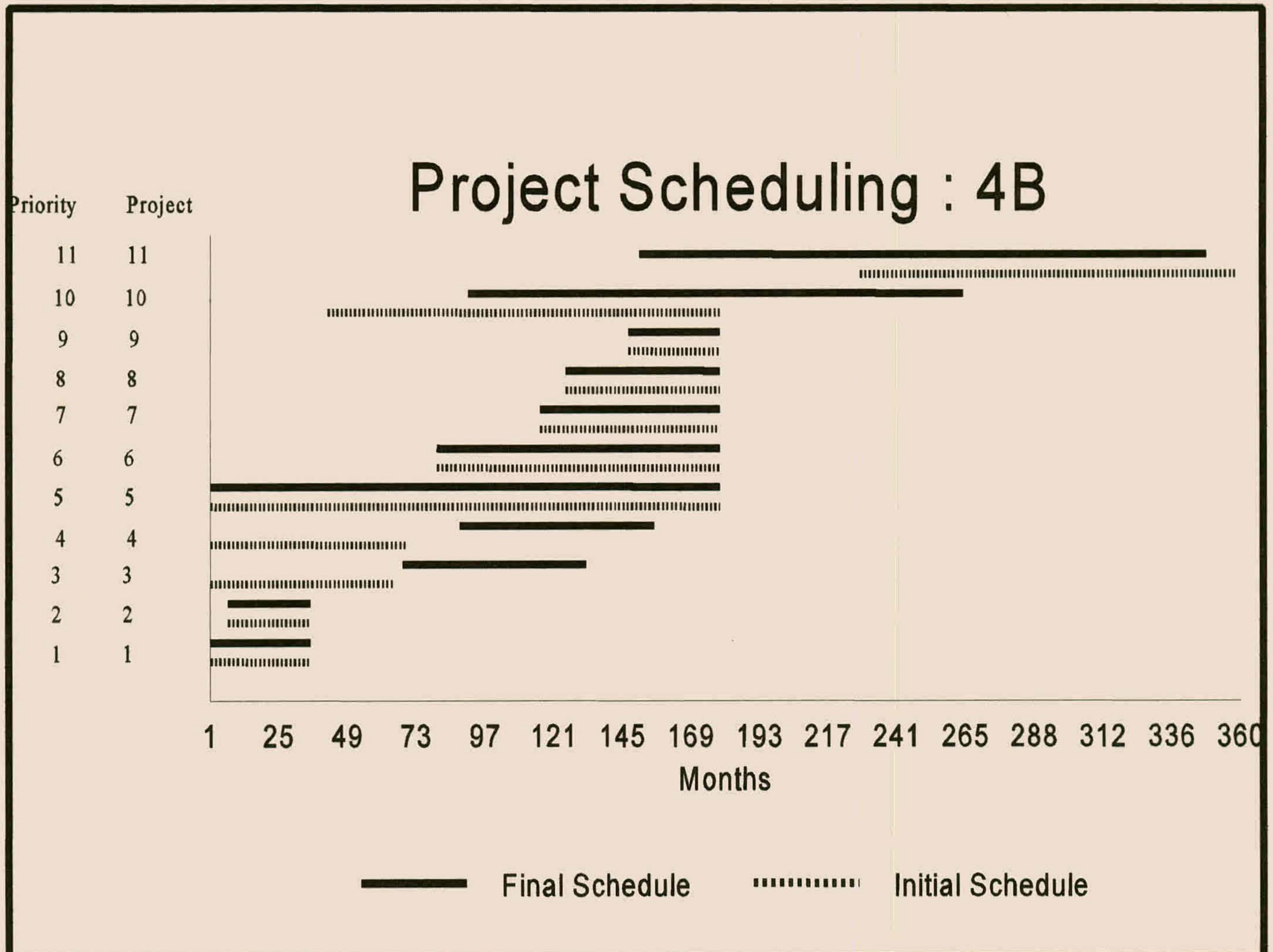
Cumulative Cash Flow
Nominal R m
25000
20000
15000
10000
5000
0
1
6
11
16
21
Years
Budget
Initial
Final


Project Scheduling : 2D
Priority
Project
11 11
10 10
9 9
8 8
7 7
6 6
5 5
4 4
3 3
2 2
1 1
1 25 49 73 97 121 145 169 193 217 241 265 288
Months
Final Schedule
Initial Schedule

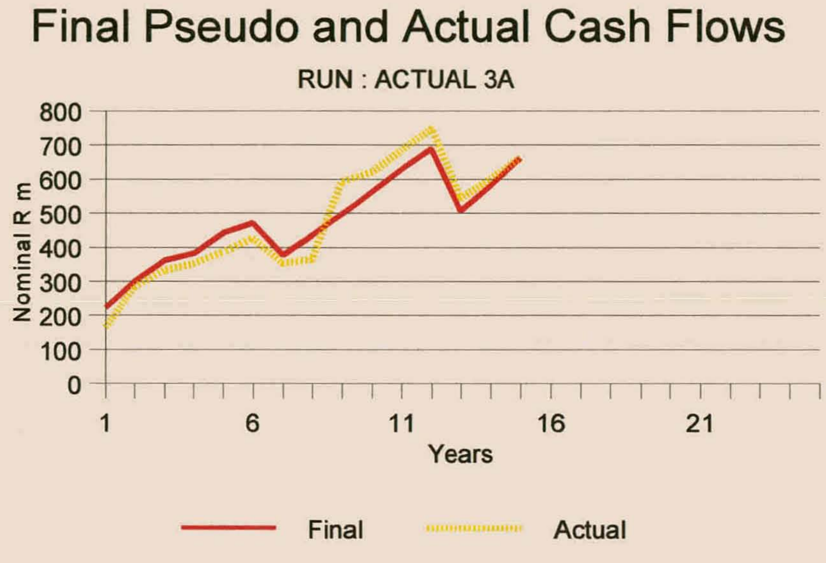

Budget and Pseudo Cash Flow
RUN : 4B
Nominal R m
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
26
Years
Budget
Initial
Final

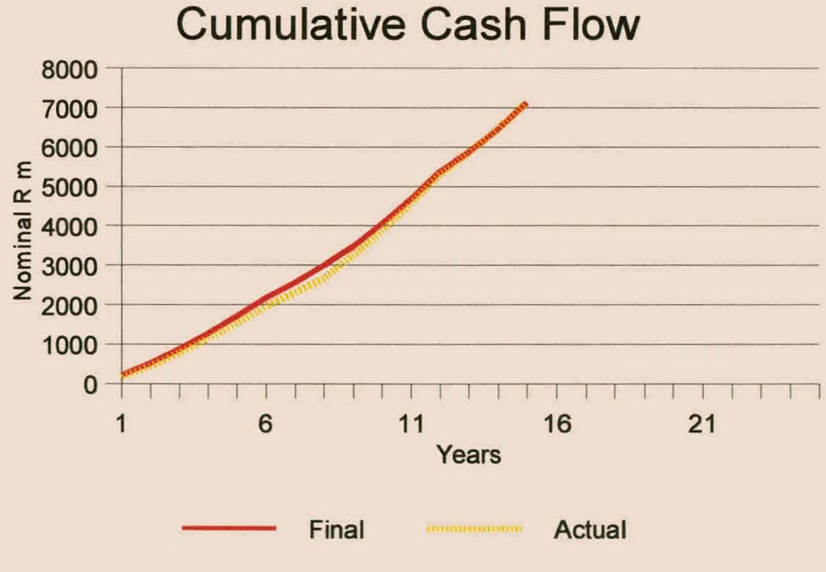

Cumulative Cash Flow
Nominal R m
35000
30000
25000
20000
15000
10000
5000
0
1
6
11
16
21
26
Years
Budget
Initial
Final

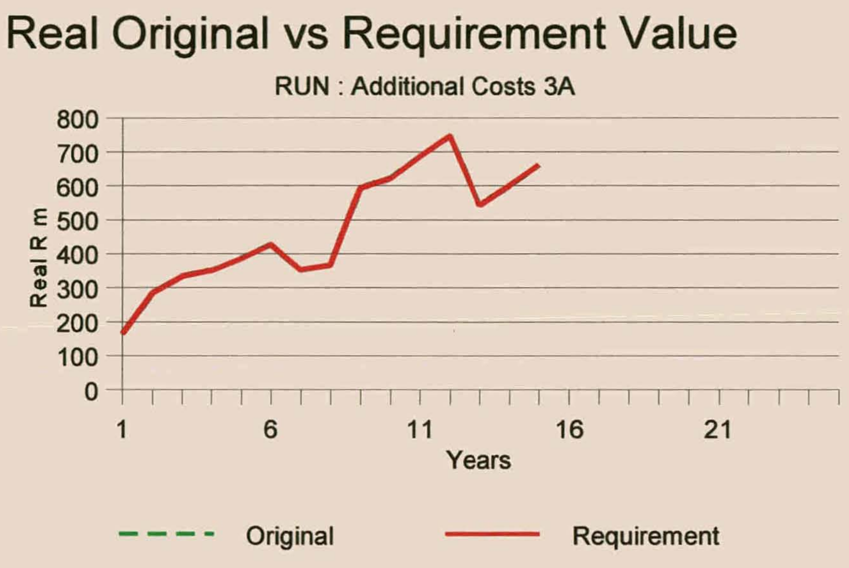
Appendix H

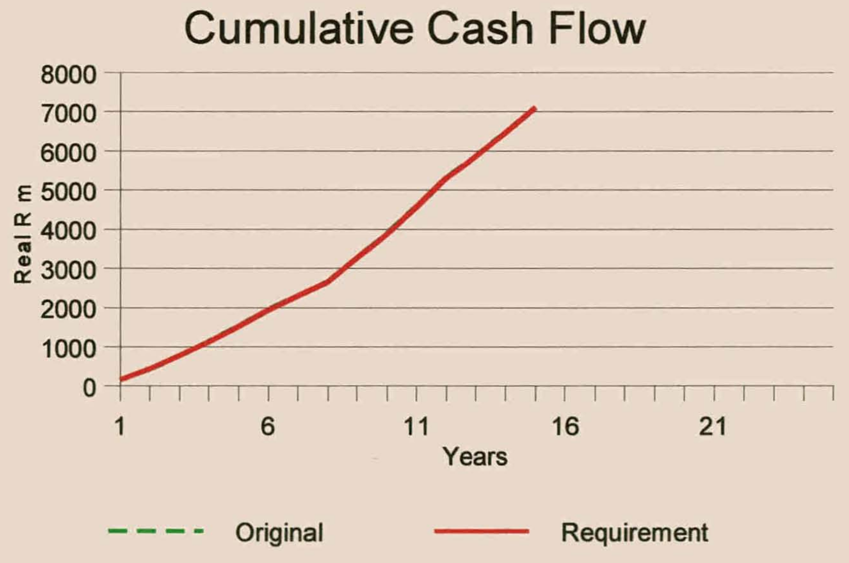


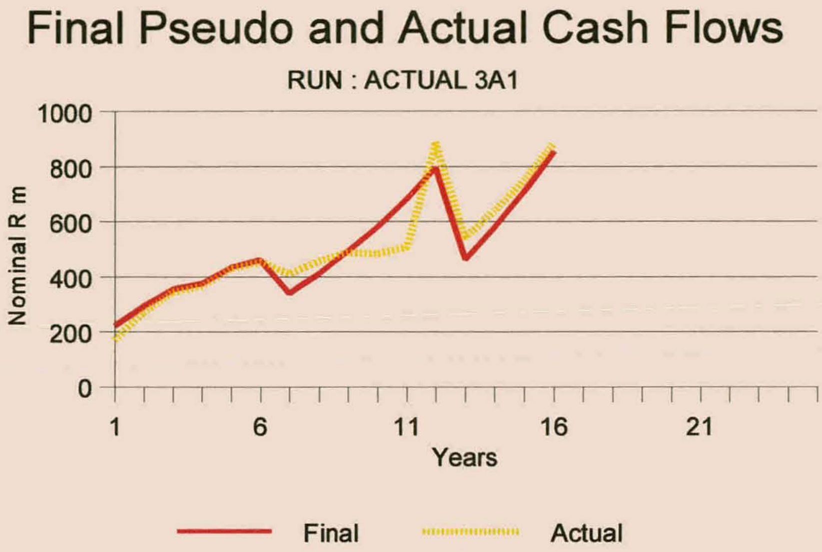
Project Scheduling : 4B
Priority
Project
11 11
10 10
9 9
8 8
7 7
6 6
5 5
4 4
3 3
2 2
1 1
1 25 49 73 97 121 145 169 193 217 241 265 288 312 336 360
Months
Final Schedule
Initial Schedule

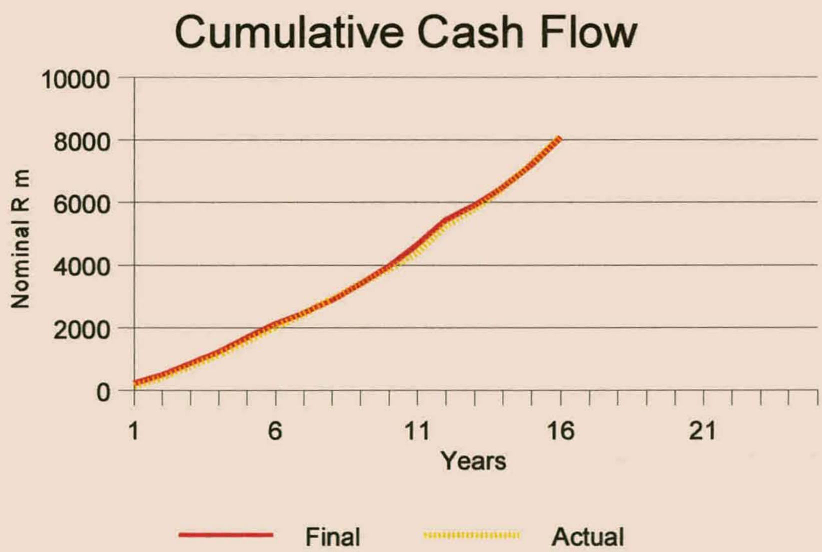

Final Pseudo and Actual Cash Flows
RUN : ACTUAL 3A
800
700
600
500
400
300
200
100
0
Nominal R m
1
6
11
16
21
Years
Final
Actual

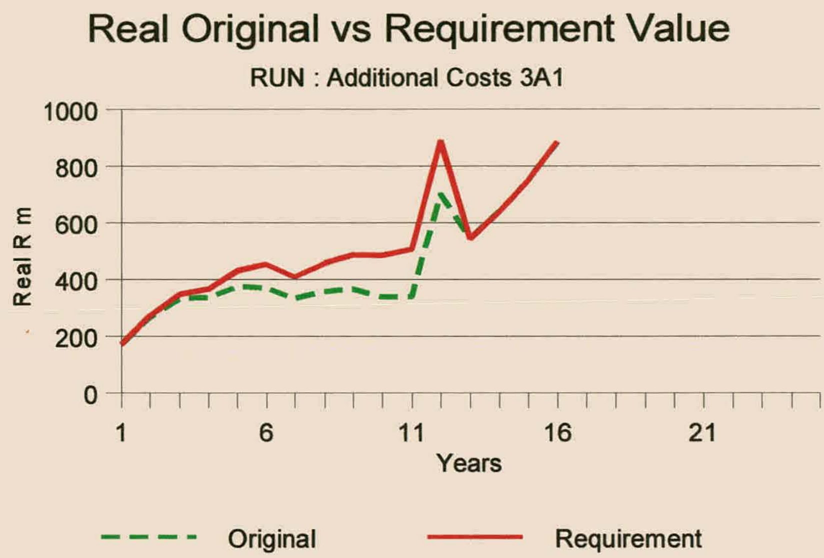

Cumulative Cash Flow
8000
7000
6000
5000
4000
3000
2000
1000
0
Nominal R m
1
6
11
16
21
Years
Final
Actual

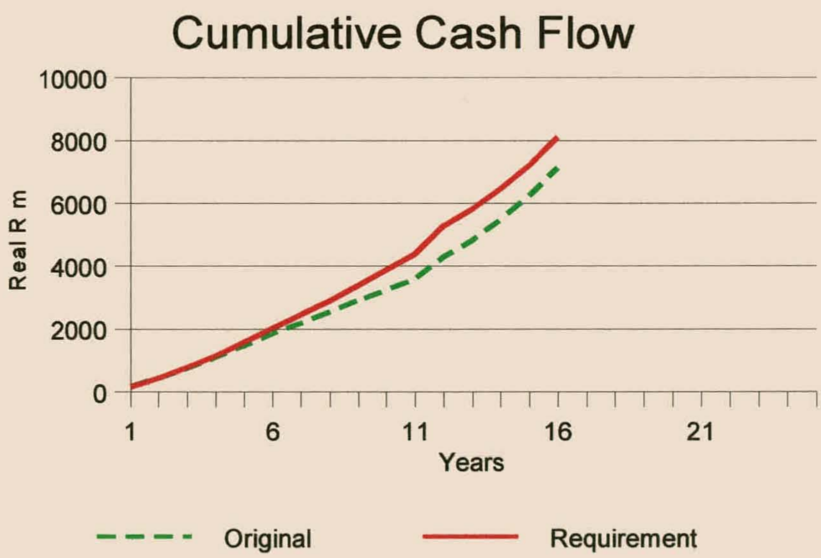

Real Original vs Requirement Value
RUN : Additional Costs 3A
Real R m
800
700
600
500
400
300
200
100
0
1
6
11
16
21
Years
Original
Requirement

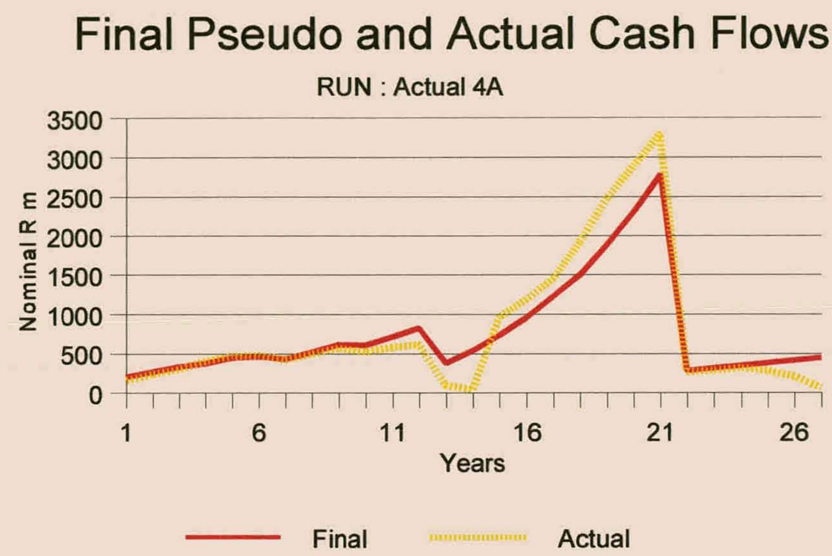

Cumulative Cash Flow
Real R m
8000
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
Years
Original
Requirement

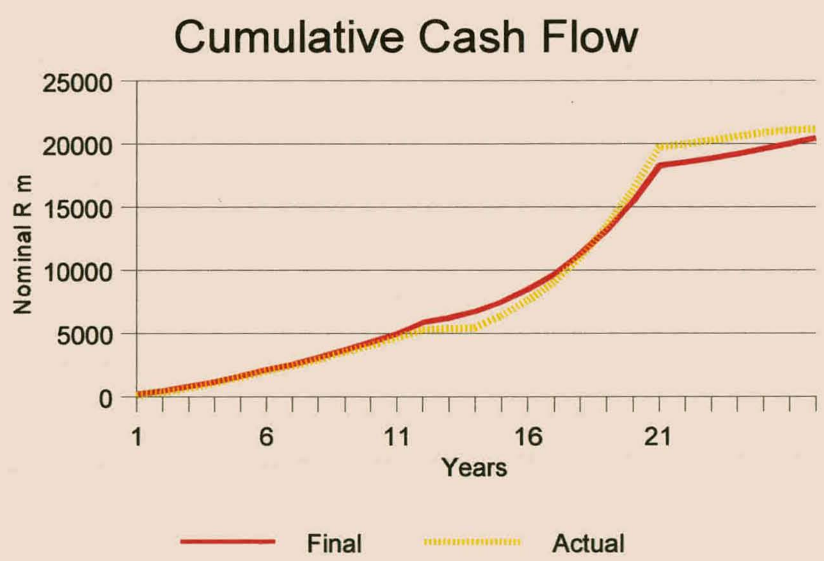

Final Pseudo and Actual Cash Flows
RUN : ACTUAL 3A1
1000
800
600
400
200
0
Nominal R m
1
6
11
16
21
Years
Final
Actual

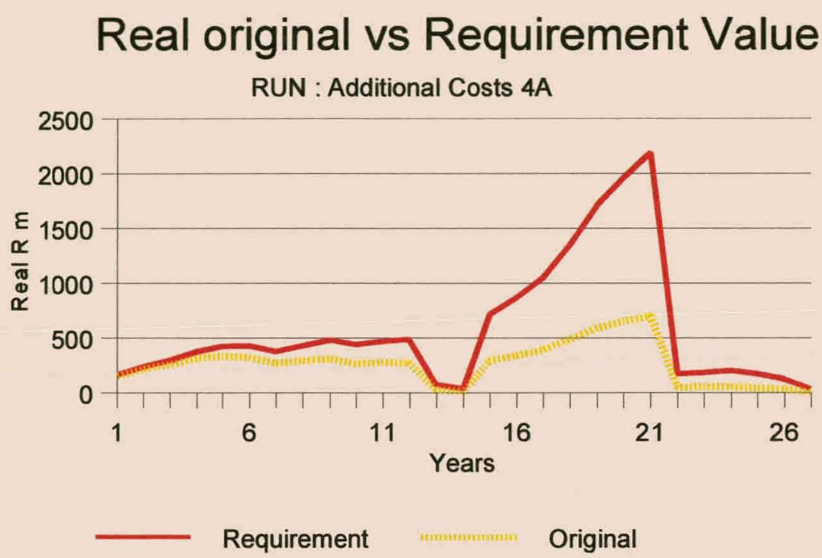

Cumulative Cash Flow
10000
8000
6000
4000
2000
0
Nominal R m
1
6
11
16
21
Years
Final
Actual

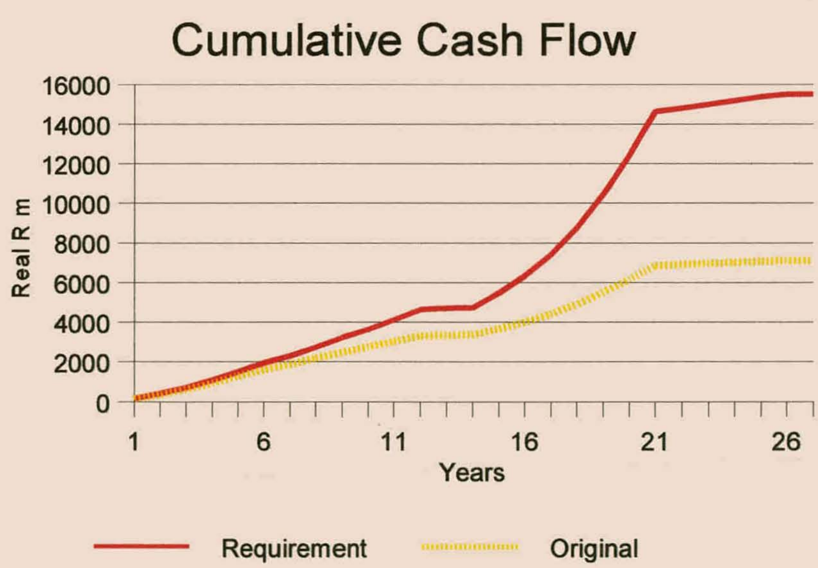

Real Original vs Requirement Value
RUN : Additional Costs 3A1
Real R m
1000
800
600
400
200
0
1
6
11
16
21
Years
Original
Requirement

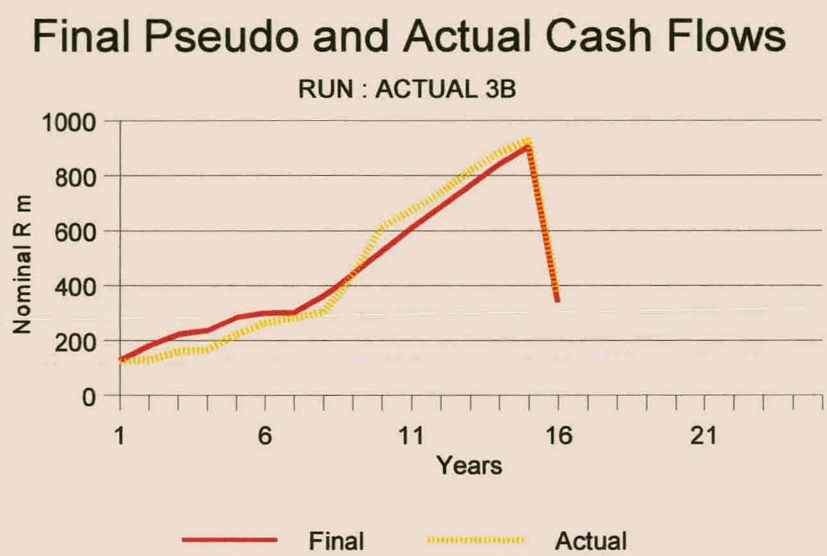

Cumulative Cash Flow
Real R m
10000
8000
6000
4000
2000
0
1
6
11
16
21
Years
Original
Requirement

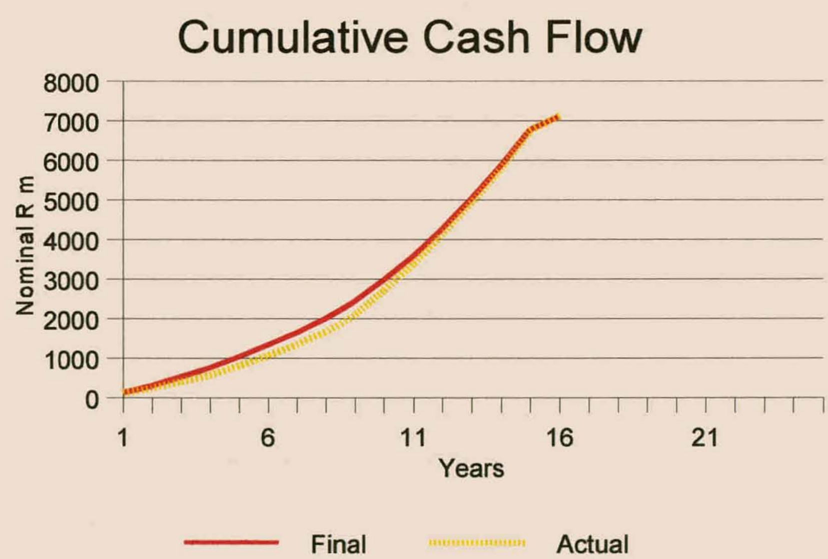

Final Pseudo and Actual Cash Flows
RUN : Actual 4A
Nominal R m
3500
3000
2500
2000
1500
1000
500
0
1
6
11
16
21
26
Years
Final
Actual

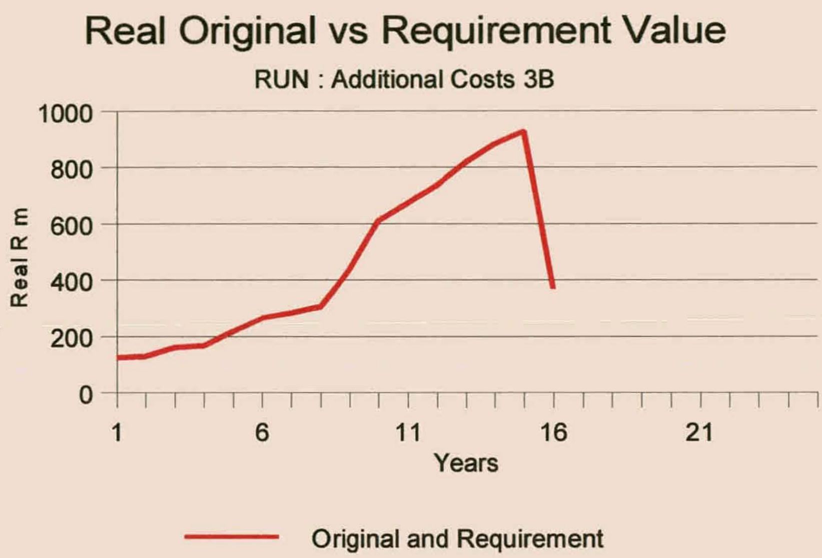

Cumulative Cash Flow
Nominal R m
25000
20000
15000
10000
5000
0
1
6
11
16
21
Years
Final
Actual

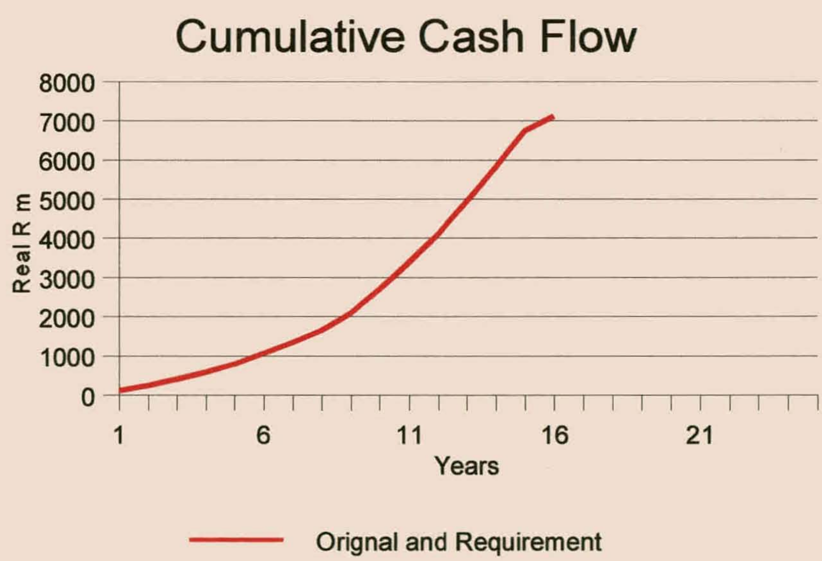

Real original vs Requirement Value
RUN : Additional Costs 4A
2500
2000
1500
1000
500
0
Real R m
1
6
11
16
21
26
Years
Requirement
Original

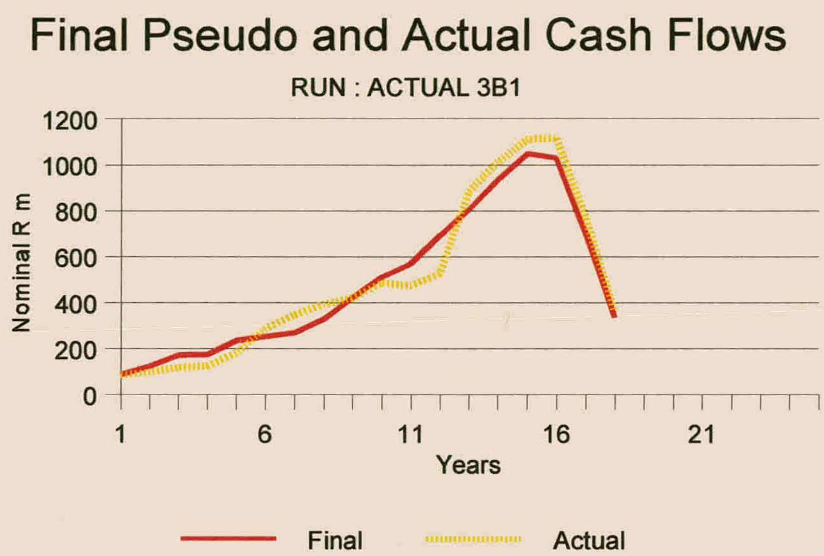

Cumulative Cash Flow
16000
14000
12000
10000
8000
6000
4000
2000
0
Real R m
1
6
11
16
21
26
Years
Requirement
Original

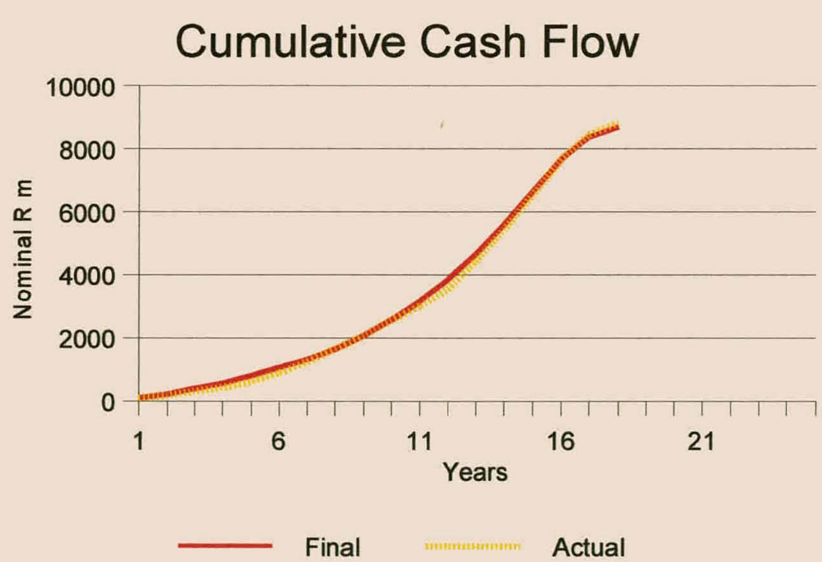

Final Pseudo and Actual Cash Flows
RUN : ACTUAL 3B
Nominal R m
1000
800
600
400
200
0
1
6
11
16
21
Years
Final
Actual

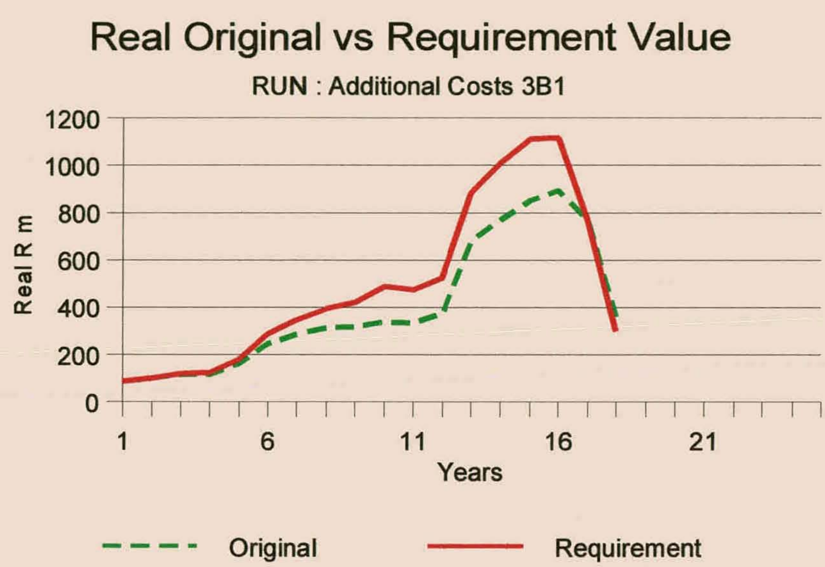

Cumulative Cash Flow
Nominal R m
8000
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
Years
Final
Actual

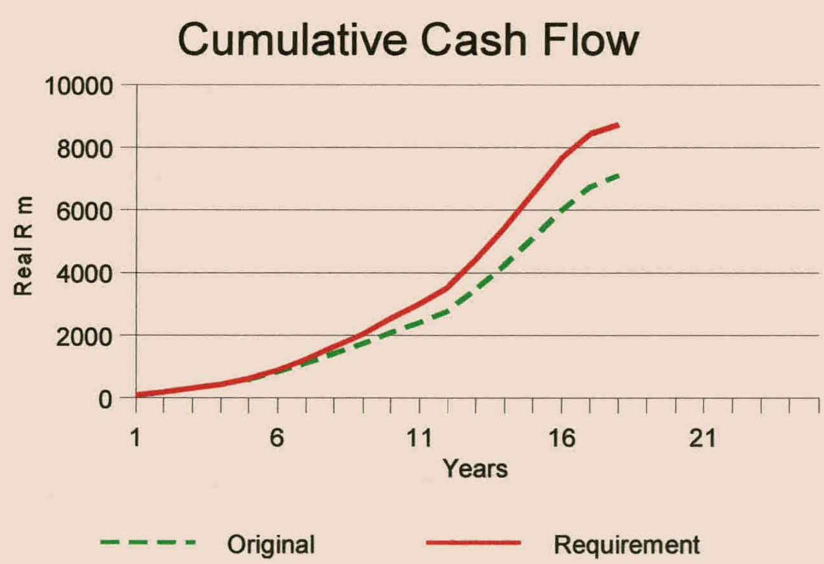

Real Original vs Requirement Value
RUN : Additional Costs 3B
Real R m
1000
800
600
400
200
0
1
6
11
16
21
Years
Original and Requirement

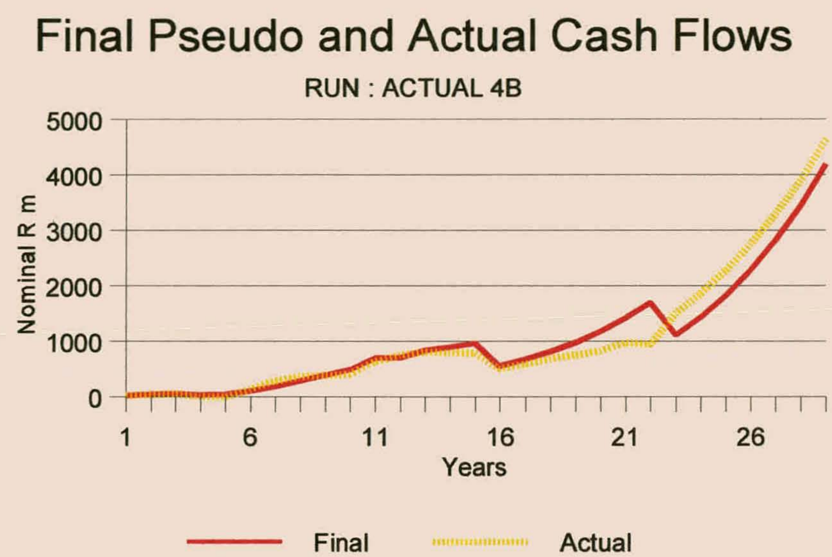

Cumulative Cash Flow
Real R m
8000
7000
6000
5000
4000
3000
2000
1000
0
1
6
11
16
21
Years
Orignal and Requirement

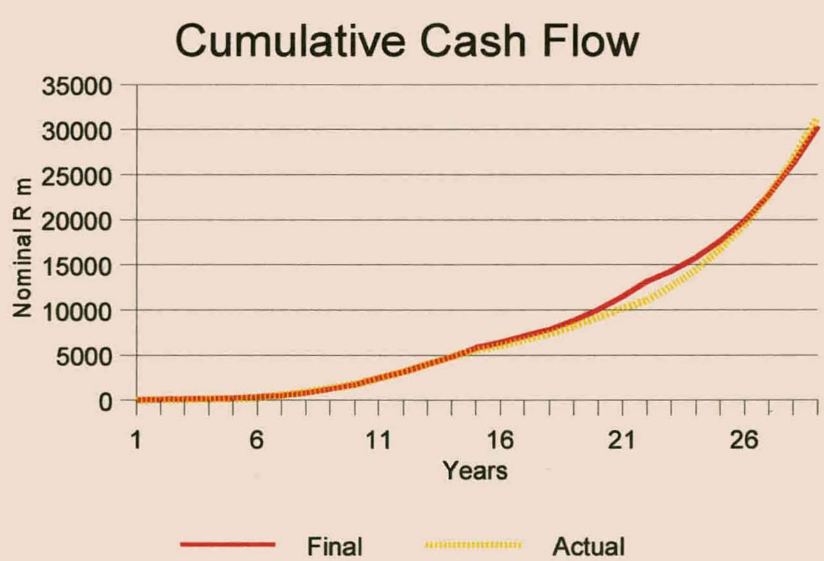

Final Pseudo and Actual Cash Flows
RUN : ACTUAL 3B1
1200
1000
800
600
400
200
0
Nominal R m
1
6
11
16
21
Years
Final
Actual

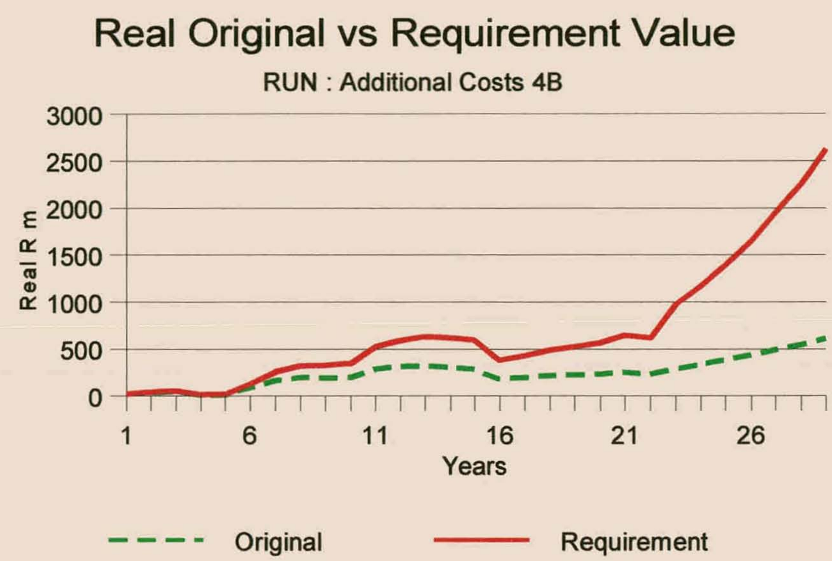

Cumulative Cash Flow
10000
8000
6000
4000
2000
0
Nominal R m
1
6
11
16
21
Years
Final
Actual

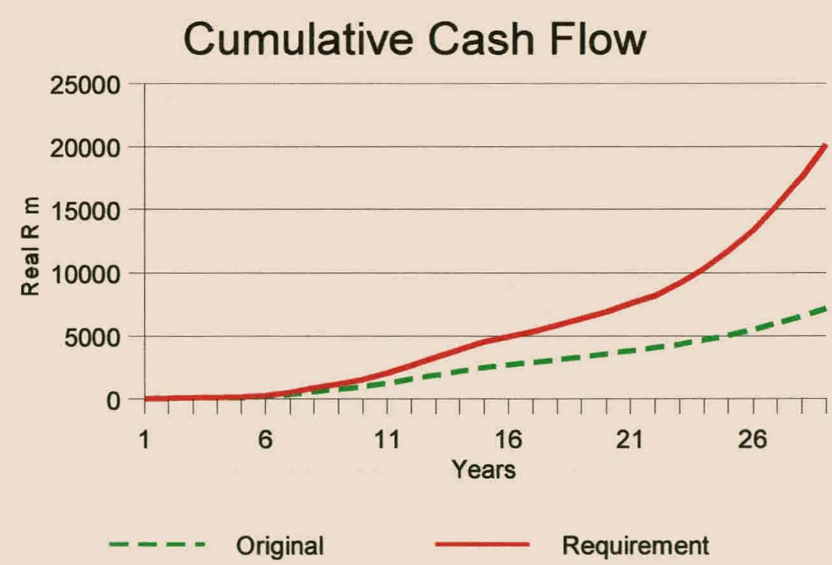

Real Original vs Requirement Value
RUN : Additional Costs 3B1
1200
1000
800
600
400
200
0
Real R m
1
6
11
16
21
Years
Original
Requirement

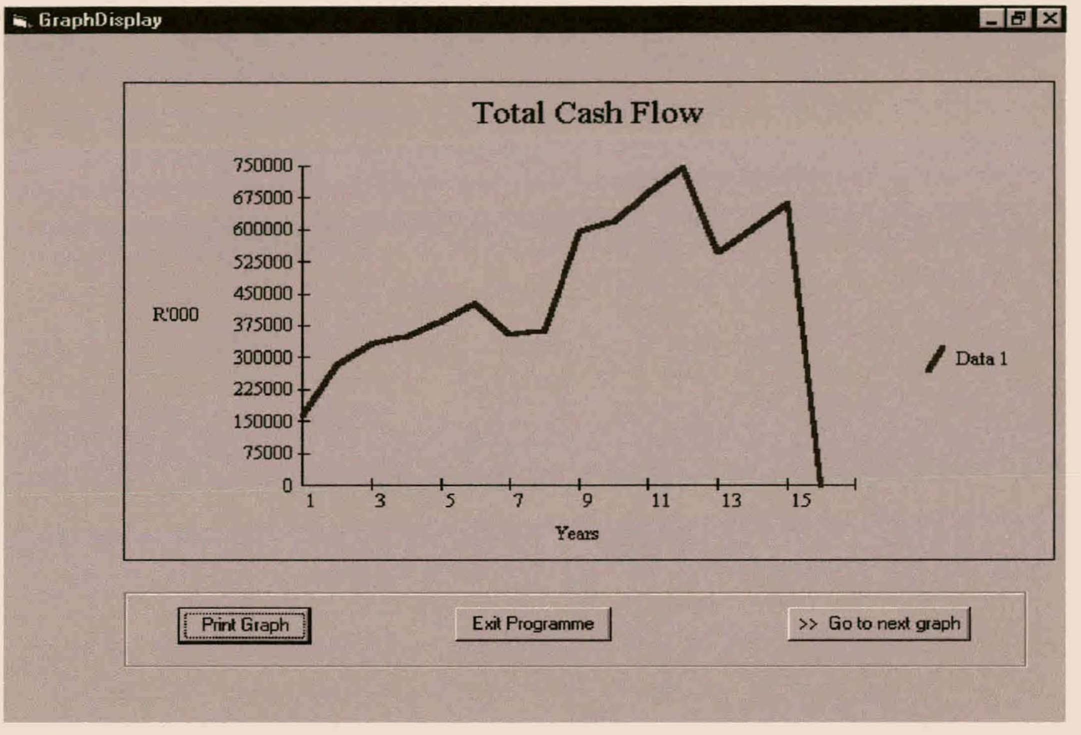

Cumulative Cash Flow
10000
8000
6000
4000
2000
0
Real R m
1
6
11
16
21
Years
Original
Requirement

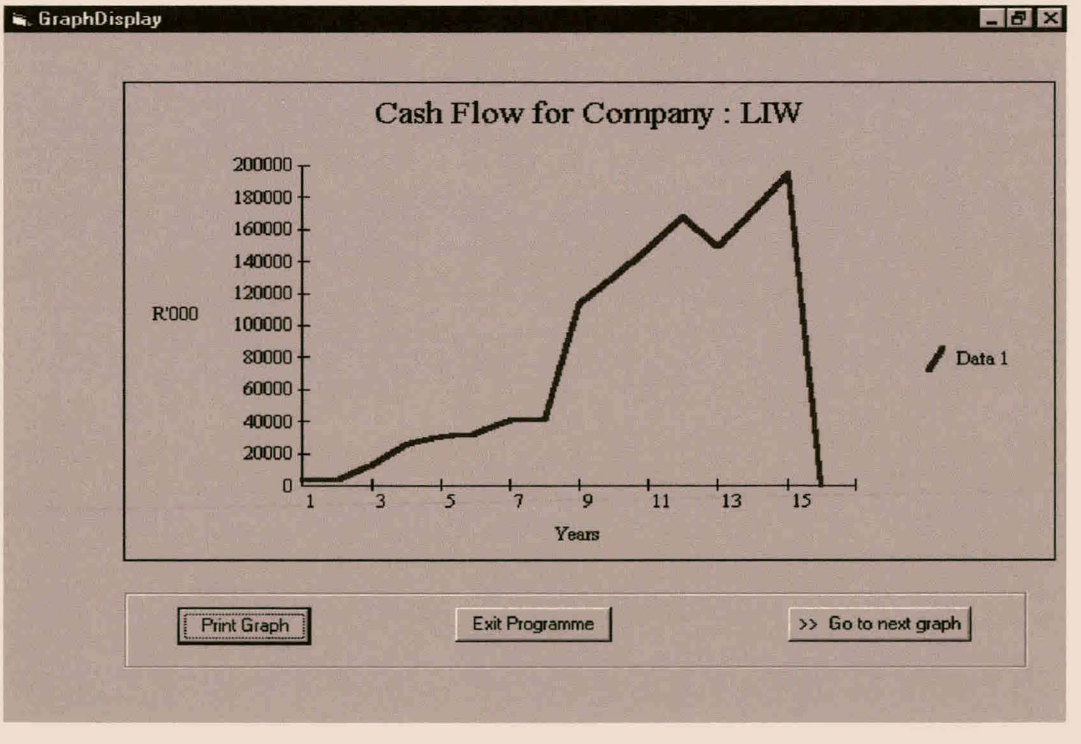

Final Pseudo and Actual Cash Flows
RUN : ACTUAL 4B
Nominal R m
5000
4000
3000
2000
1000
0
1
6
11
16
21
26
Years
Final
Actual

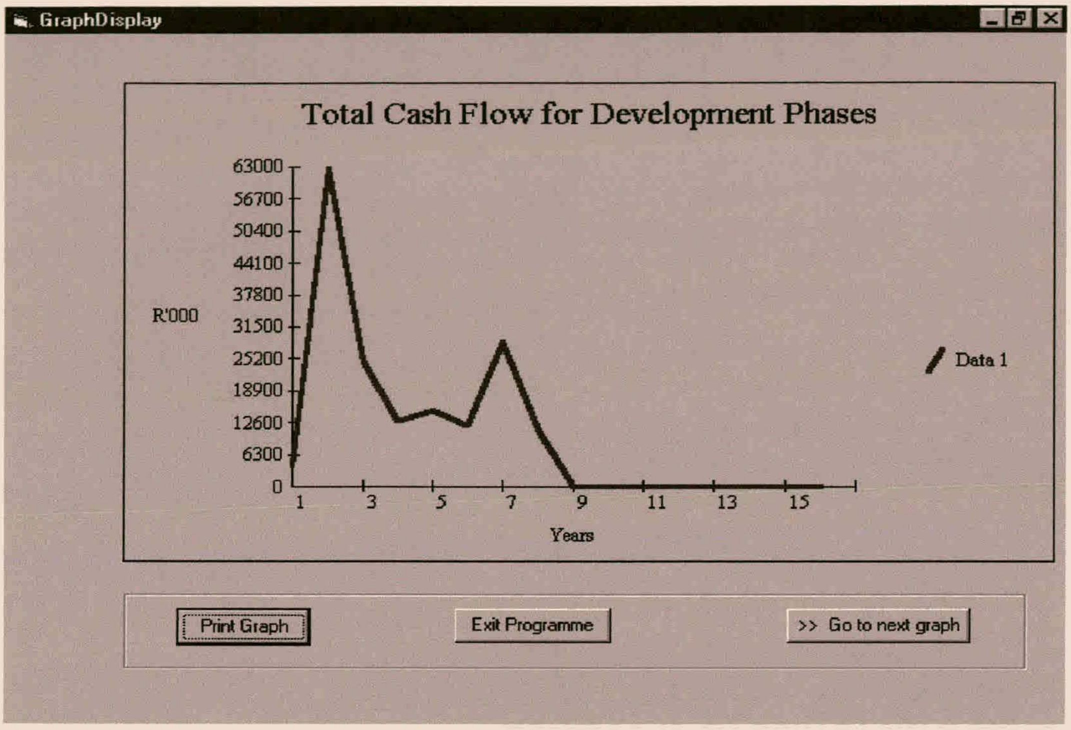

Cumulative Cash Flow
Nominal R m
35000
30000
25000
20000
15000
10000
5000
0
1
6
11
16
21
26
Years
Final
Actual

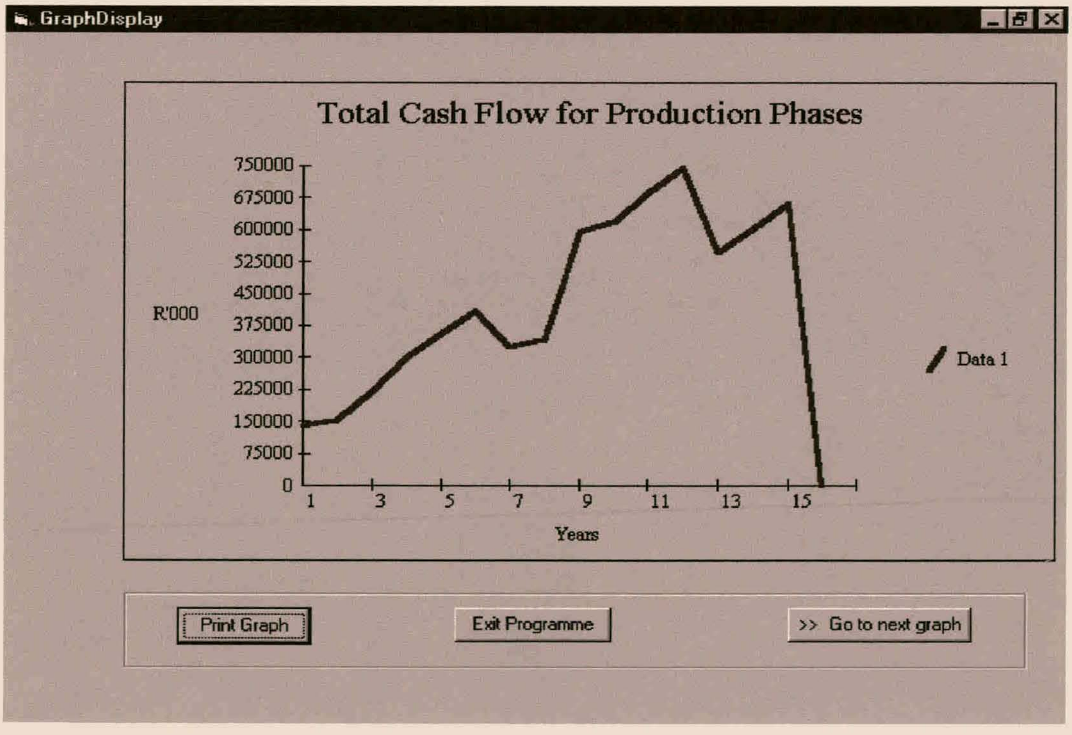

Real Original vs Requirement Value
RUN : Additional Costs 4B
3000
2500
2000
1500
1000
500
0
Real R m
1
6
11
16
21
26
Years
Original
Requirement

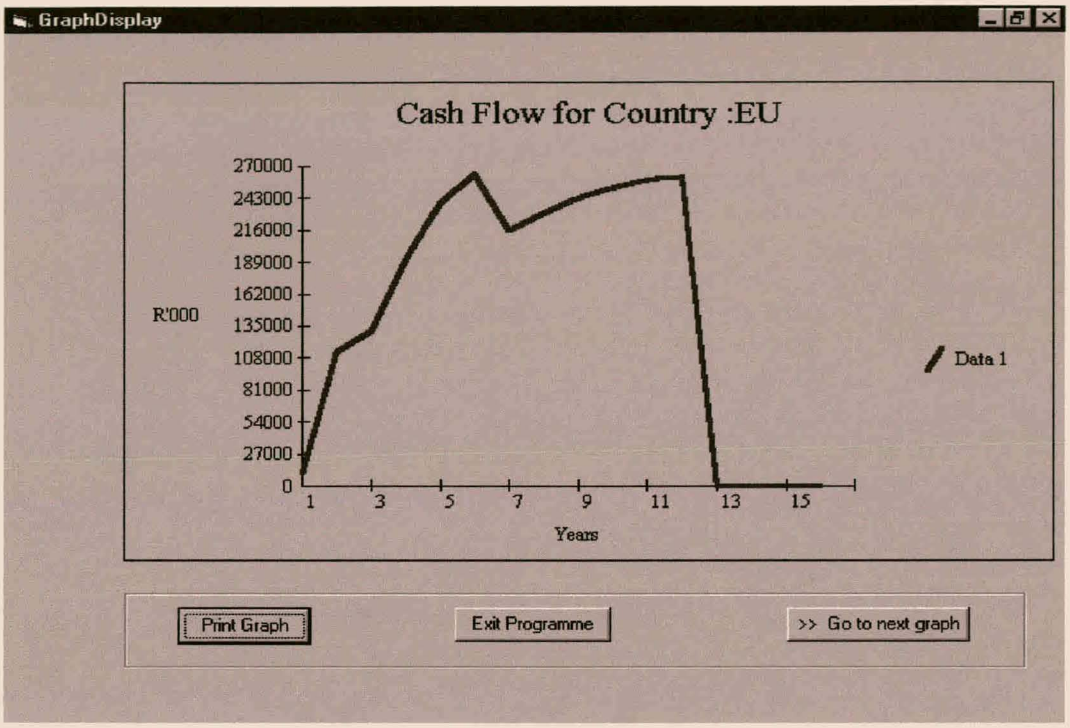

Cumulative Cash Flow
25000
20000
15000
10000
5000
0
Real R m
1
6
11
16
21
26
Years
Original
Requirement

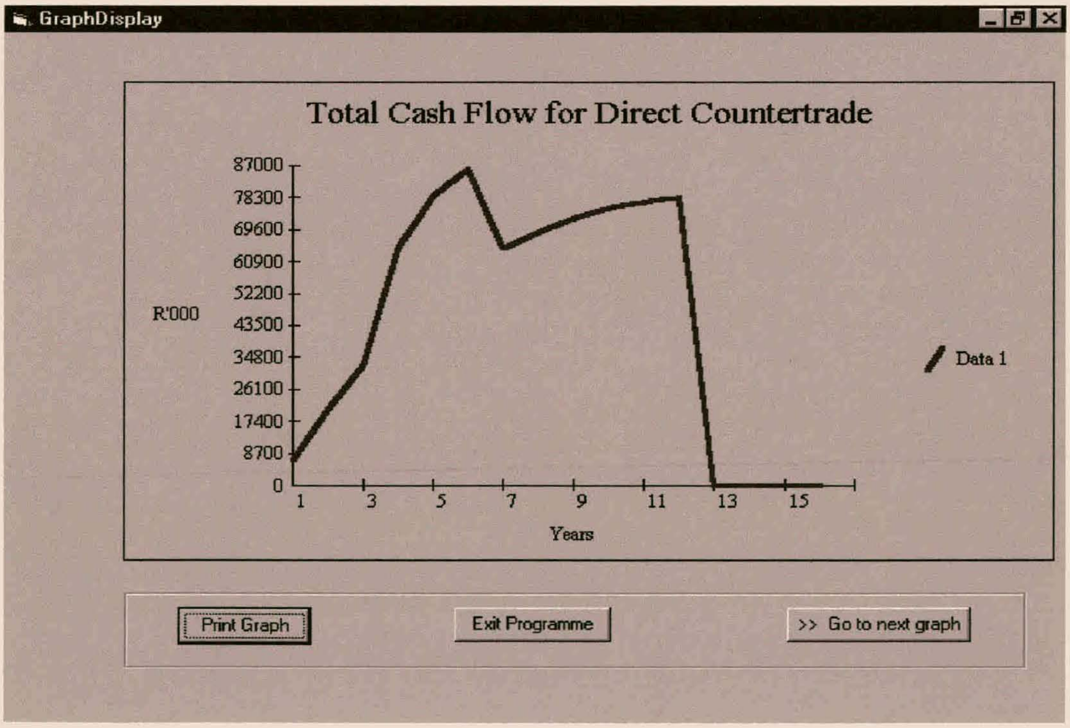

GraphDisplay
Total Cash Flow
750000
675000
600000
525000
450000
375000
300000
225000
150000
75000
0
R'000
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

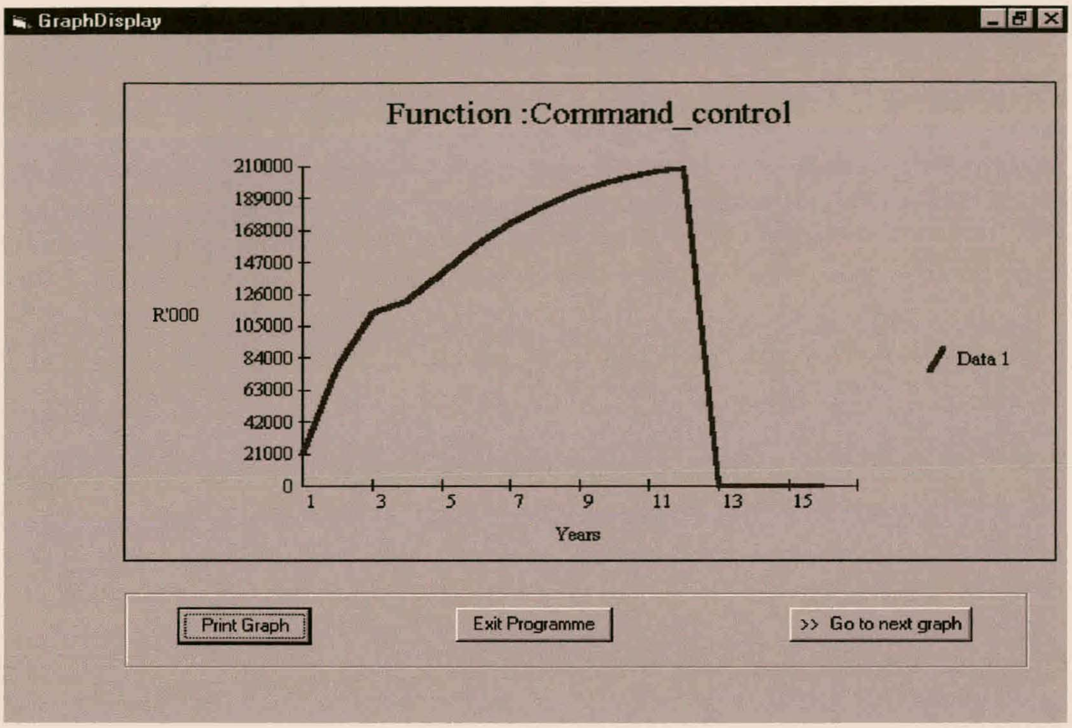

GraphDisplay
Cash Flow for Company : LIW
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
R'000
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

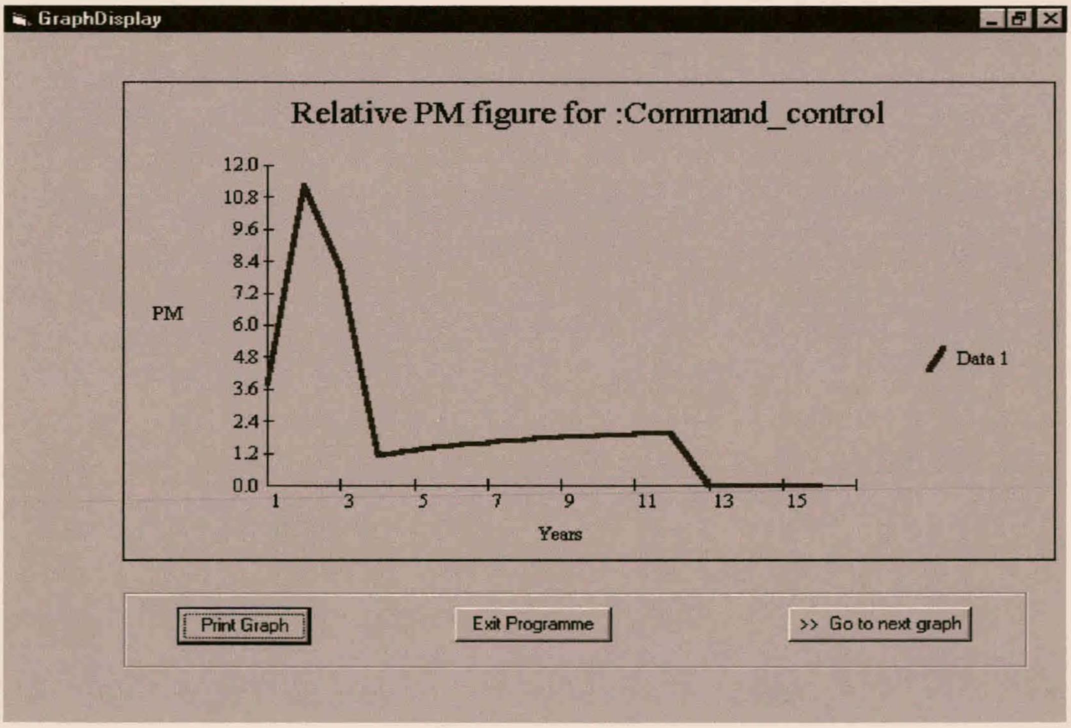

GraphDisplay
Total Cash Flow for Development Phases
63000
56700
50400
44100
37800
31500
25200
18900
12600
6300
0
R'000
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

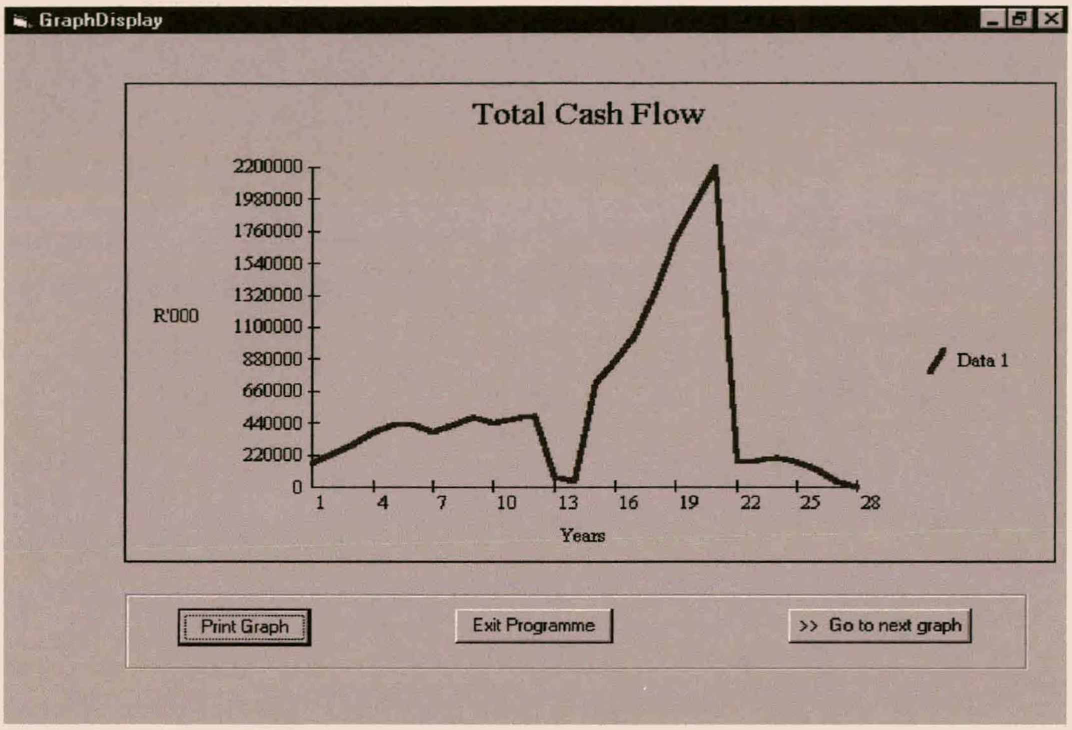

GraphDisplay
Total Cash Flow for Production Phases
750000
675000
600000
525000
450000
375000
300000
225000
150000
75000
0
R'000
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

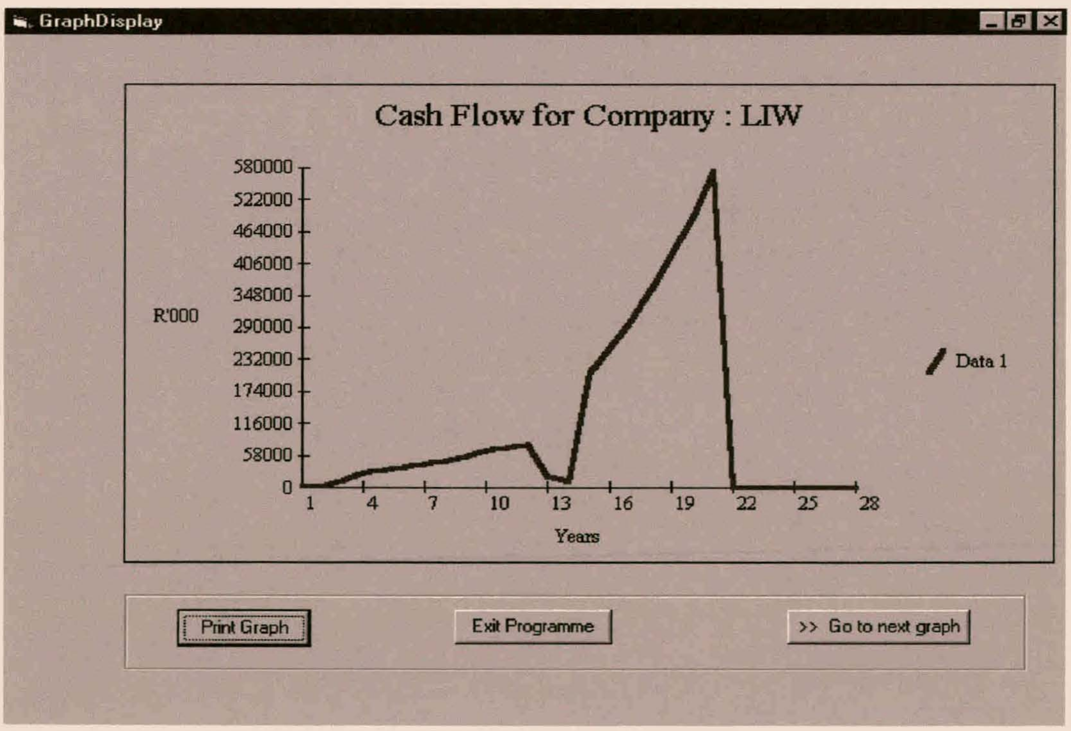

GraphDisplay
Cash Flow for Country :EU
270000
243000
216000
189000
162000
135000
108000
81000
54000
27000
0
R'000
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

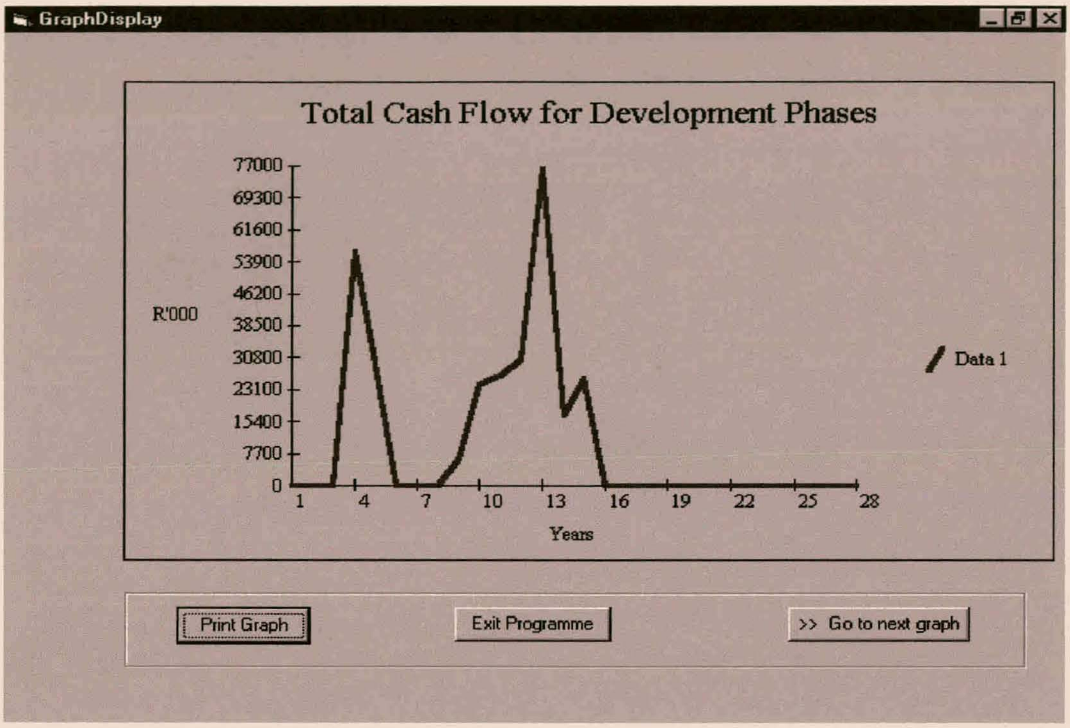

GraphDisplay
Total Cash Flow for Direct Countertrade
87000
78300
69600
60900
52200
43500
34800
26100
17400
8700
0
R'000
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

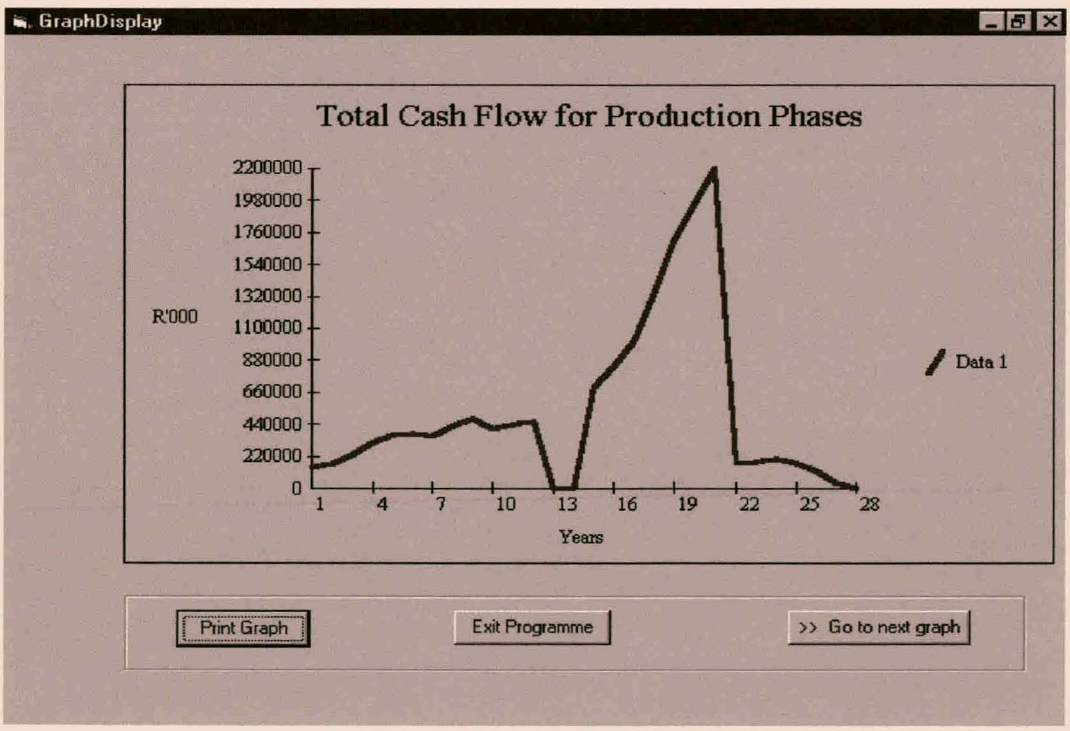

GraphDisplay
Function :Command_control
R'000
210000
189000
168000
147000
126000
105000
84000
63000
42000
21000
0
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

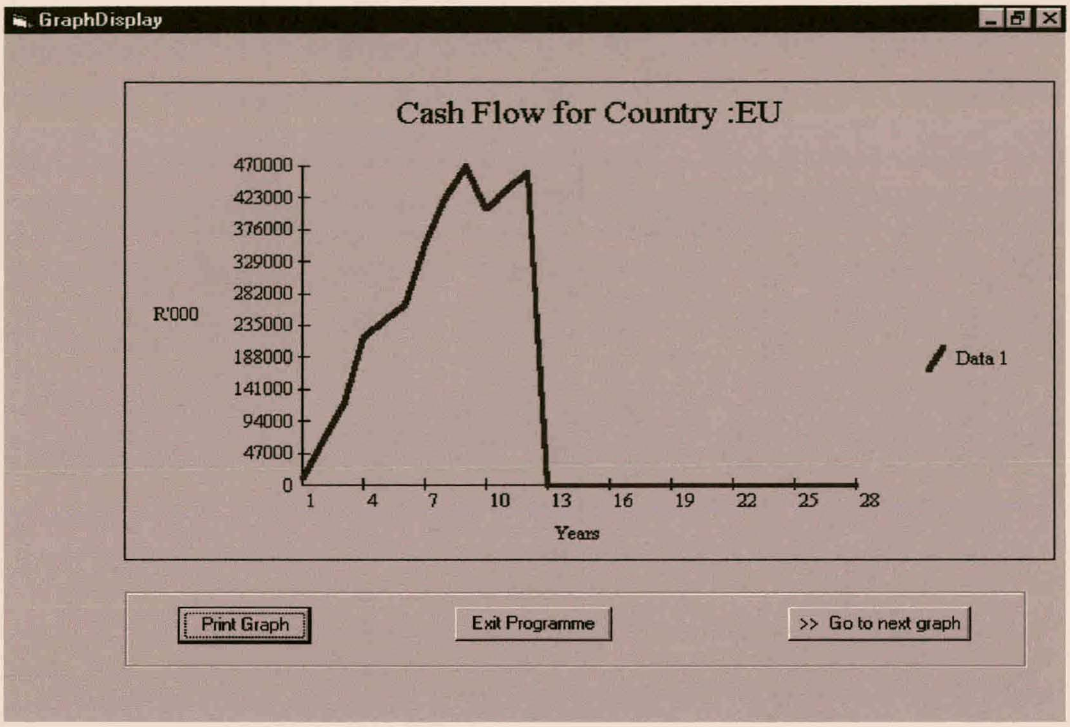

GraphDisplay
Relative PM figure for :Command_control
PM
12.0
10.8
9.6
8.4
7.2
6.0
4.8
3.6
2.4
1.2
0.0
1
3
5
7
9
11
13
15
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

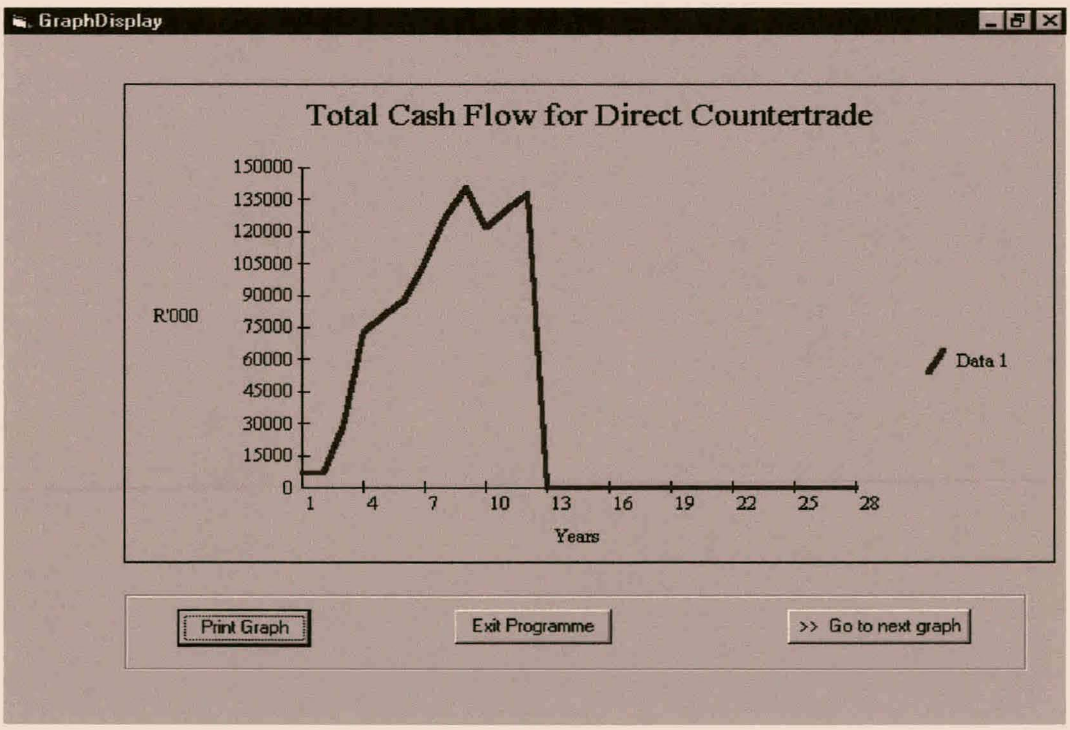

GraphDisplay
Total Cash Flow
2200000
1980000
1760000
1540000
1320000
1100000
880000
660000
440000
220000
0
R'000
1
4
7
10
13
16
19
22
25
28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

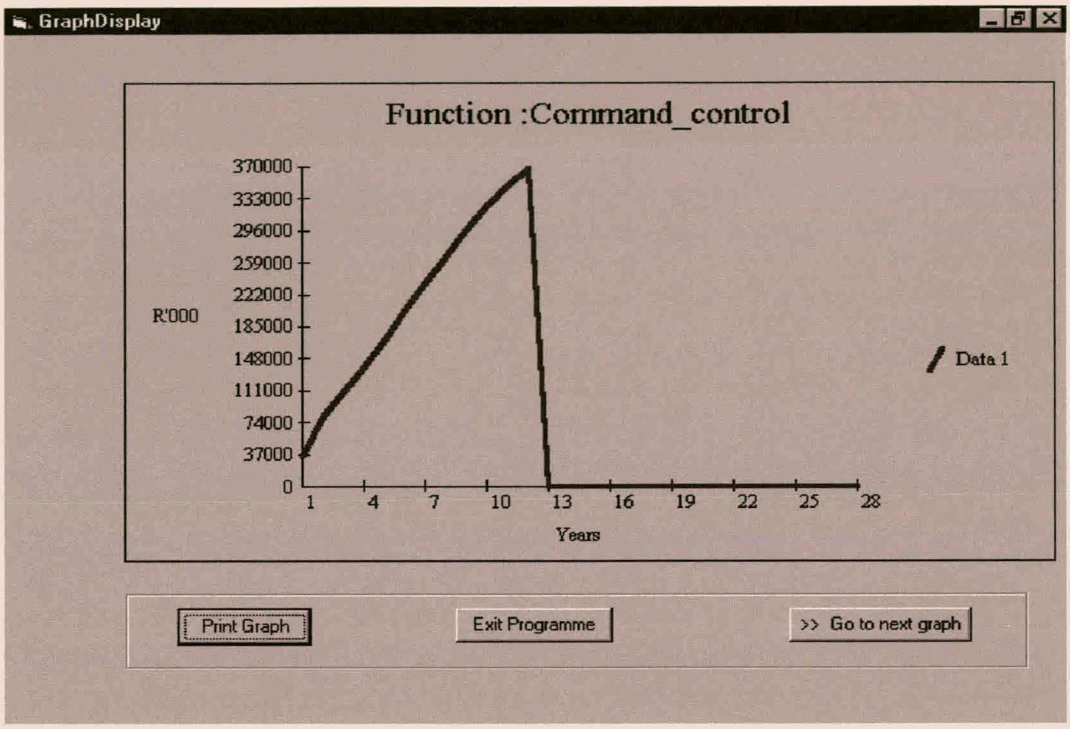

GraphDisplay
Cash Flow for Company : LIW
580000
522000
464000
406000
348000
290000
232000
174000
116000
58000
0
R'000
1
4
7
10
13
16
19
22
25
28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

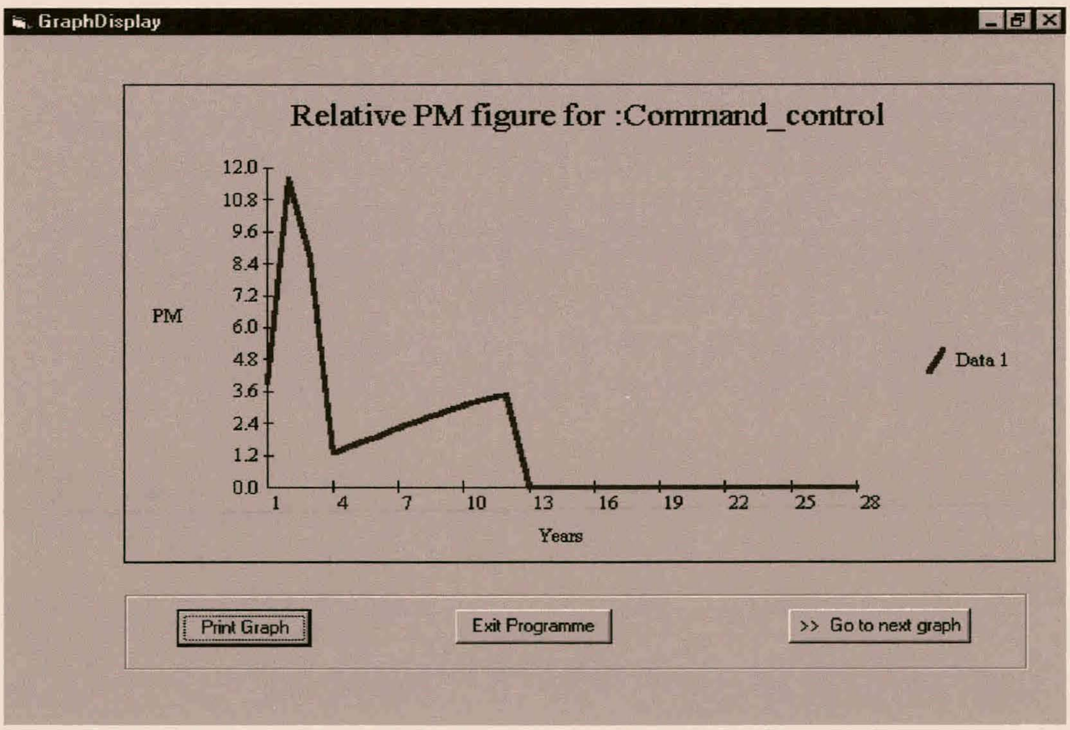

GraphDisplay
Total Cash Flow for Development Phases
77000
69300
61600
53900
46200
38500
30800
23100
15400
7700
0
R'000
1 4 7 10 13 16 19 22 25 28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph


GraphDisplay
Total Cash Flow for Production Phases
2200000
1980000
1760000
1540000
1320000
1100000
880000
660000
440000
220000
0
R'000
1 4 7 10 13 16 19 22 25 28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph


GraphDisplay
Cash Flow for Country :EU
470000
423000
376000
329000
282000
235000
188000
141000
94000
47000
0
R'000
1
4
7
10
13
16
19
22
25
28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph


GraphDisplay
Total Cash Flow for Direct Countertrade
150000
135000
120000
105000
90000
75000
60000
45000
30000
15000
0
R'000
1
4
7
10
13
16
19
22
25
28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph


GraphDisplay
Function :Command_control
370000
333000
296000
259000
222000
185000
148000
111000
74000
37000
0
R'000
1
4
7
10
13
16
19
22
25
28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph


GraphDisplay
Relative PM figure for :Command_control
12.0
10.8
9.6
8.4
7.2
6.0
4.8
3.6
2.4
1.2
0.0
PM
1
4
7
10
13
16
19
22
25
28
Years
Data 1
Print Graph
Exit Programme
>> Go to next graph

Appendix I:

Comparison of results at project level

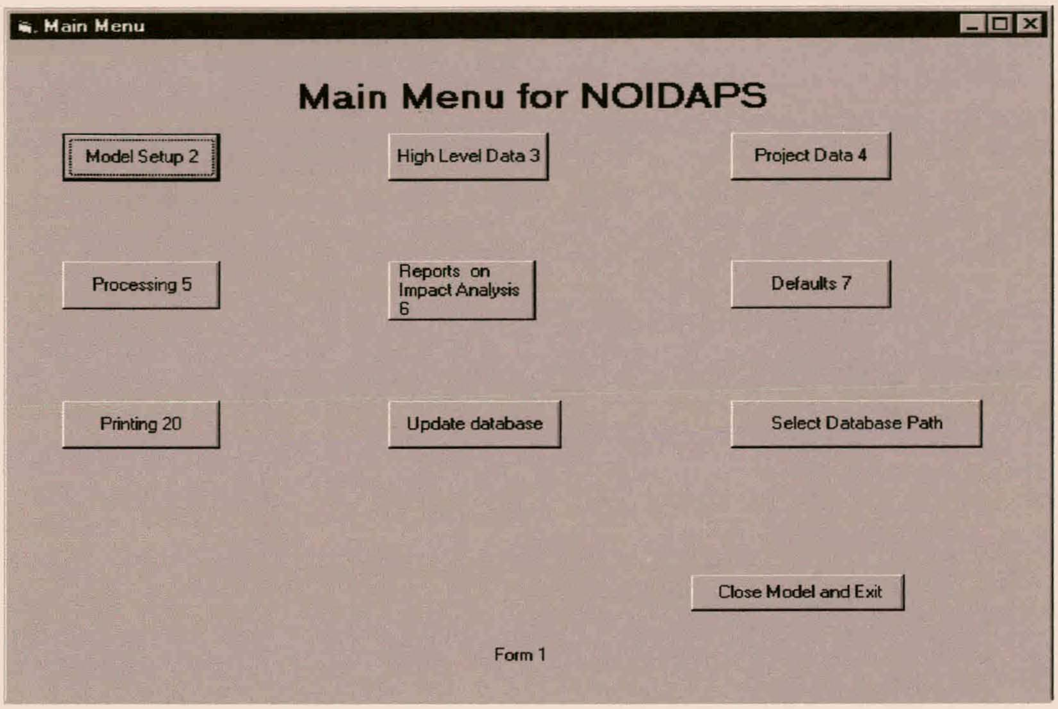
MINUMUM, MAXIMUM OR OTHER TIME SPAN PER PROJECT																																				
COMBINATION				P1 FROM 36 TO 40			P2 FROM 30 TO 36			P3 FROM 65 TO 73			P4 FROM 69 TO 75			P5 FROM 179 TO 212			P6 FROM 100 TO 114			P7 FROM 64 TO 86			P8 FROM 55 TO 65			P9 FROM 33 TO 39			P10 FROM 138 TO 174			P11 FROM 132 TO 198		
1	2	3	4	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX	MIN	OTHER	MAX
0%	MIN	MIX	1A	X					X	X				72		X			X				72		X				34		X				179	
0%	MIN	SEQ	1B	X					X	X				72		X					X			X			X			X			X		191	
0%	MIN	MIX	3A	X			X				72			72			180		X				72			60			36			144			180	
0%	MIN	SEQ	3B	X					X	X				72		X					X			X			X			X			X		185	
0%	AVE	MIX	1C	X					X	X				72			192		X				72		X			X			X				192	
0%	AVE	SEQ	1D	X					X	X				72		X					X			X			X			X			X		192	
+X	MIN	MIX	3A1	X					X		72			72			192		X				68			60			36			144		X		
+X	MIN	SEQ	3B1	X				31		X			X			X					X			X			X			X			X		138	
+%	MIN	MIX	2A	X			X				72			72		X			X				84			60		X			X					X
+%	MIN	SEQ	2B	X			X			X					X	X					X			X			X			X			X			X
+%	MIN	MIX	4A	X			X				72			72		X			X					X	X			X				144				X
+%	MIN	SEQ	4B	X			X			X			X			X			X			X			X			X					X			X
+%	AVE	MIX	2C	X			X				72			72		X			X				84			60		X			X					X
+%	AVE	SEQ	2D	X			X			X					X	X					X			X			X			X			X			X

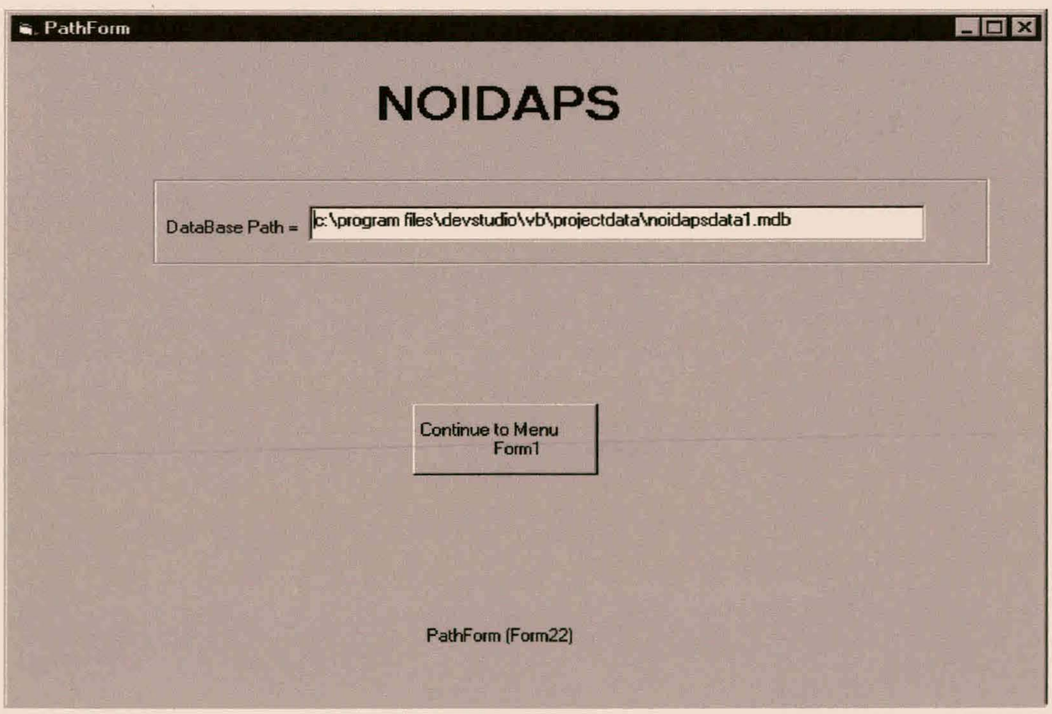
Notes on combination column:

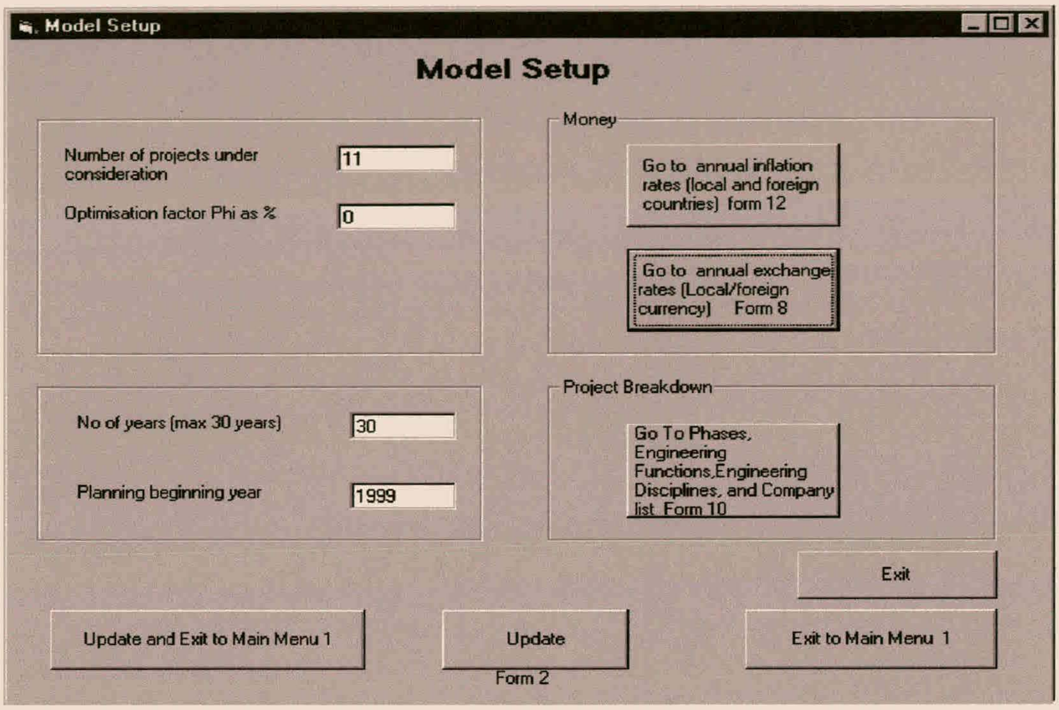
1. Zero percent escalation vs a percentage escalation
2. Minimum project duration vs average project duration
3. Mixed vs sequential priorities
4. Computer run number

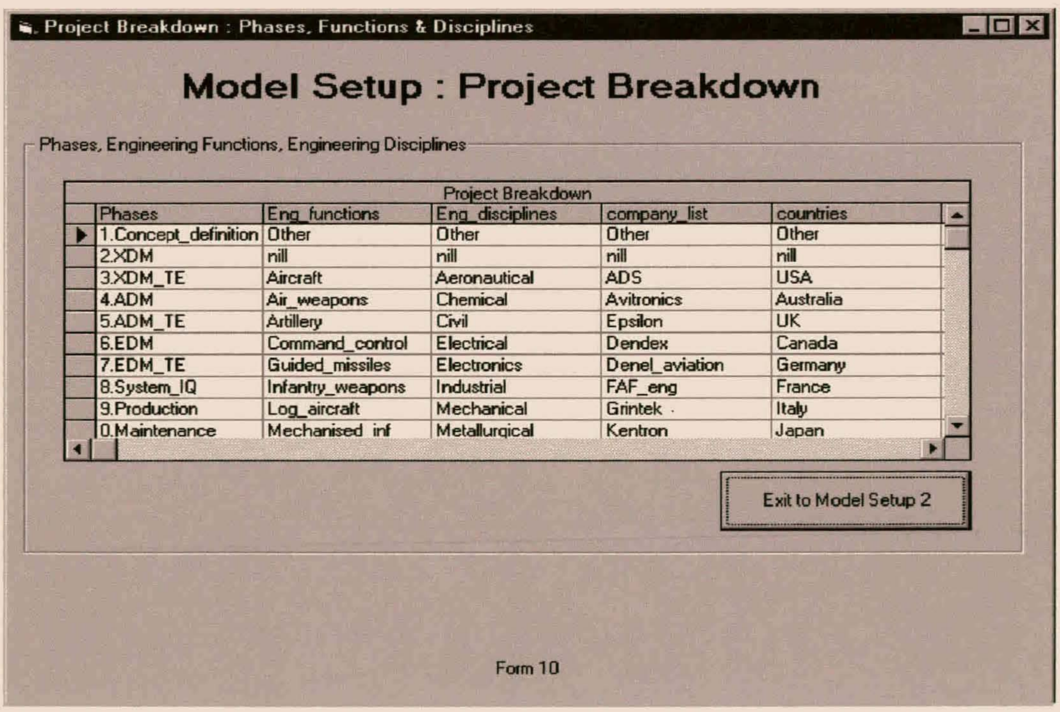
Appendix J

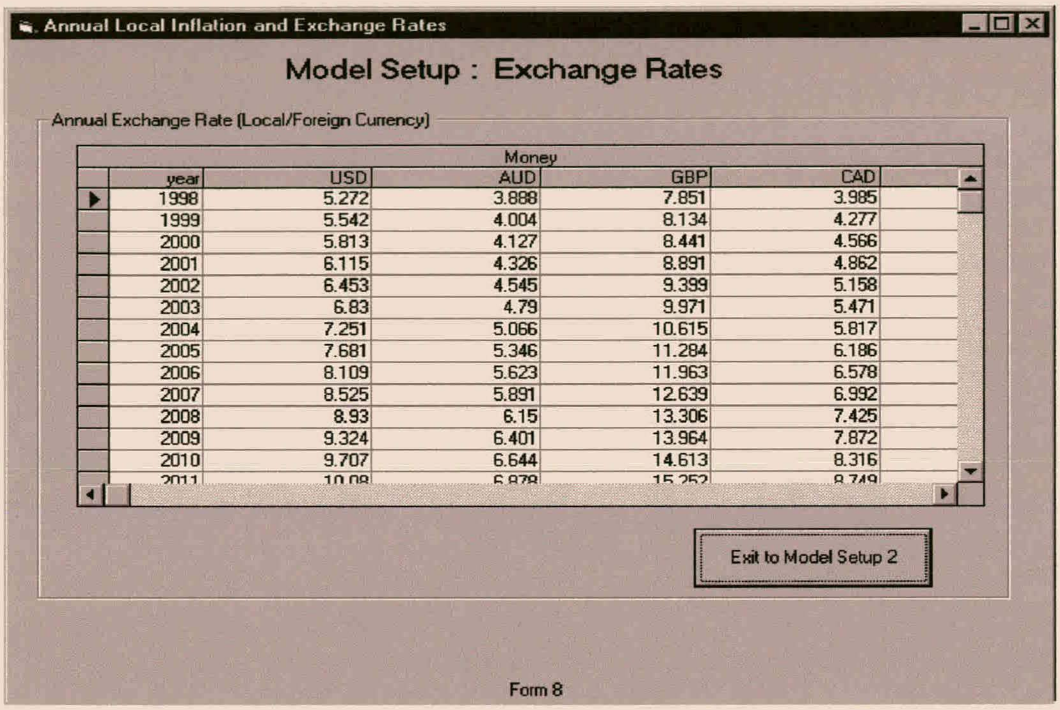
Screen menus






Model Setup
Model Setup
Number of projects under consideration
11
Optimisation factor Phi as %
0
Money
Go to annual inflation rates (local and foreign countries) form 12
Go to annual exchange rates (Local/foreign currency) Form 8
No of years (max 30 years)
30
Planning beginning year
1999
Project Breakdown
Go To Phases, Engineering Functions,Engineering Disciplines, and Company list Form 10
Exit
Update and Exit to Main Menu 1
Update
Exit to Main Menu 1
Form 2


Project Breakdown : Phases, Functions & Disciplines
Model Setup : Project Breakdown
Phases, Engineering Functions, Engineering Disciplines
Project Breakdown
Phases | Eng_functions | Eng_disciplines | company_list | countries
1.Concept_definition | Other | Other | Other | Other
2.XDM | nill | nill | nill | nill
3.XDM_TE | Aircraft | Aeronautical | ADS | USA
4.ADM | Air_weapons | Chemical | Avitronics | Australia
5.ADM_TE | Artillery | Civil | Epsilon | UK
6.EDM | Command_control | Electrical | Dendex | Canada
7.EDM_TE | Guided_missiles | Electronics | Denel_aviation | Germany
8.System_IQ | Infantry_weapons | Industrial | FAF_eng | France
9.Production | Log_aircraft | Mechanical | Grintek | Italy
0.Maintenance | Mechanised_inf | Metallurgical | Kentron | Japan
Exit to Model Setup 2
Form 10



Annual Local Inflation and Exchange Rates

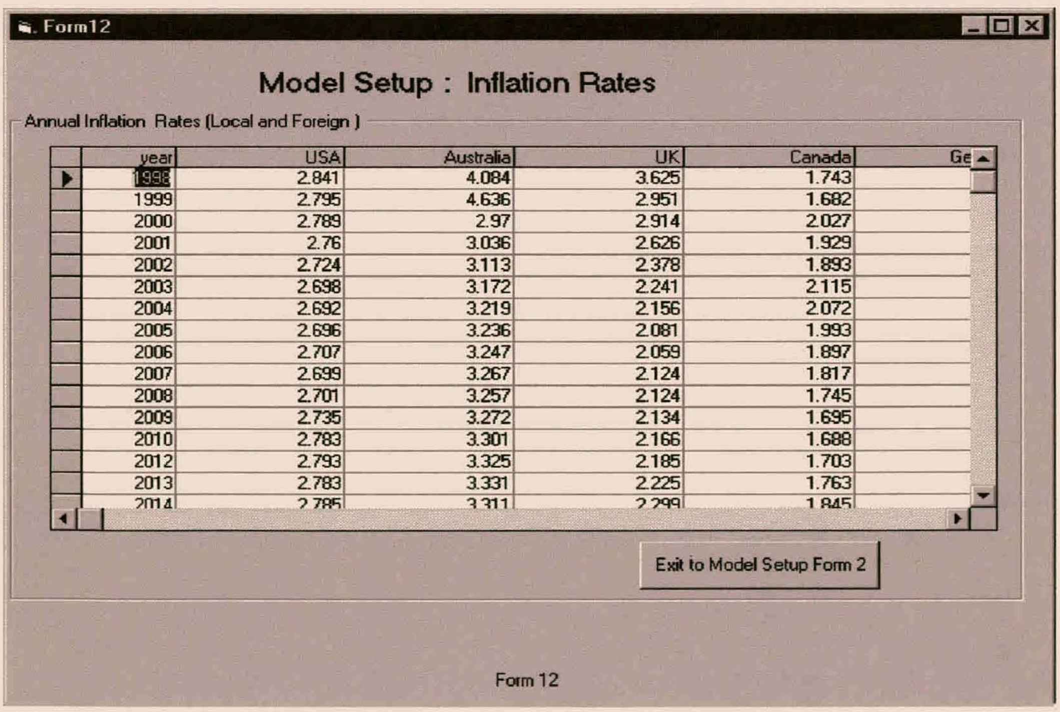
Model Setup : Exchange Rates

Annual Exchange Rate (Local/Foreign Currency)

	Money			
year	USD	AUD	GBP	CAD
1998	5.272	3.888	7.851	3.985
1999	5.542	4.004	8.134	4.277
2000	5.813	4.127	8.441	4.566
2001	6.115	4.326	8.891	4.862
2002	6.453	4.545	9.399	5.158
2003	6.83	4.79	9.971	5.471
2004	7.251	5.066	10.615	5.817
2005	7.681	5.346	11.284	6.186
2006	8.109	5.623	11.963	6.578
2007	8.525	5.891	12.639	6.992
2008	8.93	6.15	13.306	7.425
2009	9.324	6.401	13.964	7.872
2010	9.707	6.644	14.613	8.316
2011	10.08	6.879	15.252	8.749

Exit to Model Setup 2

Form 8



Form12

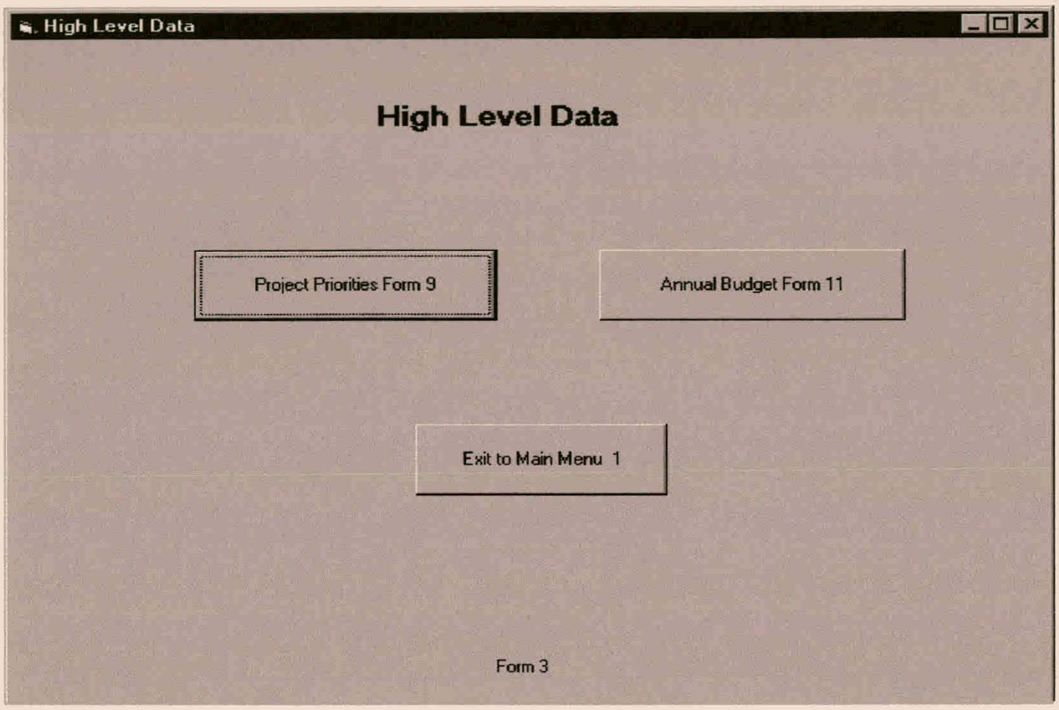
Model Setup : Inflation Rates

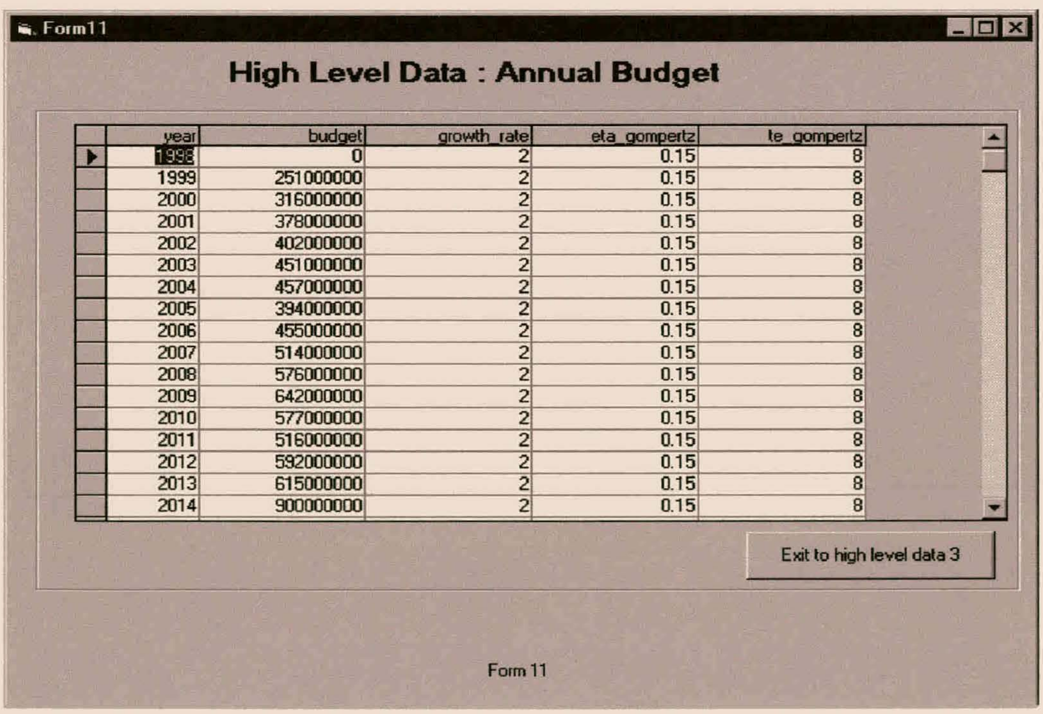
Annual Inflation Rates (Local and Foreign)

year	USA	Australia	UK	Canada	Ge
1998	2.841	4.084	3.625	1.743	
1999	2.795	4.636	2.951	1.682	
2000	2.789	2.97	2.914	2.027	
2001	2.76	3.036	2.626	1.929	
2002	2.724	3.113	2.378	1.893	
2003	2.698	3.172	2.241	2.115	
2004	2.692	3.219	2.156	2.072	
2005	2.696	3.236	2.081	1.993	
2006	2.707	3.247	2.059	1.897	
2007	2.699	3.267	2.124	1.817	
2008	2.701	3.257	2.124	1.745	
2009	2.735	3.272	2.134	1.695	
2010	2.783	3.301	2.166	1.688	
2012	2.793	3.325	2.185	1.703	
2013	2.783	3.331	2.225	1.763	
2014	2.785	3.311	2.299	1.845	

Exit to Model Setup Form 2

Form 12



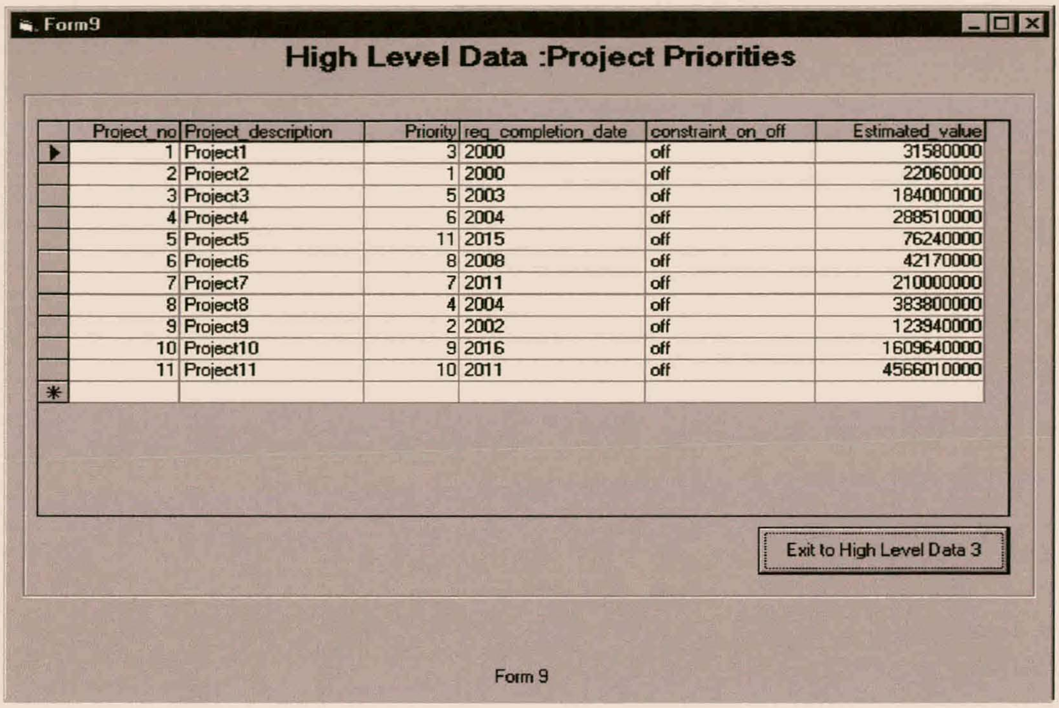

Form11

High Level Data : Annual Budget

year	budget	growth_rate	eta_gompertz	te_gompertz
1998	0	2	0.15	8
1999	251000000	2	0.15	8
2000	316000000	2	0.15	8
2001	378000000	2	0.15	8
2002	402000000	2	0.15	8
2003	451000000	2	0.15	8
2004	457000000	2	0.15	8
2005	394000000	2	0.15	8
2006	455000000	2	0.15	8
2007	514000000	2	0.15	8
2008	576000000	2	0.15	8
2009	642000000	2	0.15	8
2010	577000000	2	0.15	8
2011	516000000	2	0.15	8
2012	592000000	2	0.15	8
2013	615000000	2	0.15	8
2014	900000000	2	0.15	8

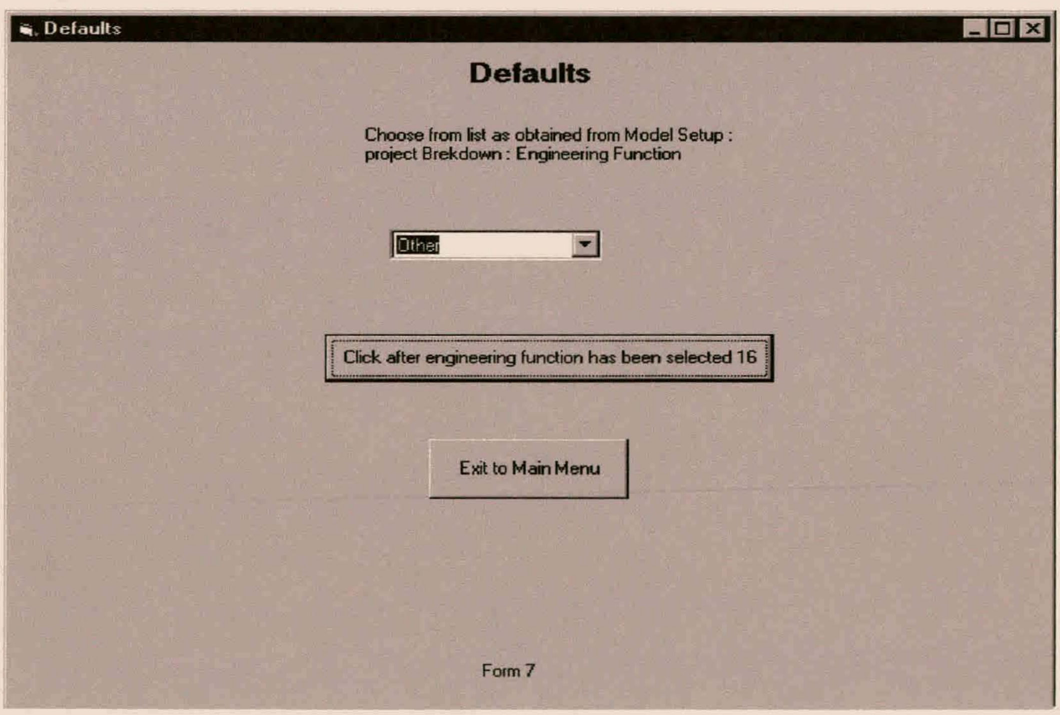
Exit to high level data 3

Form 11

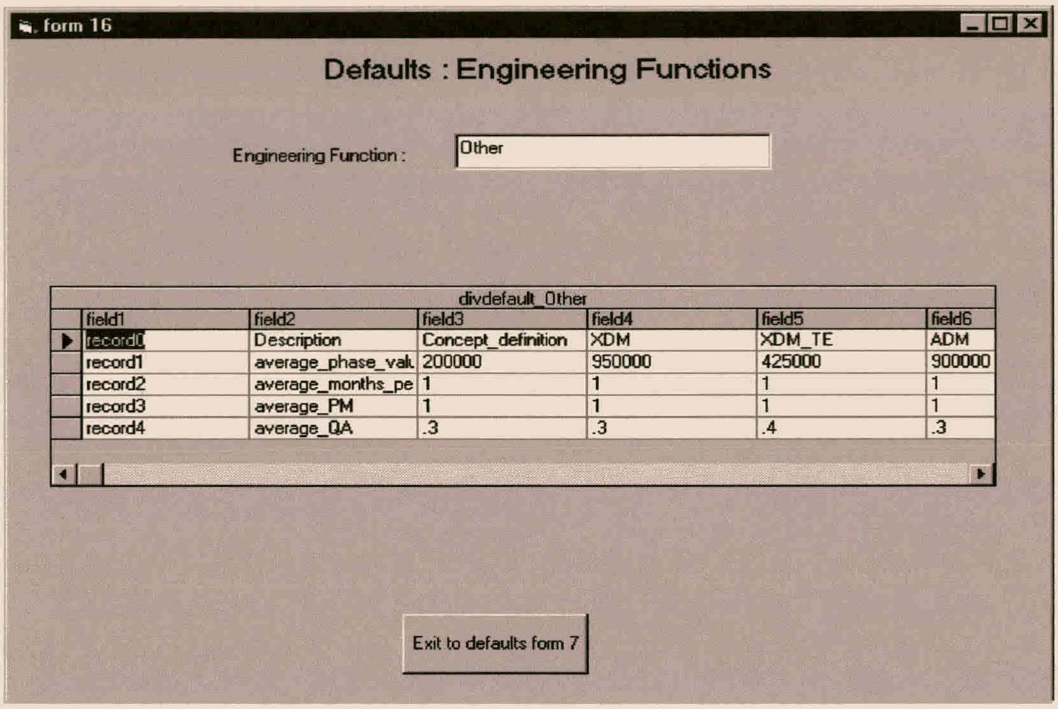


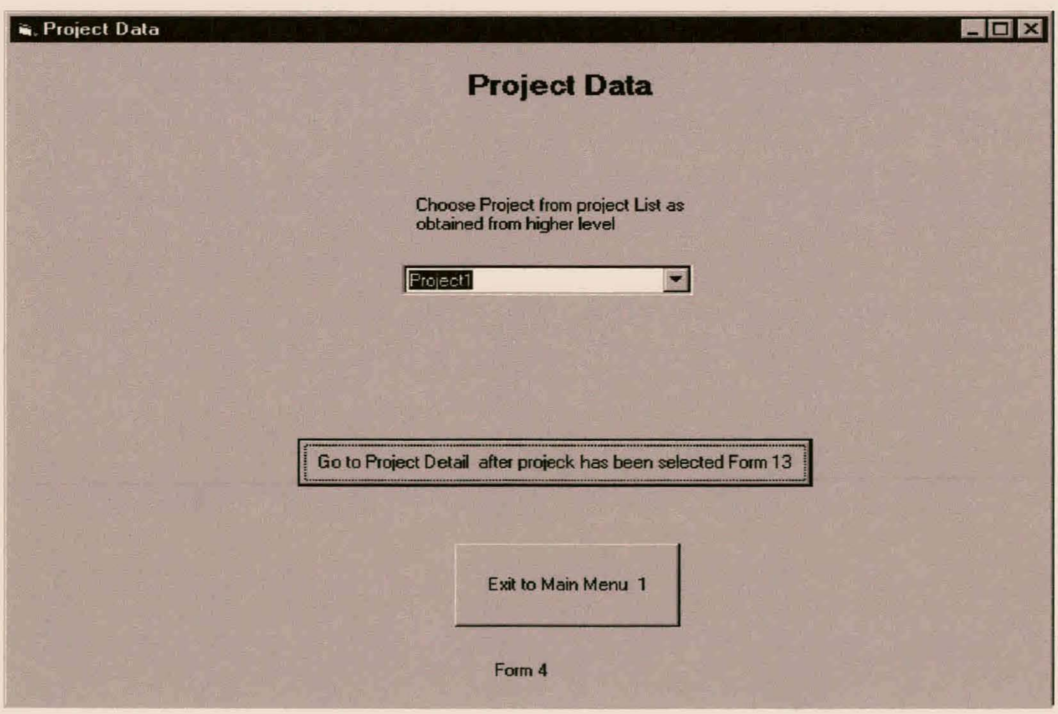
Project_no	Project_description	Priority	req_completion_date	constraint_on_off	Estimated_value
1	Project1	3	2000	off	31580000
2	Project2	1	2000	off	22060000
3	Project3	5	2003	off	184000000
4	Project4	6	2004	off	288510000
5	Project5	11	2015	off	76240000
6	Project6	8	2008	off	42170000
7	Project7	7	2011	off	210000000
8	Project8	4	2004	off	383800000
9	Project9	2	2002	off	123940000
10	Project10	9	2016	off	1609640000
11	Project11	10	2011	off	4566010000

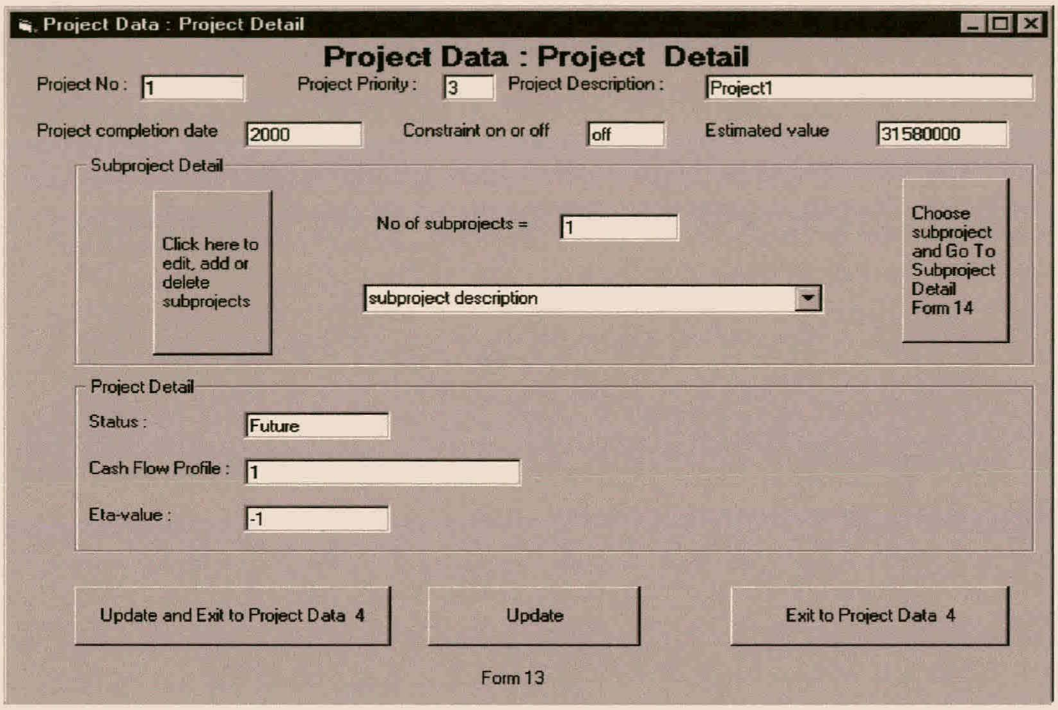
Form 9

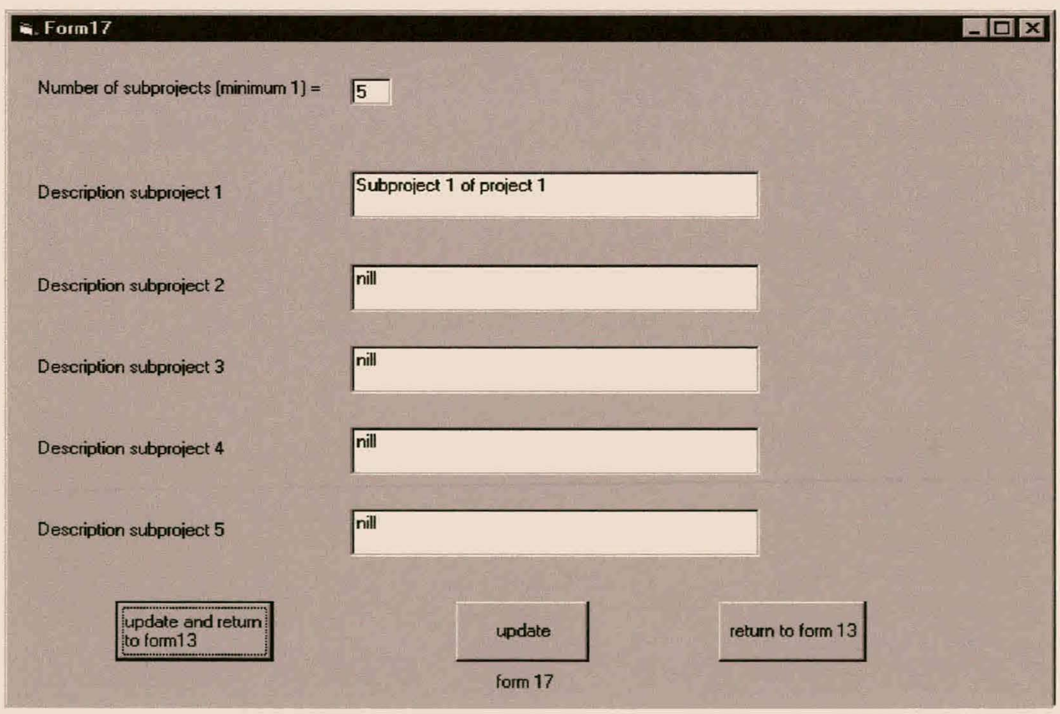


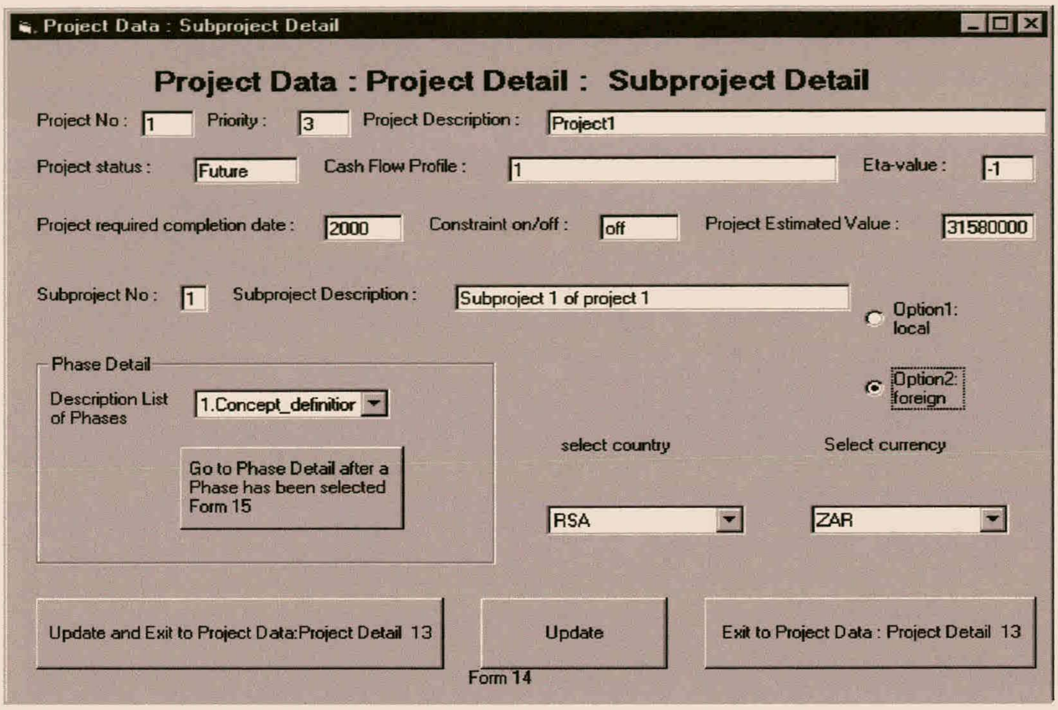
Form 7

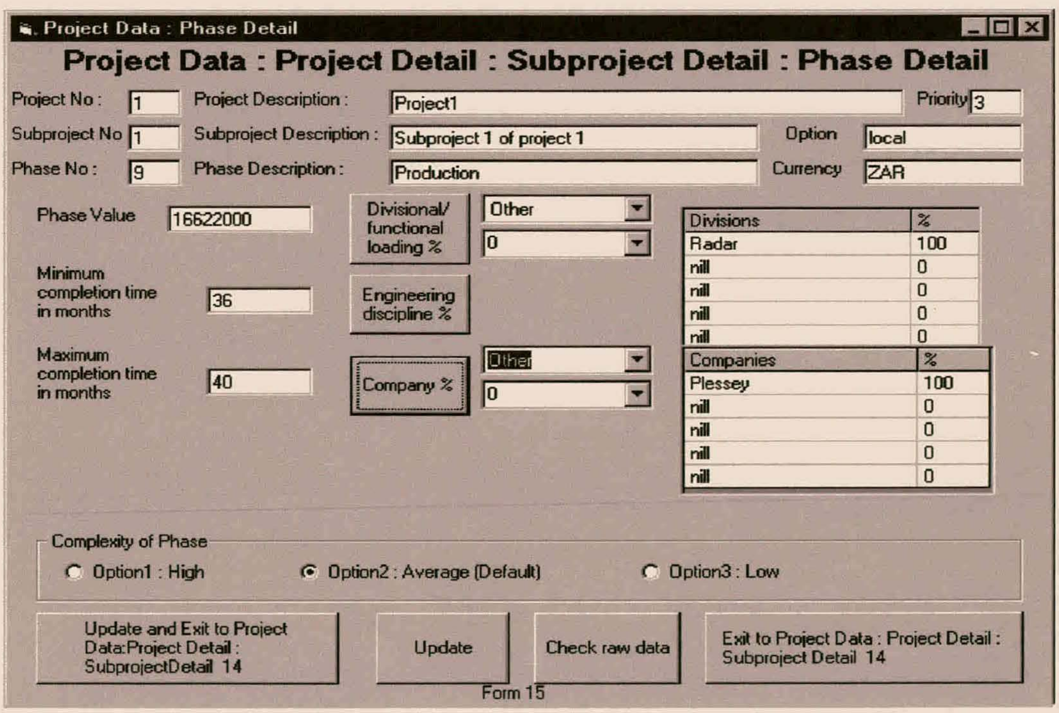

form 16
Defaults : Engineering Functions
Engineering Function :
Other
divdefault_Other
field1 field2 field3 field4 field5 field6
record0 Description Concept_definition XDM XDM_TE ADM
record1 average_phase_valu 200000 950000 425000 900000
record2 average_months_pe 1 1 1 1
record3 average_PM 1 1 1 1
record4 average_QA .3 .3 .4 .3
Exit to defaults form 7

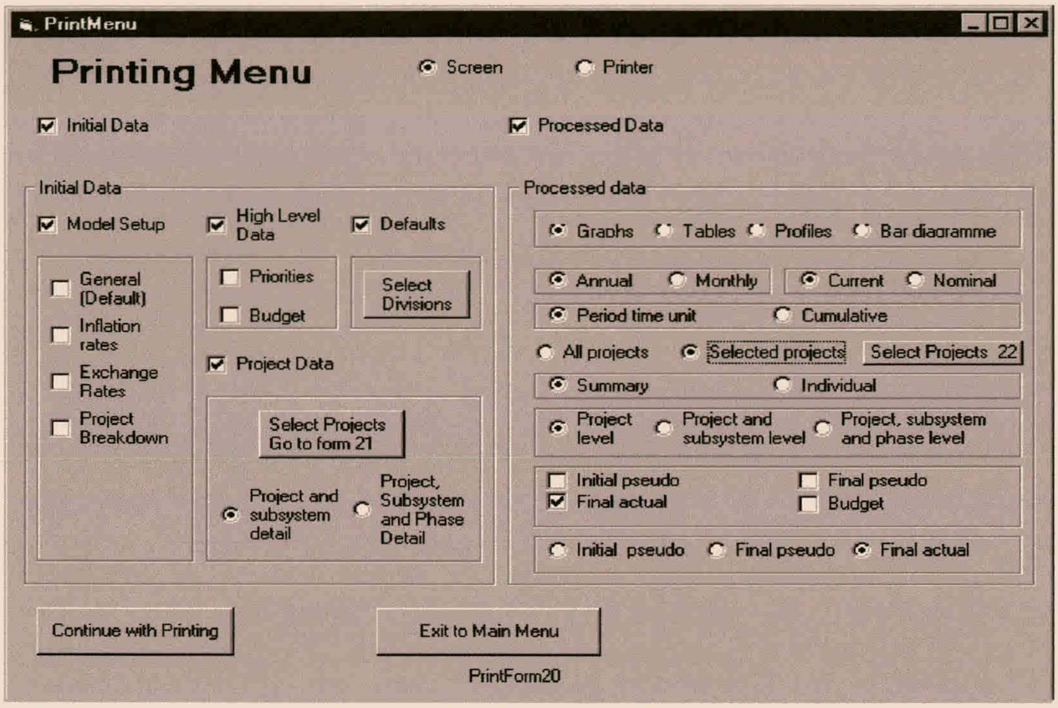

Project Data
Project Data
Choose Project from project List as
obtained from higher level
Project1
Go to Project Detail after projeck has been selected Form 13
Exit to Main Menu 1
Form 4

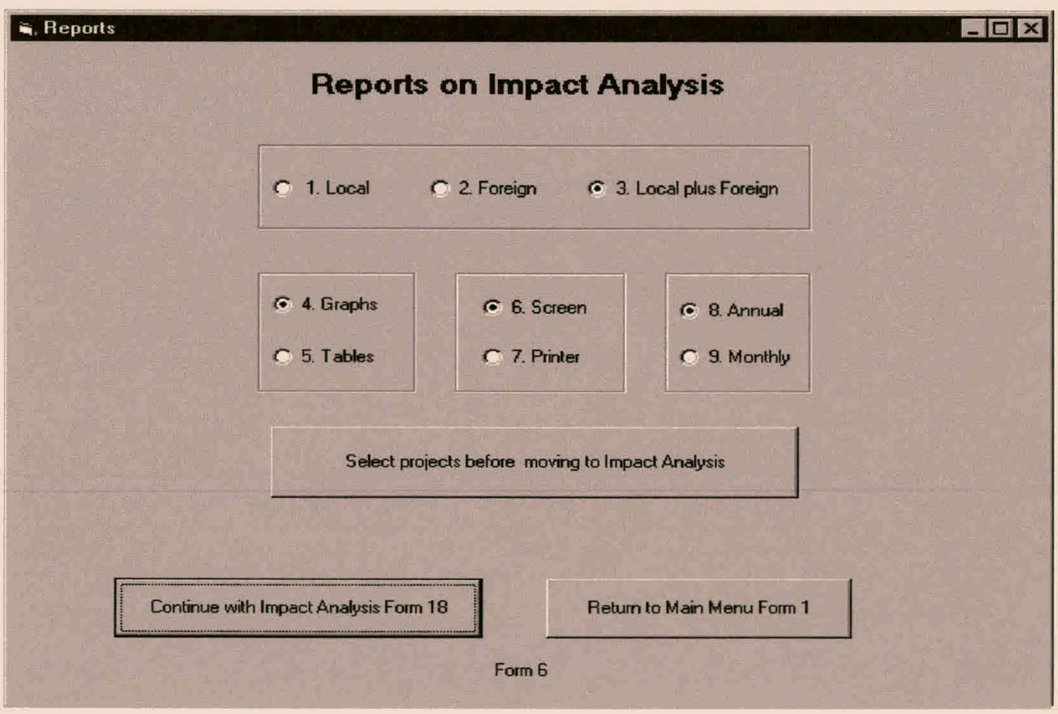

Project Data : Project Detail
Project Data : Project Detail
Project No : 1
Project Priority : 3
Project Description : Project1
Project completion date 2000
Constraint on or off off
Estimated value 31580000
Subproject Detail
Click here to edit, add or delete subprojects
No of subprojects = 1
subproject description
Choose subproject and Go To Subproject Detail Form 14
Project Detail
Status : Future
Cash Flow Profile : 1
Eta-value : -1
Update and Exit to Project Data 4
Update
Exit to Project Data 4
Form 13

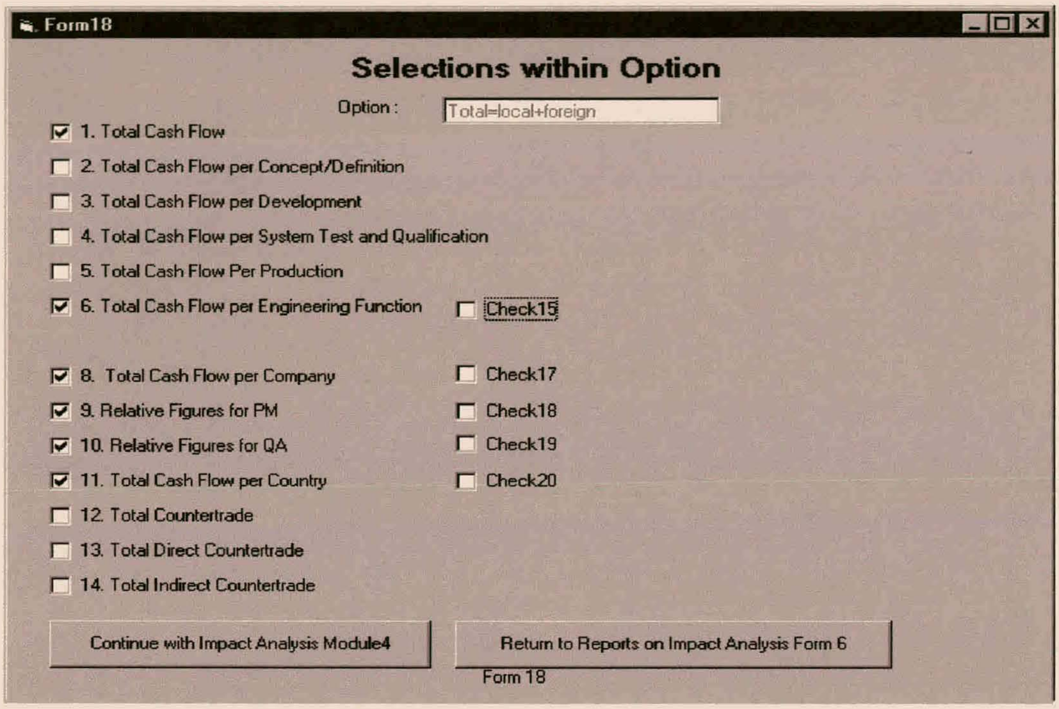

Form17
Number of subprojects (minimum 1) = 5
Description subproject 1 Subproject 1 of project 1
Description subproject 2 nill
Description subproject 3 nill
Description subproject 4 nill
Description subproject 5 nill
update and return to form13
update
return to form 13
form 17

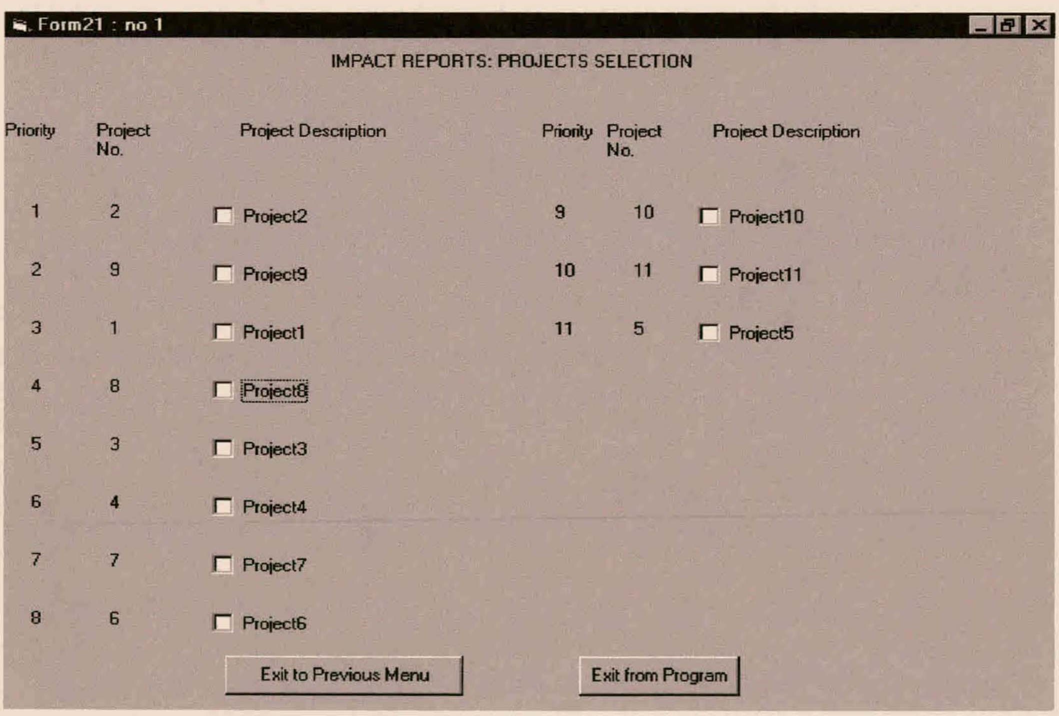

Project Data : Subproject Detail
Project Data : Project Detail : Subproject Detail
Project No : 1
Priority : 3
Project Description : Project1
Project status : Future
Cash Flow Profile : 1
Eta-value : -1
Project required completion date : 2000
Constraint on/off : off
Project Estimated Value : 31580000
Subproject No : 1
Subproject Description : Subproject 1 of project 1
Option1: local
Option2: foreign
Phase Detail
Description List of Phases
1.Concept_definitior
Go to Phase Detail after a Phase has been selected Form 15
select country
Select currency
RSA
ZAR
Update and Exit to Project Data:Project Detail 13
Update
Exit to Project Data : Project Detail 13
Form 14

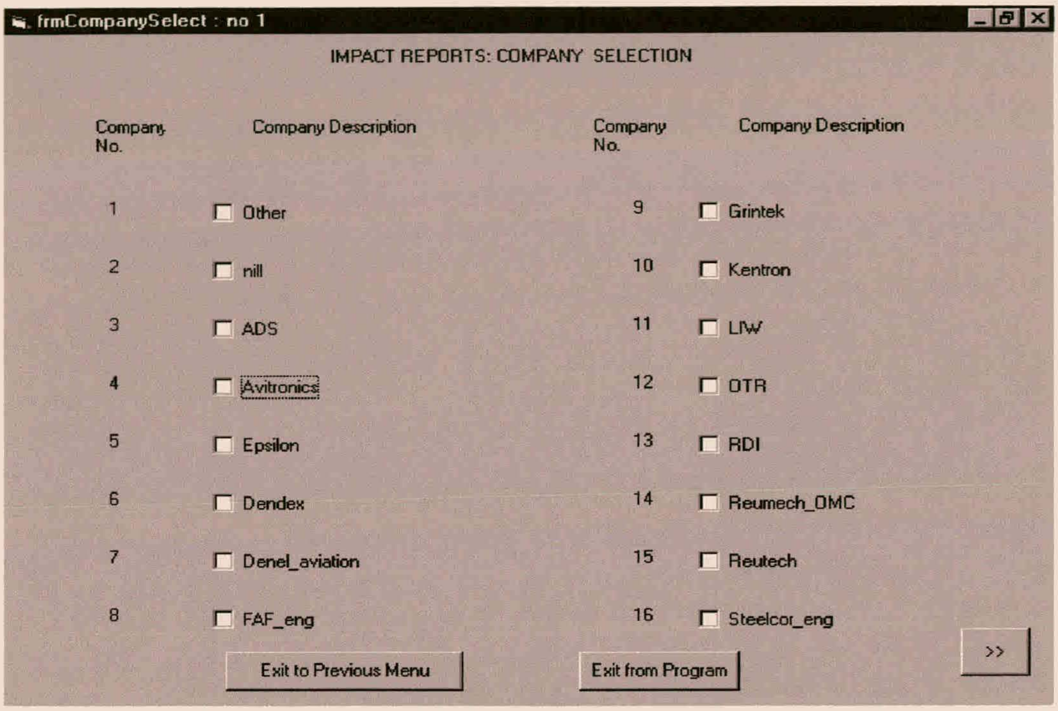

Project Data : Phase Detail
Project Data : Project Detail : Subproject Detail : Phase Detail
Project No : 1
Project Description : Project1
Priority 3
Subproject No 1
Subproject Description : Subproject 1 of project 1
Option local
Phase No : 9
Phase Description : Production
Currency ZAR
Phase Value 16622000
Divisional/ functional loading %
Other
0
Divisions %
Radar 100
nill 0
nill 0
nill 0
nill 0
Minimum completion time in months 36
Engineering discipline %
Maximum completion time in months 40
Company %
Other
0
Companies %
Plessey 100
nill 0
nill 0
nill 0
nill 0
Complexity of Phase
Option1 : High
Option2 : Average (Default)
Option3 : Low
Update and Exit to Project Data:Project Detail : SubprojectDetail 14
Update
Check raw data
Exit to Project Data : Project Detail : Subproject Detail 14
Form 15

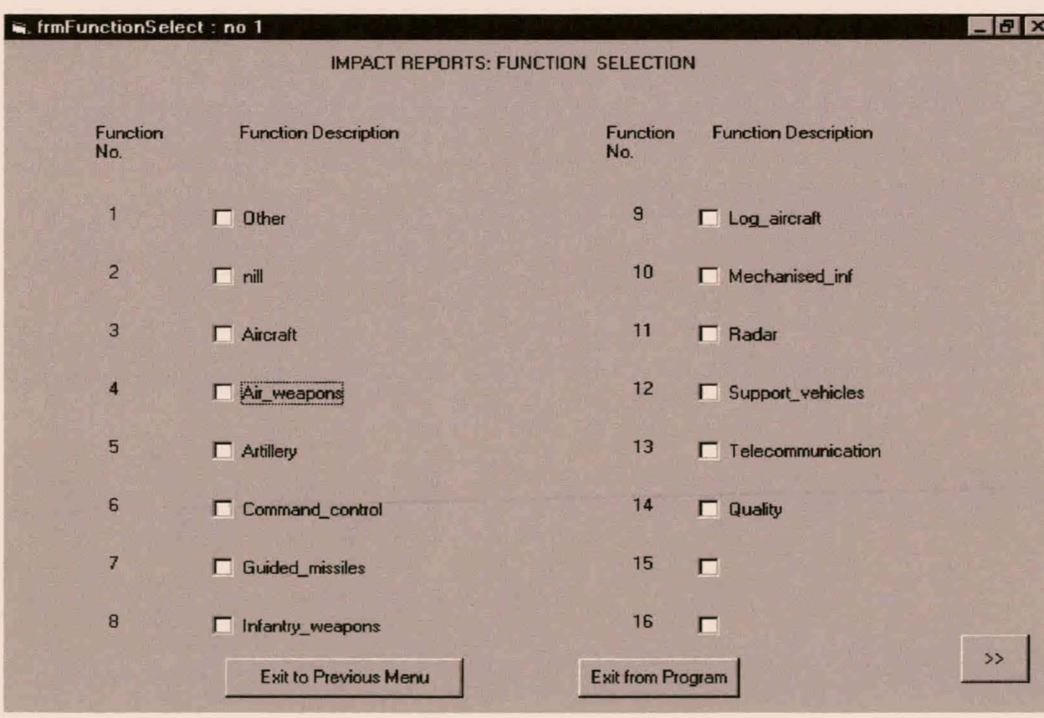

PrintMenu
Printing Menu
Screen
Printer
Initial Data
Processed Data
Initial Data
Model Setup
High Level Data
Defaults
General (Default)
Inflation rates
Exchange Rates
Project Breakdown
Priorities
Budget
Select Divisions
Project Data
Select Projects Go to form 21
Project and subsystem detail
Project, Subsystem and Phase Detail
Processed data
Graphs
Tables
Profiles
Bar diagramme
Annual
Monthly
Current
Nominal
Period time unit
Cumulative
All projects
Selected projects
Select Projects 22
Summary
Individual
Project level
Project and subsystem level
Project, subsystem and phase level
Initial pseudo
Final pseudo
Final actual
Budget
Initial pseudo
Final pseudo
Final actual
Continue with Printing
Exit to Main Menu
PrintForm20

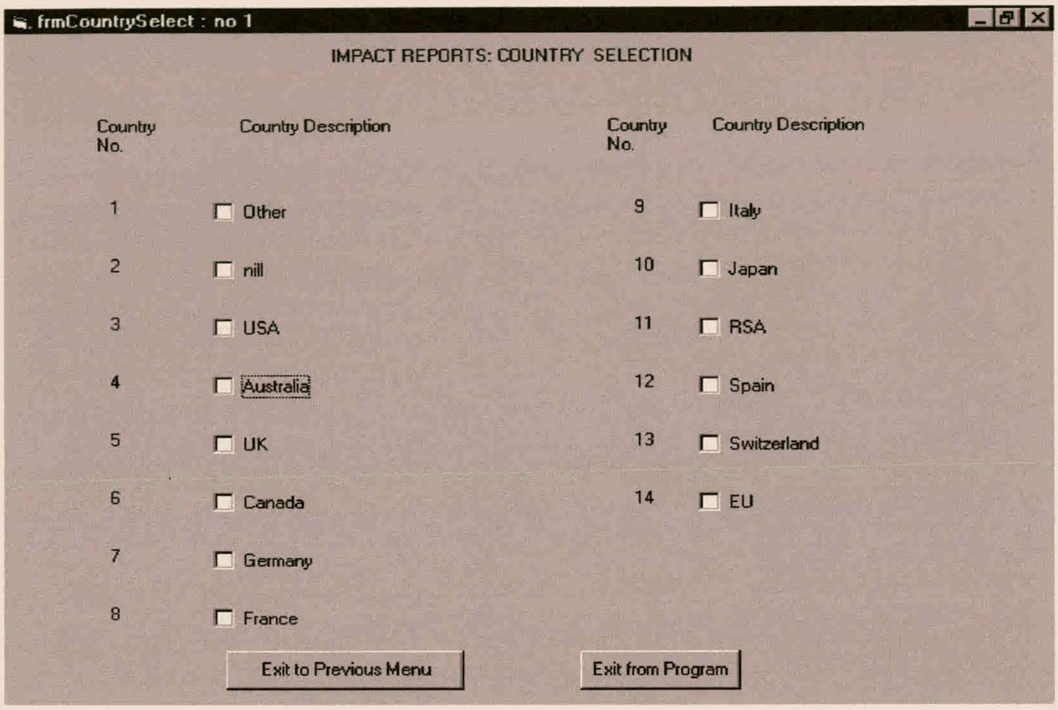

Reports
Reports on Impact Analysis
1. Local
2. Foreign
3. Local plus Foreign
4. Graphs
5. Tables
6. Screen
7. Printer
8. Annual
9. Monthly
Select projects before moving to Impact Analysis
Continue with Impact Analysis Form 18
Return to Main Menu Form 1
Form 6

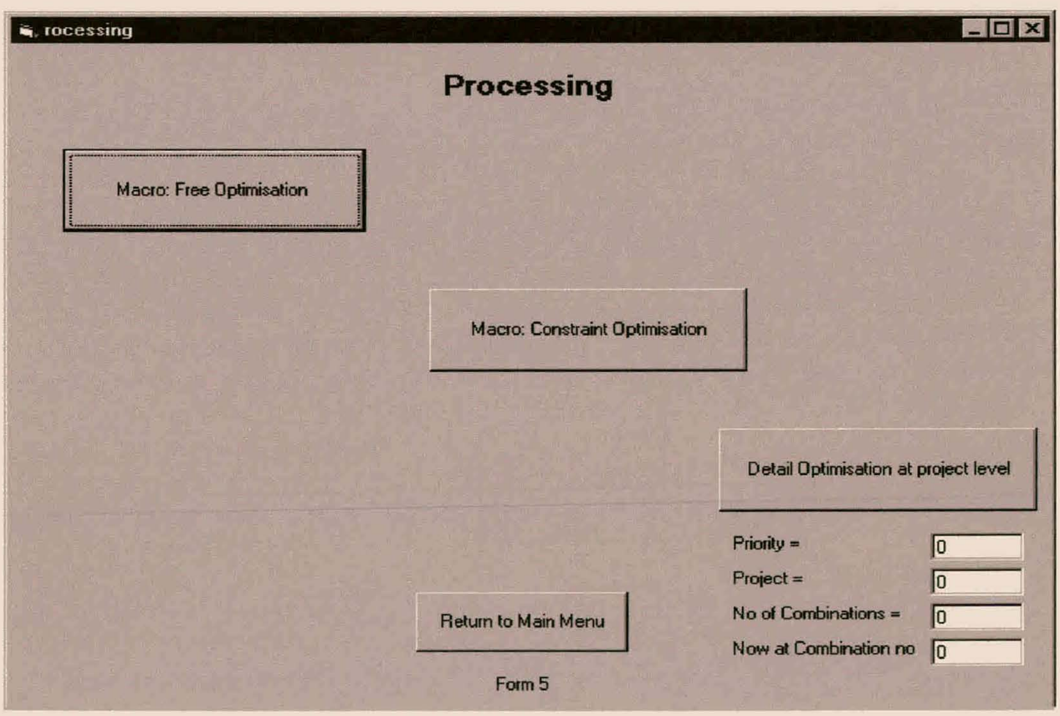

Form18
Selections within Option
Option :
Total=local+foreign
1. Total Cash Flow
2. Total Cash Flow per Concept/Definition
3. Total Cash Flow per Development
4. Total Cash Flow per System Test and Qualification
5. Total Cash Flow Per Production
6. Total Cash Flow per Engineering Function
Check15
8. Total Cash Flow per Company
Check17
9. Relative Figures for PM
Check18
10. Relative Figures for QA
Check19
11. Total Cash Flow per Country
Check20
12. Total Countertrade
13. Total Direct Countertrade
14. Total Indirect Countertrade
Continue with Impact Analysis Module4
Return to Reports on Impact Analysis Form 6
Form 18


Form21 : no 1
IMPACT REPORTS: PROJECTS SELECTION
Priority
Project No.
Project Description
Priority
Project No.
Project Description
1 2 Project2
9 10 Project10
2 9 Project9
10 11 Project11
3 1 Project1
11 5 Project5
4 8 Project8
5 3 Project3
6 4 Project4
7 7 Project7
8 6 Project6
Exit to Previous Menu
Exit from Program


frmCompanySelect : no 1
IMPACT REPORTS: COMPANY SELECTION
Company No.
Company Description
Company No.
Company Description
1 Other
2 nill
3 ADS
4 Avitronics
5 Epsilon
6 Dendex
7 Denel_aviation
8 FAF_eng
9 Grintek
10 Kentron
11 LIW
12 OTR
13 RDI
14 Reumech_OMC
15 Reutech
16 Steelcor_eng
Exit to Previous Menu
Exit from Program
>>


frmFunctionSelect : no 1
IMPACT REPORTS: FUNCTION SELECTION
Function No.
Function Description
Function No.
Function Description
1 Other
2 nill
3 Aircraft
4 Air_weapons
5 Artillery
6 Command_control
7 Guided_missiles
8 Infantry_weapons
9 Log_aircraft
10 Mechanised_inf
11 Radar
12 Support_vehicles
13 Telecommunication
14 Quality
15
16
Exit to Previous Menu
Exit from Program
>>


frmCountrySelect : no 1
IMPACT REPORTS: COUNTRY SELECTION
Country No.
Country Description
Country No.
Country Description
1
Other
2
nill
3
USA
4
Australia
5
UK
6
Canada
7
Germany
8
France
9
Italy
10
Japan
11
RSA
12
Spain
13
Switzerland
14
EU
Exit to Previous Menu
Exit from Program


rocessing
Processing
Macro: Free Optimisation
Macro: Constraint Optimisation
Detail Optimisation at project level
Priority =
0
Project =
0
No of Combinations =
0
Now at Combination no
0
Return to Main Menu
Form 5

PROCESS FLOW CHART