Developing a Generalized Optimization Model for Project Portfolio Selection

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Satvik Tripathi
(satvikt26@iimklive.com)
Sajjan Kumar
(sajjank26@iimklive.com)
G. Thangamani
Indian Institute of Management, Kozhikode
(gtmani@iimk.ac.in)

This paper develops a model for selecting an optimal project portfolio across all conventional industries using integer programming. The paper focuses on building the model with an exhaustive list of over 15 constraints, such as strategic alignment, fit to existing supply chain, different risks, market attractiveness, scalability, and many more, such that the model has high adaptability for every industry. This model will help solve a significant concern among upper management regarding project selection and quantifying the decision parameters with the highest objectivity rendered by optimization models.

Keywords: Constrained Optimization, Project Portfolio Selection, Integer Programming

1. Introduction

Project Portfolio Selection and the dilemmas concerning it have been recurrent problems across all industries, be it aviation, petroleum, or FMCG. It so happens that a firm usually has more projects to choose from than the firm can work upon, given its physical and financial constraints at any given point. In such a case, optimizing the project portfolio is of prime importance to maintain the firm's competitive advantage. Managers have dealt with this problem of optimizing portfolios by relying on techniques like financial compatibility, strategic alignment, and sometimes even plain gut feeling. While these methods have worked in the past, they are difficult to quantify or justify objectively to relevant stakeholders and also laden with decision-making biases.

Constrained Optimization using Linear Programming has been of great use in investment portfolio selection, production scheduling, allocation of advertising budget, construction of warehouses, etc. This paper illustrates the use of the Binary Integer Programming method to build an optimized portfolio while accounting for over 15 real business constraints. This could help bring down subjectivity drastically and add greater value to the organization's goals. These goals could range from financial sustainability, low operational and reputational risks, low manpower requirements, etc. Finally, we discuss a business case to showcase the use and effectiveness of the same method.

2. Literature Review

Portfolio selection is a procedure that involves the valuation of a set of available project proposals to commence a group of them that make it possible to achieve some strategic goals (Mantel, Meredith, Shafer, & Sutton, 2011). Portfolio selection is a periodic process that must promise that projects selected are within the organization's resource constraints (Ghasemzadeh & Archer, 2000). Portfolio selection looks for the best equilibrium regarding return, capital investment, risk, timing, sustainability, and other features according to the sector.

A successful project suggests not only doing the project right but also doing the correct project. For this purpose, project selection practices play an important role in portfolio management. However, there is an excess of project selection methodologies, and there is no agreement on the most effective (Archer & Ghasemzadeh, 2007). Therefore, organizations choose the procedure that best echoes their project management maturity level, organizational culture, and the kind of projects developed. Mantel et al. (2011) categorize the project selection methods into non-numeric and numeric. The following sections explain the main practices according to these two categories.

Ghasemzadeh, Archer, and Iyogun (1999) showed a methodology for project selection and development using a zero-one linear programming model accounting for organizational objectives and constraints such as resource constraints. This particular model looks to optimize the overall NPV.

Project portfolio selection has been advanced in literature as a very stimulating issue, mainly for project-based organizations. Even though the problem has been raised for more than four decades, the combinative nature of the topic is very comprehensive such that there are always opportunities for future research (Iamratanakul et al. 2008).

Multi-objectives: The strategic planning process often leads to numerous goals and objectives being achieved in diverse time horizons. Multi-objective optimization was often used alongside, in literature, through mathematical models. Christian Stummer and Kurt Heidenberger (2003) used a multi-objective integer linear programming model to predict the solution space of all Pareto-optimal portfolios. Medaglia, Graves, & Ringuest (2007) also suggested a multi-objective evolutionary technique for linearly constrained project selection problems with partly funded projects and multiple stochastic objectives. Archer and

Ghasemzadeh (1999) used one single objective function to integrate multiple objectives and noted that linear goal programming, weighted scoring, and AHP are possible techniques for determining project value.

Multiple-criteria: Both tangible and intangible, qualitative and quantitative criteria are considered depending on organization objectives. Criteria are often incompatible, considering the typical example of maximizing revenues while reducing costs. Siddhartha Sampath and co-workers (2015) built a multi-criteria optimization model while building a decision-making framework for project portfolio planning at Intel. Shang et al. (2004) used the Analytical Network Process (ANP) method to evaluate transportation projects and analyze benefits, opportunities, costs, and risks.

The huge number of alternatives: the number of possible sets of projects and programs is definitely finite, nevertheless, it can be very huge in organizations implementing many enterprises simultaneously. Each mixture of items fulfilling certain constraints is indeed a potential alternative. Therefore, typical methods for portfolio selection often do not generate all possible portfolios, but try to build the optimal portfolio from a set of potential projects and programs. Stummer and Heidenberger (2003) implemented a screening procedure in the first phase of their decision support system to identify project offers worthy of further evaluation, keeping the number of projects inflowing in the subsequent phase within a manageable size. Also, Archer and Ghasemzadeh (2000) introduced the screening stage to eradicate any obvious non-starter and thus decrease the number of projects to be considered by the decision committee.

Specific limitations: Market conditions, raw materials accessibility, government regulations, chances of technical success, social and environmental restraints could affect the project portfolio performance. High-level guidance to the portfolio selection process is generally provided earlier and includes strategic focus determination, limitation setting, and resource constraints (Archer and Ghasemzadeh 2000). These constraints are then incorporated in an optimization model, along with timing, project interdependences and balancing. Vetschera and Teixeira de Almeida (2012) defined a project portfolio selection as a problem of selecting one or several out of a set of conceivable items under some restrictions and where some combination of properties of the selected items determines outcomes. They proposed a computationally ‘‘light’’ system to manage portfolio selection based on PROMETHEE multi-criterion method, as is the case of non-compensatory attributes, cost, and other resource limitations as constraints. Mavrotas and co-workers (2008) presented a two-phase project selection approach under the policy, segmentation, and logical constraints.

Project interdependencies: By definition, the programs making a portfolio are sets of interconnected projects in terms of both resource use and benefit recognition. Several types of project interdependencies exist and have been discussed in the literature. Schmidt 1993 presented three different types of interrelations in his portfolio construction model, combining the effects of resource interactions, benefit interactions, and outcome interactions among projects using a matrix-based illustration. Synergies occur if the total amount of the benefits of interacted projects is different from the situation in which the projects are executed independently. This difference is positive (synergy effect) if the projects are harmonizing and it is negative (cannibalization effect) if they are competitive. Outcome interactions occur if the odds of success of a project change by undertaking another project in the same portfolio. This interaction echoes the relationship between the project's successes. Resource interaction arises when the projects share the same resources, where portfolio resource requirements are fewer than the sum of individual project requirements. Killen et al. 2012 highlighted learning interdependence which is “the need to incorporate the capabilities and knowledge gained through another project”.

Archer and Ghasemzadeh (1999) and Krishnan and Ulrich (2001) remarked that project selection is typically best realized using integer optimization methods when projects have many interdependencies. Dickinson and co-workers 2001 presented a real-world application of product portfolio optimization at Boeing Company, using a dependency matrix that measures the revenue interactions between projects. A nonlinear, integer program model was then established to optimize project selection, considering constraints about the budget, the maximum number of projects in a portfolio, and about the minimum number of projects that must support each of the strategic purposes.

Balance and effectiveness: Besides optimizing organization value, a project portfolio should endorse balance and effectiveness dimensions. The portfolio can be balanced in scopes such as long-term vs. short-term, low risk vs. high risk, and evaluation by strategic pillars or market segments. Therefore, balance constraints should be considered to ensure portfolio diversification in terms of several trade-offs. Dickinson and co-workers 2001 managed portfolio balance with graphical tools. Liesiö et al. 2008 acquired portfolio balance using logical constraints. Strategic effectiveness suggests that project composing the portfolio are reliable with company’s core objectives and that the projects mix permits high feasibility and also provides a good economic fit. Besides that, the definition of the minimum and maximum number of projects in a portfolio support both efficiency and balance objectives.

On the one hand, the minimum limit would be essential since the portfolios which do not contain enough projects generally might not benefit from the synergy effect and might not provide enough strategic fit. On the other hand, the maximum limit could prevent feasibility problems of complex projects as well as human resources dispersal, the latter issue is often neglected when constructing project portfolios in many organizations. The three portfolio objectives, efficiency, balance, and strategic effectiveness, have been recently discussed in Canbaz and Marle's research study (2016), including numerous constraints and several types of interdependencies among project investments and resources. They handled the problem as a constraint satisfaction problem through mathematical programming.

Uncertainty and risk: It is often highlighted that risk and uncertainty should be taken into account in project portfolio problems. The decision-maker, whether a single person or a group of people, usually does not have the complete and precise information about the future consequences of the decision because the decision environment is constantly changing. So, the assumptions and data the decision maker is requested to provide for each project are indeterminate, inaccurate, and incomplete.

Even, suppose it is possible to get more precise information. In that case, the deep analysis task may require substantial time and cost decision maker cannot virtually engage in the portfolio planning phase. Fuzzy methodology, among others, was implemented to model the evaluation data uncertainty (Chen and Gorla 1998, Wang and Hwang 2007, Ravanshadnia et al. 2010, Ahari et al. 2011, Ghapanchi et al., 2012). Sampath and co-workers (2015) applied Monte Carlo simulation to acquire more accurate values of variables' estimates related to objectives, constraints, and resource metrics to take into account the uncertainty and the time dimension related with project metrics.

Project portfolio selection methods classification

Different portfolio selection methods have been proposed in the literature, and all of them share the objective of providing a system to guide the project selection process. However, they all provide partial coverage of this combinatorial issue by addressing a few aspects among the ones described in the previous section.

This taxonomy synthesizes the literature review proposed by previous authors (Hall and Nauda 1990, Stummer and Heidenberger 1999, and Iamratanakul 2008). It is extending its work to include hybrid methods that emerged since 2006. The available techniques have been summarized into six groups: benefit measurement methods, mathematical programming models, cognitive emulation methods, simulation and heuristics models, real options, and hybrid tools. The list of references is not exhaustive but is illustrative of available and sometimes recent literature.

There is a consensus today that none of the mentioned techniques provides an all-inclusive and universal answer to the project portfolio selection problem; Stummer and Heidenberger (2003) highlighted the correlation between the level of effort in R&D and the sophistication of procedures used, indeed the higher the number of resources at stake, the more managers will be willing to go through the barrier's complexity might create. It should also be noted that user-friendly decision support approaches using advanced decision-making techniques have been proposed in the literature (Archer and Ghasemzadeh 2000, Stummer and Heidenberger 2003, Sampath et al. 2015), subdividing the portfolio selection procedure into numerous related steps rather than just evaluating and scoring projects, or solving an optimization problem.

3. Methodology

To develop the model, we compared different mathematical programming models, including Integer Programming, Goal Programming, and Linear Programming. We found Binary Integer Programming to be most appropriate for indicating project selection in a portfolio, along with a combination of Goal Programming Methods to work with multiple variables at the same time. The constraints were drawn keeping in mind the various parameters subjected to projects before their inclusion in the portfolio is decided upon.

The binary integer programming model uses 0-1 Integer Programming, wherein every project i gets assigned a value based on its inclusion in the portfolio.

$$x_i = \begin{cases} 1, if\ project\ i\ is\ selected \\ 0, if\ project\ is\ not\ selected \end{cases}$$

The constraints can be split into two major groups for computational purposes:

i. Linear quantitative
ii. Rating-scale

And their weighted average contribution to the portfolio can be used to check against the portfolio constraint.

$$Y = \sum_i w_i y_i$$

Where Y is the portfolio score of that constraint, w_i is the weight of the project in the portfolio based on their initial investment proportional to the portfolio, y_i is the score of the project on that constraint.

I) Linear quantitative

a. Total Profits (NPV): The profit contribution of the project to the portfolio is summed using Net Present Value of the project
b. Discounted Payback period: Time required in months to reach break-even for the project.
c. Budget constraints: Maximum investment required for the project
d. Latency period: Time required to start the work on the project
e. Manpower required: Labour required for the project

II) Rating-scale

Every value here is denoted on a 9-point scale ranging from 1-9. Subpoints determining the value of those points must be noted down and given appropriate weights after a thorough discussion. Thus, the projects checking more of the boxes will be rated higher.

a. Strategic alignment with the organization's strategic goals
b. Market attractiveness

c. Technological expertise
d. Fit to existing supply chains
e. Product and competitive advantage
f. Leverage of core competencies
g. Scalability
h. Business synergies
i. Reputational risk
j. Operational risk
k. Financial risk

Here, for example, Strategic alignment can be scored with a checklist of 3 subpoints, each carrying different weights:

Subpoint	**Points**	**Project A**	**Project B**
Helps build rural consumer brand awareness	4	Yes	No
Reduces net carbon emissions	2	Yes	Yes
Strengthens the digital footprint of the firm	3	Yes	Yes
	Total	9	5

4. Results and Discussions

The experiment was run on the following case (Exhibit 1) wherein the goal was set to optimize the NPV of the project portfolio (Cell L3) while using cells in the Selection row to indicate whether the project was included in the portfolio or not (Cells B2:K2).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9	Project 10	Portfolio score	Relation	Allowed score
2	Selection	0	0	0	0	0	0	0	0	0	0			
3	NPV	₹ 22,922,845	₹ 13,304,862	₹ 7,479,108	₹ 23,583,858	₹ 5,510,027	₹ 27,034,383	₹ 1,839,675	₹ 31,625,379	₹ 6,742,233	₹ 38,524,149	₹ 0	>=	₹ 15,000,000
4	Market Attractiveness	9	9	7	7	8	5	8	9	8	9	0	>=	6
5	Fit to existing supply chains	5	6	9	6	5	9	5	5	9	7	0	>=	6
6	Product and competitive advantage	8	6	5	8	8	8	6	5	5	9	0	>=	6
7	Leverage of core competencies	5	6	8	9	9	9	7	9	7	5	0	>=	7
8	Scalability	7	5	8	7	5	5	8	7	9	9	0	>=	6
9	Business synergies	8	6	7	8	9	8	8	6	8	9	0	>=	6
10	Reputational risk safeguard	9	5	9	5	5	6	9	9	8	9	0	>=	7
11	Operational risk safeguard	5	6	8	7	9	6	7	9	5	5	0	>=	6
12	Financial risk safeguard	6	9	7	8	6	7	9	5	8	5	0	>=	6
13	Strategic Alignment	5	5	5	4	9	8	4	9	7	4	0	>=	6
14	Technological expertise	7	5	7	9	7	8	9	5	9	7	0	>=	5
15	Payback Period (months)	17	46	37	30	52	22	45	30	28	16	0	<=	24
16	Estimated Budget	₹ 12,410,642	₹ 12,137,640	₹ 12,027,294	₹ 11,423,516	₹ 15,071,998	₹ 18,749,422	₹ 16,614,732	₹ 11,214,847	₹ 16,673,638	₹ 11,223,418	₹ 0	<=	₹ 90,000,000
17	Latency period (months)	9	7	6	2	12	8	8	8	2	11	0	<=	9
18	Manpower required	38	26	13	31	31	20	1	42	44	41	0	<=	200

Exhibit 1 *Initialization of the sample case*

The initialization and solving were performed on Microsoft Excel 2019 using the Solver add-in.
The Solver allows for three solution algorithms:

- Simplex LP
- GRG Nonlinear
- Evolutionary

Simplex LP is largely used to solve linear problems. It is very robust, and assuredly provides the solution which is a global optimum.

GRG stands for “Generalized Reduced Gradient”. In its most basic form, this solver method looks at the gradient or slope of the objective function as the input values (or decision variables) are altered and determines that it has reached an optimum solution when the partial derivatives equal zero. GRG Nonlinear is the swiftest and lightest of the two nonlinear solving methods. That speed comes with a cost, though. The downside is that the solution you obtain with this system relies highly on the initial conditions and may not be the global optimum solution. The solver will most likely stop at the optimum local value closest to the initial conditions, giving you a solution that may or may not be optimized globally.

The Evolutionary algorithm is more robust than GRG Nonlinear because it has a higher probability of finding a globally optimum solution. However, this solver method is slower compared to the GRG Nonlinear. The Evolutionary method is built on the Theory of Natural Selection – which works well in this case because the optimum outcome has been well-defined beforehand. In simple terms, the solver initiates with a random “population” of sets of input values. These sets of input values are plugged into the model and the results are assessed relative to the target value. The sets of input values that result in a solution that’s closest to the target value are designated to create a second population of “offspring”. The offspring are a “mutation” or variation of the best set of input values from the first population. The second population is then assessed and a winner is chosen to create the third population. This goes on until an optimal is reached.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9	Project 10	Portfolio score	Relation	Allowed score
2	Selection	1	0	0	1	0	1	0	1	0	1			
3	NPV	₹ 22,922,845	₹ 13,304,862	₹ 7,479,108	₹ 23,583,858	₹ 5,510,027	₹ 27,034,383	₹ 1,839,675	₹ 31,625,379	₹ 6,742,233	₹ 38,524,149	₹ 143,690,614	>=	₹ 15,000,000
4	Market Attractiveness	9	9	7	7	8	5	8	9	8	9	7.495202343	>=	6
5	Fit to existing supply chains	5	6	9	6	5	9	5	5	9	7	6.674330219	>=	6
6	Product and competitive advantage	8	6	5	8	8	8	6	5	5	9	7.655175534	>=	6
7	Leverage of core competencies	5	6	8	9	9	9	7	9	7	5	7.546084935	>=	7
8	Scalability	7	5	8	7	5	5	8	7	9	9	6.768508445	>=	6
9	Business synergies	8	6	7	8	9	8	8	6	8	9	7.827653675	>=	6
10	Reputational risk safeguard	9	5	9	5	5	6	9	9	8	9	7.432183369	>=	7
11	Operational risk safeguard	5	6	8	7	9	6	7	9	5	5	6.329643015	>=	6
12	Financial risk safeguard	6	9	7	8	6	7	9	5	8	5	6.294642347	>=	6
13	Strategic Alignment	5	5	5	4	9	8	4	9	7	4	6.206682462	>=	6
14	Technological expertise	7	5	7	9	7	8	9	5	9	7	7.294774164	>=	5
15	Payback Period (months)	17	46	37	30	52	22	45	30	28	16	22.79532019	<=	24
16	Estimated Budget	₹ 12,410,642	₹ 12,137,640	₹ 12,027,294	₹ 11,423,516	₹ 15,071,998	₹ 18,749,422	₹ 16,614,732	₹ 11,214,847	₹ 16,673,638	₹ 11,223,418	₹ 65,021,845	<=	₹ 90,000,000
17	Latency period (months)	9	7	6	2	12	8	8	8	2	11	7.654574551	<=	9
18	Manpower required	38	26	13	31	31	20	1	42	44	41	172	<=	200

Exhibit 2 *The solution obtained using the Evolutionary solver*

As seen in the results above, the method helped select the optimal project portfolio that satisfies all constraints and maximizes the objective function.

5. Conclusions

This paper describes the different methods used in project selection, highlighting mathematical programming and optimization techniques. The complexity of mathematical programming can be condensed for the end user with the development of a decision support system, which assists the decision maker in selecting the set of projects that adds greater to the organization.

Some of the benefits of optimization models are: they lead to optimal project selection without bias and subjectivity. Optimization techniques consider relations between projects and other factors that other methods do not believe. Optimization techniques allow users to discover scenarios through sensitivity analysis for respective factors in the objective function and the constraints. Mathematical programming and optimization techniques depend on the availability and quality of the information about the candidate projects. The more details of the candidate projects, the more accurate the evaluation and selection process.

The high potential of mathematical programming and optimization techniques is based on their capacity to customization according to the needs of the executive team. The objectivity and robustness of the project selection process are improved setting the objective function and constraints that best reflect a precise situation.

This model is largely exhaustive of constraints that occur in real-world business problems and, hence, has a higher flexibility for use across various industries.

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