

Model for the Selection and Scheduling of Interdependent Projects

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Abstract— The selection and scheduling of interdependent projects is essential to any company’s planning division. Project selection and scheduling is complex due to several reasons: presence of multiple decision criteria, business and operational constraints, and project interdependencies, for instance. Three types of project interdependencies can be identified: benefit, resource and technical interdependencies. Each type of interdependency is inherently different, adding difficulty to the modeling process. The proposed mixed-integer programming model is a tool for solving the problem of selecting and scheduling interdependent projects. The model chooses, from a bank of projects, those in which it is best to invest and also recommends when to invest. It maximizes the net present value of the portfolio of selected projects, which takes into account benefits and costs savings that may result from interdependencies between any pair of projects. The model satisfies time windows for starting dates, exogenous budget limits; endogenous cash flow generation and technical interdependence through the use of precedence relations and sets of mutually exclusive projects.

I. INTRODUCTION

THE success of any company’s planning process depends to a large extent on the optimal selection and scheduling of projects. This is a complex process due to several reasons: the number of investment projects; presence of multiple decision criteria such as revenue maximization or risk minimization; business and operational rules such as budget limits and time windows for starting dates. In addition, decision making is even more difficult with the presence of project interdependencies, where project characteristics change according to the set of selected projects. Three types of project interdependencies are recognized in the literature: benefit, resource and technical interdependencies [Aaker & Tyebjee (1978), Fox et al. (1984)]. Each type of interdependency is inherently different and so must be dealt with in a particular way.

Several methods and mathematical models have been developed to tackle the problem of selecting and scheduling projects. Since the pioneering ranking method from Lorie & Savage (1955) other methods have been proposed: Scoring [Rengarajan & Jagannathan (1997)], Analytical Hierarchy Process (AHP) [Lockett et al. (1986), Murahaldir et al.

(1990)], and Goal Programming [Lee & Kim (2000), among others. However, these methods assume that project interdependencies do not exist [Santhanam & Kyparisis (1996)].

Other authors have proposed project selection models that deal with the existence of interdependencies. According to Lee & Kim (2000), these models, classified by the underlying solution method, are: Dynamic Programming [Caraway & Schmidt (1991), Nemhauser & Ullman (1969)] models reflect interdependency in special cases; Quadratic/Linear 0-1 programming models have a quadratic objective function and linear constraints, they restrict interdependency solely in the objective and between two projects; Multiobjective Evolutionary Algorithms [Medaglia et al. (2004)] models allow uncertainty and interdependency in the objective function and project allocation is subject to linear constraints; Quadratic/Quadratic 0-1 programming [Aaker & Tyebjee (1978)] with interdependency between two projects in the objective function and in the resource constraints; and Nonlinear 0-1 programming, with interdependency reflected in the objective function and the constraints among as many projects as necessary [Santhanam & Kyparisis (1996)].

Very few methods or mathematical models handle both project interdependencies and project scheduling. Stummer & Heidenberger (2003), model projects so that each one of them lasts for a number of periods, some of which are spending periods and others are benefit periods. It is assumed that all selected projects begin on the first planning period and so the model presents a time profile, but it does not schedule projects along the time horizon. In Dickinson et al. (2001) an optimal scheduling of projects is presented, taking into account the effects of benefit interdependency in a nonlinear model. However, this model leaves aside technical and resource interdependencies. It also assumes the same marginal benefit for interdependency disregarding the periods in which each interdependent project begins, which could be restrictive in some real-world scenarios.

Ghazemzadeh et al. (1999) presents a linear 0-1 programming model for the selection and scheduling of projects, which includes technical interdependency. Medaglia et al. (2006) and Sefair & Medaglia (2005) also present some features of technical interdependence in linear project selection and scheduling models. Even though this is

a step towards a general model for the selection and scheduling of interdependent projects, it still lacks of benefit and resource interdependencies.

Modeling interdependencies is especially relevant in the selection of Information Technology (IT) and Research and Development (R&D) projects, because of the widespread presence of shared costs and benefit dependencies [Weingartner (1966), Aaker & Tyebjee (1978), Fox et al. (1984), Dos Santos (1989), Karimi (1990), Apte et al. (1990), Santhanam & Kyparisis (1996), Lee & Kim (2000)]. Interdependencies may have a significant effect on the portfolio's net present value and the chosen projects [Fox et al. (1984)]. Santhanam & Kyparisis (1996) also point out the effect that interdependencies may have over the optimal portfolio. By means of an example, they also illustrate the complexity of project selection with interdependencies, showing how a ranking heuristic is unable to reach an optimal solution in this situation.

The proposed mixed-integer programming model sets apart from previous approximations in that it not only selects but it also schedules projects, while simultaneously taking into account all three project interdependencies and maintaining linearity. The model maximizes the net present value of the portfolio of selected projects and satisfies time windows within early and tardy starting dates; exogenous budget limits, and endogenous cash flow generation.

This article is divided into 4 sections. Section II explains the different types of interdependencies. In Section III the proposed mixed-integer programming model is formulated. Section IV presents computational experiments and Section V presents some concluding remarks.

II. TYPES OF INTERDEPENDENCY

The existence of interdependencies is identified when the selection of a project affects the characteristics of other projects. These characteristics lead to a taxonomy of interdependencies; which have been classified as benefit, resource and technical interdependencies.

A. Resource Interdependency

Resource interdependency occurs when the amount of resources required to develop a set of projects independently is greater than the amount of resources required when all of them are selected. IT projects frequently present this type of interdependency due to the high volume of hardware, software, and programming expertise that can be shared between different projects (e.g., software applications). An R&D example is the acquisition of costly lab equipment that can be shared between different research endeavors. In this latter case, if the cost of each project includes the equipment cost, the total cost is simply overestimated by not taking into account the synergies [Aaker & Tyebjee (1978)].

B. Benefit Interdependency

Benefit interdependency results from an increment or decrement with respect to the individual sum of benefits of interrelated projects. Projects that fall within this category are recognized as complementary or competitive [Aaker & Tyebjee (1978), Fox et al. (1984)]. Lets suppose that there is a pair of projects, each one of them consisting on introducing a new product to the market. The projects are complementary if when both products are introduced, a larger demographic group can be reached, causing greater sales in comparison to the sum of individual sales. These projects would be competitive if they target the same demographic group, possibly reducing sales for each individual product [Fox et al. (1984)]. Therefore, projects are deemed complementary if they generate benefit synergies and competitive if they cannibalize each other.

C. Technical Interdependency

If a set of mutually exclusive projects is identified, a project belonging to this set can only be chosen if no other project from the set is selected. If the projects in the set are contingent upon each other, a project belonging to the set can only be selected if all other projects in the set are selected [Fox et. al (1984)]. These are considered technical interdependencies.

III. MODEL

Sefair & Medaglia (2005) proposed a mixed-integer programming model for the selection and scheduling of projects. The objectives are to maximize the sum of the net present value of the selected projects (NPV) and minimizing risk in the project portfolio. The model satisfies a set of precedence relations between projects, time windows, budget limits and allows endogenous cash flow generation. This work extends this model by considering interdependent projects, but does not consider the second objective of risk minimization.

A. Definitions

Let P be the set of candidate projects; N_l and N_u are the minimum and maximum number of projects to be included in the portfolio; and let A be a precedence relation set. If project $i \in P$ precedes project $j \in P$ then $(i, j) \in A$ and their precedence gap is $g_{ij} \in Z_+^1$. If $g_{ij} = 0$, then the last investment period of project i must be over before the investment cycle of project j begins; if $g_{ij} < 0$, an overlap of at most g_{ij} investment periods is allowed; finally, if $g_{ij} > 0$ the last investment period of project i must be over at least g_{ij} periods before project j begins.

The project life and the number of investment periods

(investment life) are defined by parameters v_i and u_i , respectively. The parameter T represents the planning horizon for the investment decisions, thus no investments are allowed after time T . The time window for project $i \in P$ is defined by the early and tardy starting dates t_i^- and t_i^+ . This means that a given project may not begin earlier than t_i^- or later than t_i^+ (i.e., $t_i^- \leq t_i^+$).

Let c_{ik} be the investment cost of project $i \in P$ in period k where $k \in \{0, 1, \dots, u_i - 1\}$ and b_{it} be the benefit (or expected positive cash flow) on year t if project i is selected. Let NPV_{it} be the net present value (NPV) of project i given that it starts on year t . The budget available for year $t \in \{0, 1, \dots, T\}$ is r_t^0 .

Let the decision variables be y_{it} , x_{ikt} , and r_t , where y_{it} equals 1 if project i begins on year t and it is 0 otherwise ($t = t_i^-, \dots, \min\{t_i^+, T - u_i + 1\}$); x_{ikt} equals 1 if period k of project i is assigned to year t , and it is 0 otherwise ($t = t_i^-, \dots, \min\{t_i^+ + v_i - 1, T\}$ and $k \in \{0, 1, \dots, v_i - 1\}$); and r_t is the amount of unused investment resources at the end of year t , which is part of the available budget for year $t + 1$.

Due to resource and benefit interdependencies, the costs and benefits of the portfolio are affected by the selection of a set of interdependent projects and their starting dates. This relation must be identified beforehand, to accurately reflect the effect on the net present value. This work assumes that according to the year in which the interdependent projects are scheduled, the additional benefits or costs due to interdependency may vary. It is therefore not enough to know that a set of interdependent projects have been selected, but it is also important to identify the time when each project will begin; this allows to accurately calculate the change in NPV and the years where changes in costs and benefits occur.

Let $D = \{P_1, P_2, \dots, P_d, \dots, P_Z\}$ be the set of interdependence relations, where P_d is the set of projects that belong to interdependence d such that $P_d = \{i, j\}$, $i \in P$, $j \in P$, $i \neq j$, $P_d \in D$ and the type of interdependence that exists between projects i and j is either resource or benefit, or both.

The benefit interdependence implies that when a set of interdependent projects is selected, the benefits of the elements of the set either increase or decrease by a given percentage. Let $f_{d \ t(i) \ t(j) \ t}$ be the increment (percentage)

of benefits for project $i \in P_d$ attained on year t , given that the interdependent projects $i \in P_d$ and $j \in P_d$ are scheduled for years $t(i)$ and $t(j)$, respectively. Similarly, $f_{d \ t(i) \ t(j) \ t}$ represents the incremental benefits for project $j \in P_d$. Thus, the total benefits generated by interdependence P_d are shown in (1).

$$f_{d \ t(i) \ t(j) \ t} \cdot b_{it} + f_{d \ t(i) \ t(j) \ t} \cdot b_{jt} \quad (1)$$

The maximum cost savings generated by interdependence P_d is defined by Δc_d , which needs to be known beforehand by the decision maker. The function $h_{d \ t(i) \ t(j) \ t}$ reflects the expected fraction of savings attained at period t (with respect to the maximum allowable savings) due to the interdependence of projects $i \in P_d$ and $j \in P_d$ scheduled for years $t(i)$ and $t(j)$. The total savings generated by interdependence P_d on year t are shown in (2).

$$h_{d \ t(i) \ t(j) \ t} \cdot \Delta c_d \quad (2)$$

If the interdependence benefits are acquired along several time periods, $\sum_{t \in T} h_{d \ t(i) \ t(j) \ t}$ equals 100% for a given d , $t(i)$, $t(j)$. For modeling purposes, the percentage over the maximum savings varies depending on the scheduled time of each project. For instance, as projects i and j are scheduled further apart, the percentage attained, from the maximum savings, might reflect a sharp reduction.

The parameter $\Delta NPV_{d \ t(i) \ t(j)}$ is the marginal NPV generated by projects $i \in P_d$ and $j \in P_d$ scheduled for years $t(i)$ and $t(j)$. This value must be consistent with the costs and benefits shown in (1) and (2).

The binary decision variable $w_{d \ t(i) \ t(j)}$ takes the value of 1 if projects $i, j \in P_d$ have both been selected and scheduled for years $t(i)$ and $t(j)$, respectively; it takes the value of 0, otherwise.

Let $M = \{P_1, P_2, \dots, P_m, \dots, P_a\}$ be the set of mutually-exclusive interdependence relations. Let P_m be a set of mutually exclusive projects, where only one project from the set may be selected.

The objective function of the proposed model is shown in (3). The first term accounts for the individual NPVs of the projects, while the second term accounts for the marginal NPVs due to interdependencies.

$$\max \sum_{i \in P} \sum_{t=t_i^-}^{\min\{t_i^+, T-u_i+1\}} NPV_{it} y_{it} +$$

$$\sum_{d \mid P_d \in D} \sum_{t(i)=t_i^+ \mid (i,j) \in P_d} \sum_{t(j)=t_j^+ \mid (i,j) \in P_d} \Delta NPV_{d \ t(i) \ t(j)} w_{d \ t(i) \ t(j)} \quad (3)$$

The budget constraint is shown in (4). The first four terms include the balance of resources coming from the previous time period, the available budget, minus costs, plus benefits. The remaining terms adjust project costs and benefits to reflect their change due to active interdependencies.

$$\begin{aligned} r_{t+1} = & r_t + r_t^0 - \sum_{i \in P} \sum_{k=0}^{u_i-1} c_{ik} x_{ikt} + \sum_{i \in P} \sum_{k=u_i}^{v_i-1} b_{it} x_{ikt} \\ & - \sum_{P_d \in D} \sum_{t(i)=t_i^+ \mid i,j \in P_d} \sum_{t(j)=t_j^+ \mid i,j \in P_d} h_{dt(i)t(j)t} \cdot \Delta c_d \cdot w_{dt(i)t(j)} \\ & + \sum_{P_d \in D} \sum_{t(i)=t_i^+ \mid i,j \in P_d} \sum_{t(j)=t_j^+ \mid i,j \in P_d} (f_{dt(i)t(j)it} \cdot b_{it} + \\ & f_{dt(i)t(j)jt} \cdot b_{jt}) w_{dt(i)t(j)t}, \quad t = 0, 1, \dots, T \quad (4) \end{aligned}$$

When variable $w_{d \ t(i) \ t(j)}$ takes the value of 1 it implies that both $y_{i \ t(i)}$ and $y_{j \ t(j)}$ are 1. To avoid nonlinearity, the family of linear constraints in (5) expresses this implication [Sefair & Medaglia (2005)]

$$y_{i \ t(i)} + y_{j \ t(j)} \geq 2w_{d \ t(i) \ t(j)}$$

$$y_{i \ t(i)} + y_{j \ t(j)} \leq w_{d \ t(i) \ t(j)} + 1$$

$$t(q) = t_q^-, \dots, \min\{t_q^+, T - u_q + 1\} \text{ for } q \in P_d, P_d \in D \quad (5)$$

The set of constraints in (6) allows the selection of at most one project from each set of mutually exclusive projects P_m .

$$\sum_{s \in P_m} \sum_{t=t_s^-}^{\min\{t_s^+, T - u_s + 1\}} y_{st} \leq 1 \quad P_m \in M \quad (6)$$

The technical interdependence of contingent projects had already been formulated within Sefair & Medaglia (2005) through precedence relations. Precedence relations imply that a project j may not be selected unless another project i has been selected with a precedence gap of g_{ij} . The set of constraints in (7) model precedence relations.

$$y_{jt} \leq \sum_{t'=t_i}^{t-u_i-g_{ij}} y_{it'} \quad (i, j) \in A; t - u_i - g_{ij} \geq 0; t = t_i^-, \dots, t_i^+ \quad (7)$$

Every project is scheduled to begin at a certain time period (or may not be scheduled at all). The set of constraints (8) achieves this condition.

$$\sum_{t=t_i^-}^{\min\{t_i^+, T - u_i + 1\}} y_{it} \leq 1 \quad i \in P \quad (8)$$

A lower and an upper bound for the number of projects to be selected can be set by the decision maker through relation (9).

$$N_l \leq \sum_{i \in P} \sum_{t=t_i^-}^{\min\{t_i^+, T - u_i + 1\}} y_{it} \leq N_u \quad (9)$$

Finally, once a project is set to begin on a given year, it is necessary to match each internal time period of a project with a given year in the horizon. This is done via expression (10).

$$\begin{aligned} y_{it} = x_{ik(t+k)} \quad & i \in P; k = 0, \dots, \min\{v_i - 1, T - t\}; \\ & t = t_i^-, \dots, \min\{t_i^+, T - u_i + 1\} \quad (10) \end{aligned}$$

IV. COMPUTATIONAL EXPERIMENT

A. Example

Consider a company with 10 available projects to be selected and scheduled along a 13-year planning horizon. It is assumed that there is certainty on the investment costs, of every project, which are shown for each investment period in Table I. With these investment costs and the benefit flow it is possible to calculate de NPV for each project at any starting date. To this end 100 simulations of the behavior of the benefit flows were carried out to obtain the mean NPV, according to the methodology outlined in Sefair & Medaglia (2005). The discount rate used was 14%.

The project and investment lives, the time windows, and the precedence relations for each project are shown in Table II. Three possible investment budget scenarios were used for the computational experiments. The budgets are shown in Fig. 1. Budget A is the most restrictive budget, whereas budget C is the least restrictive.

Table III shows resource, benefit and mutually exclusive interdependencies that exist between pair of projects. So it follows that: $D = \{P_1, P_2, P_3, P_4\}$ and $M = \{P_5\}$; $P_1 = \{1, 5\}$, $P_2 = \{4, 9\}$, $P_3 = \{3, 10\}$, $P_4 = \{2, 6\}$ and $P_5 = \{2, 9\}$.

Interdependence 1, as seen in Table III, is defined between projects 1 and 5. For every benefit period of project 1, posterior to the investment periods of project 5, the benefits of project 1 increase by 20% percent. Therefore if project 1 starts on year 0 (2008) and project 5 starts on period 1 (2009) the additional interdependence benefit for each period will be $0.2 * b_{1t} + 0 * b_{5t}$ according to (1). These additional benefits will only be acquired on years $t = 4, \dots, 10$ because these are the only years when both projects have positive cash flows at the same time. Note that project 5 has three investment periods (Table I), so it begins to show benefits on year 4; and project 1 ends on period 10.

Suitable functions $f_{d \ t(i) \ t(j) \ t \ i}$ and $f_{d \ t(i) \ t(j) \ t \ j}$ must be defined for all possible $t(i)$ and $t(j)$ that comply with the early and tardy starting dates of both projects. These functions were defined for interdependencies 2 and 3, according to the characteristics of each particular

interdependency.

TABLE I
INVESTMENT COSTS (MILLION PESOS)

Project	Investment Periods		
	0	1	2
p1	246	0	0
p2	532	0	0
p3	182	0	0
p4	285	285	0
p5	185	185	185
p6	1000	0	0
p7	645	445	0
p8	33	33	33
p9	186	186	0
p10	850	0	0

TABLE II
TIME CONSTRAINTS

Project	u_i	v_i	t_i^-	t_i^+	g_{ij}
p1	1	11	2008	2020	-
p2	1	12	2008	2020	-
p3	1	4	2008	2020	-
p4	2	10	2008	2014	$g_{8,4} = 0$
p5	3	12	2009	2009	-
p6	1	10	2011	2018	-
p7	2	8	2008	2011	-
p8	3	9	2008	2008	-
p9	2	10	2008	2011	-
p10	1	6	2008	2011	$g_{9,10} = 0$

TABLE III
INTERDEPENDENCIES

Number	Projects	Interdependencies	Characteristics
1	1, 5	Benefit	Complementary
2	4, 9	Benefit	Competitive
3	3,10	Benefit	Complementary
4	2, 6	Resource	Shared costs
5	2, 9	Technical	Mutually Exclusive

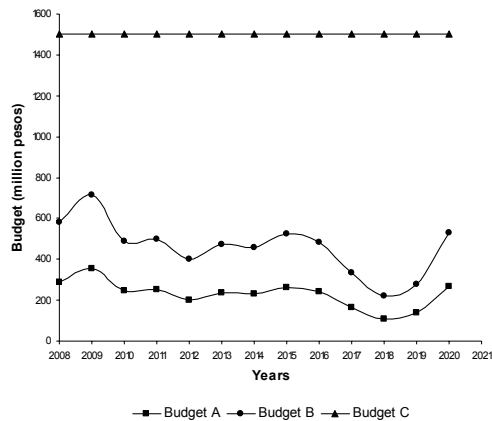


Figure 1: Budget scenarios

Resource interdependence 4 presents shared costs between projects 2 and 6. Given the characteristics of this interdependence, costs will only be shared if both projects start on the same year and the shared cost will be 150 monetary units. This means that $\Delta c_d = -150$ (savings) must be allocated to the first year of investment of both projects. Thus, $h_{d_{t(i) t(j) t}} = 1$ if $t(2) = t(6) = t$ and $h_{d_{t(i) t(j) t}} = 0$, otherwise. The best way to take advantage of this interdependence is for projects 2 and 6 to begin on the same time period.

Interdependence 5 shows that either project 2 or project 9 may be selected, but not both.

B. Results

For all experiments the technical interdependence of contingent projects that is modeled through precedence relations is included as it is part of the model set forth in Sefair & Medaglia (2005). Fig. 2 through 4 show the selected projects and their schedule. For simplicity only the investment periods are shown.

Experiment I: Base case

For this experiment no interdependencies were considered and the budget used was budget B from Fig. 1. As shown in Fig. 2 projects 5 and 7 were excluded. The latter is excluded because it presents a negative NPV, no matter when it starts. On the other hand, project 5 has a very narrow time window (Table II) and so there is not enough budget to undertake it.

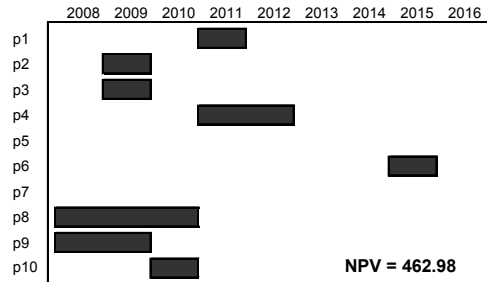


Figure 2: Selection and scheduling of projects without interdependencies (NPV in millions of pesos).

Experiment II: Restrictive budget

The budget used is budget A from Fig. 1. For experiment IIa only interdependence 1 from Table III is included with a percentage increase of benefits for project 1 of 20%; whereas for Experiment IIb this percentage is 50%.

In experiment IIa the budget is so restrictive, that it does not allow to include project 5. Also, the value generated by the interdependence is not large enough to justify its inclusion (Fig. 3). The budget reduction from budget B to A has the only effect of reprogramming projects along the horizon so that they are carried out when there is enough budget available. In experiment IIb it can be seen that project 5 becomes more attractive as the increment on the interdependence benefit justifies its inclusion in the

portfolio. This comes at the expense of excluding project 10 from the portfolio. Projects 3, 4 and 9 are also reprogrammed. Note that Fig. 3a and Fig. 3b reflect changes with respect to experiment I and experiment IIa, respectively.

This experiment shows that the impact on the optimal schedule may well depend on the magnitude of the benefit interdependence. The impact on the objective of the interdependence considered in this example is high as it increases NPV by 9% (from experiment IIa to experiment IIb). On the other hand, the NPV in both experiments is less than de NPV in experiment I because the budget is tighter in II. Nevertheless, the benefit interdependence ameliorates the negative impact of the tighter budget in experiment IIb.

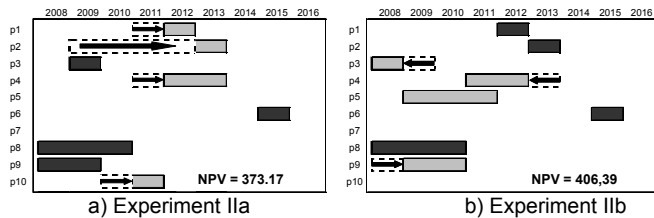


Figure 3: Selection and scheduling of projects under experiments IIa and IIb (NPV in millions).

Experiment III: All interdependencies

All interdependencies are included in this experiment. Experiment IIIa uses budget A, experiment IIIb uses budget B, and experiment IIIc uses budget C.

Experiments IIIb and IIIc reflect similar changes in relation to experiment IIIa. On both of these cases, projects 2, 4 and 8 are excluded and project 5 is included opposed to what happens in IIIa. In addition projects 1 and 3 are reprogrammed. The results for IIIb and IIIc can be interpreted in the following way: since projects 2 and 9 are mutually exclusive, only one of them may be selected and so project 2 is excluded. Projects 9 and 4 are competitive so that if both are chosen project's 4 benefits diminish enough as to make project 4 unattractive and so it is excluded. Project 8 has a negative NPV, but it must precede project 4, so that the only reason to include project 8 is to be able to include project 4. As project 4 has been excluded from the portfolio there is no reason to include project 8.

Due to the low budget used in experiment IIIa, the optimal schedule changes in a significant way with respect to experiments I, IIIb and IIIc. Results from experiment IIIa can be interpreted as follows: between the mutually exclusive projects 2 and 9, project 2 is chosen. By excluding project 9, competitive interdependency between projects 9 and 4 has no effect, so project 4 still is attractive and therefore is selected. To be able to select project 4 the precedence of project 8 must be fulfilled and so this project enters the efficient portfolio as well. Resource interdependency P_4 states that if projects 2 and 6 begin on the same year there is a saving in costs of 150 monetary units, which presses towards scheduling both projects in 2010. Projects 1 and 5 present benefit interdependence and

so project 5 is included in the portfolio. The budget in this case is very restrictive and so the benefit interdependence between projects 3 and 10 does not appear to be large enough to be able to include project 10.

From experiment III the impact of the budget on the optimal portfolios is clear. As a result the interdependencies that become relevant in each experiment IIIa, IIIb and IIIc, change. It can also be seen in Fig. 4 a, b and c that the interdependencies have an effect on the number of selected projects, the combination of projects in the optimal portfolio, and the schedule of the selected projects. When the budget becomes less tight, the NPV of the portfolio increases as there is more freedom to program the projects where it is more favorable to take the best advantage of the possible interdependencies. If the positive and negative effects of interdependencies are not considered, the resulting selection and scheduling may be suboptimal as it can be seen when experiments II and III are compared against experiment I, the base case with no interdependence. Note that in Fig. 4 changes with respect to Experiment I appear in light grey.

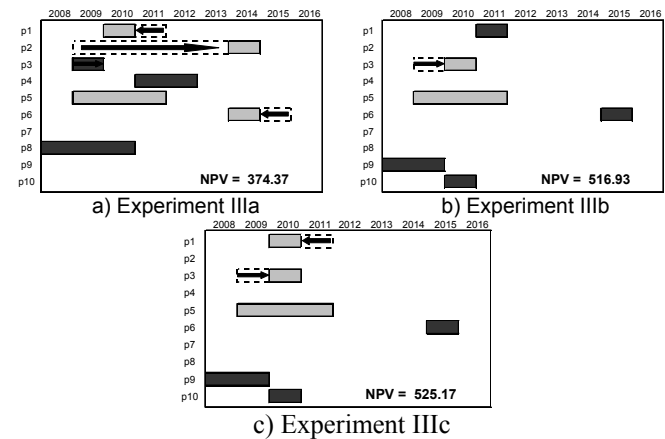


Figure 4: Selection and scheduling under Experiments III (NPV in millions).

V. CONCLUSION

This paper presents an integrated model for the selection and scheduling of projects via mixed-integer (linear) programming. The model includes three types of interdependencies found in the project selection literature: technical, resource, and benefit interdependencies. This model may be of great value for planning managers at companies, especially those with a high number of interdependent projects. In particular, the model can be useful when selecting and scheduling IT or R&D projects, where interdependencies are ubiquitous.

The computational experiments showed that interdependencies have an important impact on the optimal scheduling of projects. Interdependencies affect the number and combination of projects in the optimal portfolio in addition to their schedule. With interdependencies, it is possible to take advantage of the characteristics that relate

the projects and/or avoid loss of benefits. Furthermore, these relations may have a significant impact on the NPV of the portfolio.

The proposed model takes into account interdependencies of second degree (between a pair (two) projects). A natural extension to this model is to include higher degree interdependencies.

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