Is it Worth the Effort? – A Decision Model to Evaluate Resource Interactions in IS Project Portfolios

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Abstract. The adequate consideration of resource interactions among IS projects is a challenging but important requirement within IS project portfolio selection. However, the literature is silent on potential techniques for the identification and assessment of resource interactions. Moreover, the literature has so far neglected the question of the trade-off between time and effort invested in identifying and evaluating resource interactions caused by resource sharing among projects, compared to the benefits derived from this exercise, and the extent to which it is worth doing so thoroughly. Hence, our contribution is twofold. First, we suggest a technique to support the identification and evaluation of potentially economically relevant resource interactions. Second, we propose a decision model that allows to calculate a theoretical upper bound for the amount of effort that should be invested in improving estimates for identified interactions as part of the portfolio planning process.

Keywords: IS project portfolio selection, resource interactions, sensitivity analysis, identification, assessment, decision model

1 Introduction

Companies often use projects as an organizational form to conduct unique and complex tasks in increasingly dynamic markets (Gareis 1989). As a result, a so-called “projectification” of many organizations (Maylor et al. 2006) can be observed and the management strategy “management by projects” (Gareis 1989; Gareis 1991) has been suggested. Many firms therefore have to find ways of dealing with a growing number of project proposals and with the selection of the most appropriate projects for a project portfolio. As the Research and Development (R&D) literature suggests, there is evidence that the implementation of a consistent portfolio management process can provide the necessary tools to improve decision making in this area (Cooper et al. 2001). Such a consistent portfolio management – often implemented in form of a project management office (PMO) – typically impacts multiple organizational functions, such as multi-project resource management, knowledge management, and project selection (Pravitz and Levin 2006).

Project selection has become an increasingly “important and recurring activity in many organizations” (Archer and Ghasemzadeh 1999), which is also reflected in numerous project portfolio management approaches suggested in the literature (e.g., Archer and Ghasemzadeh 1999; Project Management Institute 2008; Bayney and Chakravarti 2012). Due to limited resources and organizational restrictions, there are usually more project proposals available for selection than can actually be undertaken within the financial and organizational constraints of a firm, so “choices must be made in making up a suitable project portfolio” (Archer and Ghasemzadeh 1999). In this regard “it is widely accepted that organizations must be able to understand the dependencies between projects in their portfolio in order to make appropriate project decisions for the best portfolio outcomes” (Killen and Kjaer 2012). Considering these interactions[1] may lead to valuable cost savings and higher benefits to an organization (Santhanam and Kyparisis 1996). According to Graves and Ringuest (2003) this especially holds for Information Systems (IS) projects.

The existence and potential impact of interactions is also supported by empirical evidence from practice. For example, based on a data set of 623 U.S. firms, Aral et al. (2006) identify non-proportional performance gains and, as an explanation, discovered complementarities between the implementation of Enterprise Resource Planning, Customer Relationship Management, and Supply Chain Management Systems. Engelstätter (2013) finds comparable results in a study of 927 German firms, and observes positive effects among three enterprise software systems when they are used together. Engelstätter attributes this observation to possible complementary effects among these software systems.

Whilst accounting for interactions among IS projects is an important requirement for avoiding unfavorable project portfolio selection (PPS) decisions, it is also a challenging and time

[1] In line with, e.g., Eilat et al. (2006) we use the term *interaction* synonymously to *interdependency* in this article.

consuming task. In this context Lee and Kim (2001) state that the "cost of [the] difficulty in data gathering for modeling is not as critical as the risk in selecting the wrong project without considering the interdependencies". In contrast, Phillips and Bana e Costa (2007) conclude that only the strongest interactions have an effect on decision making and therefore, only those should be considered.

Considerable effort is required in order to identify interactions among projects. In addition, determining an interaction's economic effect at the time of planning involves a high degree of uncertainty. This uncertainty may be mitigated by an in-depth analysis and assessment of potential interactions and their effects. However, the more detailed the assessment at an early stage of portfolio planning, the more effort has to be invested. This results in a trade-off between considering interactions in greater detail, on the one hand, and realizing the benefits of their consideration in the planning process, on the other.

Marsden and Pingry (1993) classify this kind of problem for situations in which accurate and technically solvable models exist, but for which the necessary input parameters are not available right away, as *unstructured* problems characterized by so-called *information unstructure*. To solve such problems Marsden and Pingry (1993) suggest developing or using adequate Decision Support Systems to gather the necessary information. Consequently, appropriate techniques have to be developed to support the decision regarding which interactions to account for and at which level of detail.

Aaker and Tyebjee (1978) introduced the following classification of interactions: (1) *overlap in project resource utilization* (hereafter referred to as *resource interactions*), (2) *technical interdependencies*, and (3) *effect interdependencies*. A similar classification has been used in numerous other articles (see, e.g., Eilat et al. 2006; Santhanam and Kyparisis 1996; Lee and Kim 2001). In addition, interactions may also manifest themselves in the form of risk, which may cause delays or budget overruns (Buhl 2012), and therefore, as part of assessing the overall risk of an optimal project portfolio, these types of interactions also have to be considered (Wehrmann et al. 2006). The interactions discussed most frequently in this context in the IS (e.g., by Santhanam and Kyparisis 1996; Lee and Kim 2001; Kundisch and Meier 2011b) as well as in the R&D literature (e.g., by Stummer and Heidenberger 2003; Doerner et al. 2006; Eilat et al. 2006) seem to be those associated with the sharing of common resources across projects. As reported to us during an explorative interview with a business executive from a mid-sized IT consulting firm, a typical example for such a resource interaction in practice results from assigning one project manager to similar projects. Often, the project manager may be able to carry over management related tasks conducted within one project to other projects. The interview partner reported that trying to leverage this type of synergy is, while guided by intuition and experience, not a rare occurrence in his company. Despite the high practical relevance of resource interactions, surprisingly little research can be found that supports the identification and quantification of resource interactions in greater detail. The focus of our paper, therefore, is the consideration of resource interactions.

Resource interactions arise from the shared use of different types of resources among two or more projects. Commonly, IS resources are categorized into human resources and assets, such as hard- and software, contracts and licenses (e.g., access to databases), and facilities (Bonham 2005). The literature features numerous articles on the question of how to address resource interactions in the context of Operations Research (OR) decision models (e.g., Carazo et al. 2010; Doerner et al. 2006; Eilat et al. 2006; Lee and Kim 2001). Nevertheless, two major issues remain to be addressed: first, the lack of techniques for the *identification* and *evaluation of* potentially influential resource interactions and, second, the lack of clarity as to whether or not it actually pays off to identify and assess all the potential resource interactions occurring among a set of projects. Thus, the application of elaborate OR decision models in business practice is severely hampered. In this paper we contribute to filling this research gap by answering the following two research questions:

1) How can the identification and evaluation of potential *economically relevant* resource interactions among projects be adequately supported?
2) How much effort should be invested in the assessment of those resource interactions?

The decision problem at hand is to select the most promising projects for a project portfolio while simultaneously considering potential resource interactions. Thus, the focus is on resource interactions which could influence the selection decision. For the remainder of this paper, therefore, we regard any resource interaction as *economically relevant* if it can be expected to have sufficient potential for affecting not only the optimal portfolio composition but, by implication, the expected business value of the portfolio. To address research question 1), we extend the widely acknowledged portfolio selection framework presented by Archer and Ghasemzadeh (1999). Using these extensions, and following the Design Science research approach (Hevner et al. 2004), we then describe the concept of our IS artifact by which resource interactions can be identified semi-automatically. The artifact aims at identifying, pre-evaluating and ruling out a large number of resource interactions before the planner has to invest any efforts in their identification or quantification. The theoretical foundation of our work is rooted in the field of decision theory. For our research, we adapt the concept of *perfect clairvoyance* (or *perfect information*) from *information value theory* by Howard (1966) as the high level kernel theory (see Kuechner and Vaishnavi 2012). To address research question 2), inspired by Kira et al. (1990), we utilize this concept and combine it with sensitivity analysis.

It is important to note that the decision making activities and tasks presented in this paper only form one of the elements of a thorough portfolio management approach. A more comprehensive approach should comprise a series of other tasks which overlap with other key organizational functions of a PMO, such as multi-project resource management and knowledge management. Collecting, compiling and providing historical project data is one of the key functions of a PMO (Pravitz and Levin 2006). Such data can provide valuable inputs for, and hence, enhance our approach. For example, storing the resource matching, estimates and calculations conducted within our approach could improve future iterations of the PPS as part of the PMO's knowledge management responsibilities, at the same time as facilitate organizational learning.

2 Literature Review

Project portfolio selection (PPS) is a "[…] multi-person decision making process involving a group of decision makers […]" (Tian et al. 2005). An important challenge in PPS is the closer investigation of resource interactions among project candidates and their adequate incorporation into the PPS decision process. A number of sophisticated approaches have already been developed in the IS, the R&D and the OR literature (e.g., Aaker and Tyebjee 1978; Carazo et al. 2010; Doerner et al. 2006; Gear and Cowie 1980; Lee and Kim 2001; Santhanam and Kyparisis 1996; Stummer and Heidenberger 2003; Lourenco et al. 2012; Weingartner 1966)[2] providing useful techniques for modeling and solving PPS problems under consideration of resource interactions. Santhanam and Kyparisis (1996), for example, utilize linear programming techniques to account for higher order (more than pairwise) interactions, or more recently, Stummer and Heidenberger (2003) were among the first to provide modeling techniques that take into account interactions for groups of projects. According to Fox et al. (1984), one of the major difficulties when applying such models, however, is the difficulty "to assess the interactions directly [which] can be traced back at least in part to the lack of a modeling framework within which different types of interaction can be identified and related to project and portfolio benefit".

Few articles can be found in the literature that facilitate the process of identification and evaluation of interactions. Dickinson et al. (2001) and Eilat et al. (2006), for example, suggest using so-called *dependency matrices*. For each specific resource, a matrix is created, where rows and columns represent the candidate projects. The elements on the diagonal represent the requirements of the individual project for this resource, while those off the diagonal represent the positive or negative effect on the demand for the resource resulting from an interaction between two projects. While this approach provides first assistance for visualizing resource interactions, its applicability and comprehensibility for IS PPS is limited due to the potentially large number and size of tables required. Another issue with dependency matrices is that this type of visualization "does not reveal accumulated or multi-level interdependencies" (Killen and Kjaer 2012), a factor deemed necessary for IT modeling (see e.g., Santhanam and Kyparisis 1996; Graves and Ringuest 2003).

Killen and Kjaer (2012) suggest visualizing interactions by using a network-based visualization technique they call *visual project mapping* to identify projects within the set of project proposals that yield a high interaction density. Using a visualization of a directed graph that consists of nodes and connecting edges between them, each project is depicted as a node in a network and each connection represents an interaction between two projects. The diameter of the nodes represents the degree of interconnectedness of the particular project.

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[2] For comprehensive literature reviews see Chien (2002), or Kundisch and Meier (2011a).

The larger the node, the more interactions the corresponding project is involved in. The authors note that different visual elements such as, for example, different arrow types, may be used to further distinguish between different types of interactions.

Kundisch and Meier (2011b) present a *resource classification scheme* that provides a basis for the identification of resource interactions. They suggest identifying interactions at different levels of granularity (either by *resource unit* or by *type of resource*), depending on the corresponding properties and availability of the resources. Potential resource interactions are then identified either for each physical unit of a certain resource (e.g., a specific server), or for a set of similar resources (e.g., man hours of Java programming skills).

Another recent approach for the assessment of interactions has been suggested by Ghapanchi et al. (2012). The authors use *data envelopment analysis* to calculate the best portfolios under the consideration of interactions. For the assessment of interactions, they suggest providing detailed descriptions of each project to a group of experts who are tasked with estimating the interaction for each pair of projects by filling out a questionnaire.

The following issues remain unsolved by the approaches found in the literature: First, adequate techniques for the actual identification of interactions are widely missing, as current approaches focus on *visualization* rather than on *identification*. Second, it remains unclear how much effort should be invested in the identification and evaluation of interactions. Expert estimation constitutes a very useful but expensive technique to estimate interactions: for a pairwise consideration the number of potential interactions needing to be analyzed increases quadratically with the number of projects. Even without considering higher order interactions, this would require a substantial a priori estimation effort, while at the early stages in the planning process it is still unclear whether the estimated interactions will have any influence on the portfolio selection decision. Motivated by these research gaps, we suggest an approach that leverages the modeling flexibilities and analytical rigor provided by OR techniques. Combining them with concepts from information value theory and expert estimation to identify economically relevant resource interactions in a pragmatic but effective manner then allows us to develop a technique that may provide the foundation for a more elaborate and theoretically founded investigation of the economic value of resource interactions in IS PPS.

3 Identification and Evaluation of Resource Interactions

3.1 Design Choices and Model Description

Several design choices have to be made when formulating a decision model. In the following sections, we conceptually describe the key features of our decision model and explicate the most important design choices. Numerous techniques are available for the modeling of an IS PPS problem. The selection of an adequate modeling technique often depends on the special requirements resulting from a specific organizational context. Among the techniques most frequently used in the literature are scoring models (e.g., Nelson 1986), dynamic programming (e.g., Nemhauser and Uhlmann 1969), multi-criteria optimization (e.g., Stummer and Heidenberger 2003) and multi-criteria heuristic optimization (e.g., Doerner et al. 2006) as well as linear integer programming techniques (e.g., Ghasemzadeh et al. 1999). We employ 0-1 quadratically-constrained programming on account of the modeling flexibilities it offers, the wide range of high end mathematical solvers available as well as the available interfaces to high level programming languages (e.g., Java or C#).

We assume a typical, recurring situation in business practice where a set of project proposals is available for selection at a given point in time (Archer and Ghasemzadeh 1999). Each of these projects may either be conducted completely or not be selected for the portfolio. While in some papers partial funding of projects is also applied (e.g., Beaujon et al. 2001), we utilize this binary formulation mainly because of its ease of interpretation by decision makers. Additionally, different discrete levels of funding may be realized by introducing a binary decision variable for each funding level and declaring the different modes of a single project as mutually exclusive projects (see, e.g., Ghasemzadeh et al. 1999). We use a single criterion objective function that is aimed at maximizing the monetary benefits of the portfolio, whereas resource costs, resource constraints and budget constraints are formulated exclusively within the restrictions of the model, but without directly influencing the value of the objective function (see, e.g., Santhanam and Kyparisis 1996; Ghasemzadeh and Archer 2000). This enables the given resources to be exploited as much as possible without violating the given constraints. The binary decision variable x_j is defined as follows:

$$x_j = \begin{cases} 0, project\ j\ has\ not\ been\ selected\ into\ the\ portfolio \\ 1, otherwise \end{cases} \tag{1}$$

With b_j being the benefit of project j and N the total number of projects available for selection, this results in the objective function depicted in Eq. (2). The second summand has been added to the objective function to force the non-negative auxiliary variable z_r for each resource r (see Eq. (8)) to become zero, if no additional resource units of the corresponding resource is required. The parameter m represents a marginally small positive number, which is required for modelling purposes.

$$max \sum_{j=1}^{N} x_j \cdot b_j - m \cdot \sum_{r \in R} z_r \tag{2}$$

Furthermore we define the following sets:

R	:	Set of available resources
P_i	:	Set of projects belonging to a resource interaction i
S	:	Set of resource interactions
S_r	:	Set of resource interactions for a particular resource $r \in R$

Additionally we define the following variable:

$$g_{j,i} = \begin{cases} 1, project\ j\ is\ participating\ in\ interaction\ i\ (j\ \in\ P_i) \\ 0, otherwise \end{cases} \qquad (3)$$

A resource interaction can be defined as $i \in S$. Let I represent the total number of resource interactions. The effect f_i of a given interaction i can either be cannibalizing or synergistic. For each interaction i the effect f_i has to be determined based on the set P_i of projects constituting this particular interaction, and the number of projects from P_i being chosen for the portfolio. With a minimum of m_i and a maximum M_i projects out of P_i are chosen for the portfolio, interaction i is considered to be *active*, inducing the effect f_i (this modeling technique is also used in Stummer and Heidenberger 2003). To represent this within the model, we introduce the variable $h_i = h_i^m \cdot h_i^M$, which equals 1 if the interaction is active, and 0 if it is not.

$$h_i^m = \begin{cases} 0, & when\ up\ to\ m_i - 1\ projects\ out\ of\ P_i\ are\ selected \\ 1, & when\ at\ least\ m_i\ projects\ out\ of\ P_i\ are\ selected \end{cases} \qquad (4)$$

$$h_i^M = \begin{cases} 0, & when\ at\ least\ M_i + 1\ projects\ out\ of\ P_i\ are\ selected \\ 1, & when\ up\ to\ M_i\ projects\ out\ of\ P_i\ are\ selected \end{cases} \qquad (5)$$

The following two constraints set the variables h_i^m and h_i^M.

$$\left(\sum_{j \in P_i} x_j\right) - m_i + 1 \le N \cdot h_i^m \le \left(\sum_{j \in P_i} x_j\right) - m_i + N \qquad (6)$$

$$M_i - \left(\sum_{j \in P_i} x_j\right) + 1 \le N \cdot h_i^M \le M_i - \left(\sum_{j \in P_i} x_j\right) + N \qquad (7)$$

Resources are usually scarce and therefore resource constraints need to be included in the model. The demand of project j for a resource r is denoted as $d_{j,r}$. A_r is the maximum available capacity of the resource r. We also provide for the possibility that the maximum capacity for a specific resource r may be exceeded. This allows the planner to model the procurement of additional units of a particular resource from outside sources (e.g., acquiring additional hardware). The variable z_r represents the exceeding demand for resource r and is equal to zero, if no additional resource units are required. With the possible occurrence of interactions, this results in the following resource constraints:

$$\sum_{j=1}^{N} x_j \cdot d_{j,r} \cdot \left(1 + \sum_{i \in S_r} h_i \cdot f_i \cdot g_{j,i}\right) \le A_r + z_r \qquad \forall r \in R \qquad (8)$$

The costs induced by all realized projects must not exceed the budget B. We need to distinguish between resource specific fixed costs c_r^{FIX} and resource specific variable costs c_r^{VAR} and c_r^{VARex}, respectively.[3] We define the overall variable costs C_r^{VAR} caused by the consumption of each resource in Eq. (9). Therefore, we have to separate the demands $d_{j,r} - z_r$ and z_r to be able to apply the two different cost parameters c_r^{VAR} and c_r^{VARex}. The additionally required resource units z_r are accounted for with the cost parameter c_r^{VARex} in the calculation of the variable costs in Eq. (9) as well as in the budget constraint in Eq. (12).[4]

With $X^{sum} = \sum_{j=1}^{N} x_j$ being the number of chosen projects we have:

$$C_r^{VAR} = c_r^{VAR} \cdot \left(\sum_{j=1}^{N} x_j \cdot \left(d_{j,r} - \frac{z_r}{X^{sum}} \right) \cdot \left(1 + \sum_{i \in S_r} h_i \cdot f_i \cdot g_{j,i} \right) \right) + z_r \cdot c_r^{VARex} \; \forall r \in R \quad (9)$$

To account for fixed costs, we define the binary variable y_r as depicted in Eq. (10):

$$y_r = \begin{cases} 0, if\ none\ of\ the\ selected\ projects\ has\ a\ demand\ for\ r \\ 1, if\ at\ least\ one\ selected\ project\ has\ a\ demand\ for\ r \end{cases} \quad (10)$$

The sum of the fixed costs C^{FIX} is:

$$C^{FIX} = \sum_{r \in R} y_r \cdot c_r^{FIX} \quad (11)$$

And the budget constraint is:

$$C^{FIX} + \sum_{r \in R} C_r^{VAR} \leq B \quad (12)$$

The variable y_r is set using the following constraints (depending on the problem at hand, L has to be set to a value large enough not to restrict the solution):

$$\sum_{j=1}^{N} x_j \cdot d_{j,r} \leq L \cdot y_r \; \forall r \in R \quad (13)$$

[3] Alternatively to the fixed cost parameters introduced above, it is also possible to formulate parametric functions that represent the marginal cost decrease or increase for additional resource units.

[4] Please note that Eq. (8) and Eq. (9) implicitly assume that additionally acquired resources, and not just internally available resources, are able to contribute to synergies/cannibalization effects.

$$y_r \leq \sum_{j=1}^{N} x_j \cdot d_{j,r} \ \forall r \in R \tag{14}$$

Additionally, all variables must be equal to or greater than zero. The quadratically-constrained model presented above can be solved with top of the line solvers (e.g., Gurobi, http://www.gurobi.com). If the used solver is not capable of solving quadratically-constrained programming problems the mathematical model might have to be linearized by a set of linear constraints.

3.2 Procedural Approach

Resource interactions can be identified automatically by the system[5] if the necessary information about the available resources and the resource demands are provided in a sufficiently detailed and consistent format. Our procedural approach is inspired by the portfolio selection framework presented by Archer and Ghasemzadeh (1999). We refine the framework by introducing the phases *Resource Matching*, *Identification Phase*, and *Evaluation Phase* (as depicted in Fig. 1). The three phases will be discussed in the following.

3.2.1 Resource Matching

Archer and Ghasemzadeh (1999) define the estimation of a set of common measures (such as Net Present Value, Return on Investment) which enables the comparison of different projects as a main goal of their *Individual Project Analysis* Step. We extend this step with *Resource Matching* (see Fig. 1). As part of *Resource Matching*, the resource requirements are estimated in greater detail by experts (e.g., members of the IS department). As an extension to Archer and Ghasemzadeh's framework, we suggest creating a superset of all resources based on their denotations taken from the project proposals. Resources comprise human resources and assets like hard- and software, infrastructure and facilities, as well as contracts and licenses (e.g., access to databases) (Bonham 2005). This means that our proposed approach is very generic in nature. It is worth drawing attention to the existence of key resources with limited capacity such as human specialists with a unique skill set or know-how required across many projects, and which often are of particular interest to an organization. To be able to consider potential interactions, each key resource has to be treated explicitly as a single resource unit in our approach and added separately to the resource pool. Non-key resources may simply be pooled by resource type (see Kundisch and Meier 2011b). Once all resources from project proposals have been identified, the resulting superset of resource denotations has to be semantically matched (e.g., following Colucci et al. 2013). Based on this matching the denotations of the resources are unified. After the matching, the superset must not contain resources that are *functionally* or *physically identical*, but are referred to *differently* within different proposals. This allows the removal of unnecessary and unwanted ambiguity from the resource

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[5] The optimization *model* is part of a prototypically implemented decision support software; in the following referred to as *system*.

specifications. When no matching is conducted, inconsistencies may arise in the portfolio selection process. For example, when a functionally similar (or even identical) resource is referred to inconsistently across project proposals, it is more costly for a portfolio planner to identify potential resource interactions within the corresponding proposals. This may result in unnecessary identification efforts or in higher overall resource demands of the portfolio. Once the resource demands of project proposals are unified, the system is able to automatically identify the usage of the same resource (or resource type).

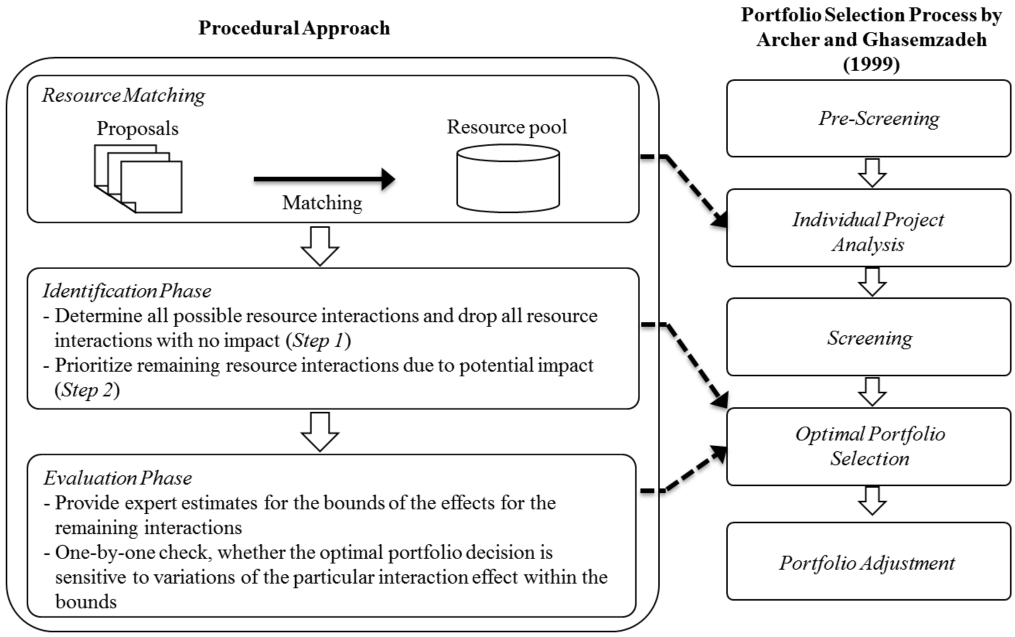

Fig.1. Procedural Approach

3.2.2 Identification Phase

The Identification Phase is integrated in the Optimal Portfolio Selection Step by Archer and Ghasemzadeh (1999). In this phase, the goal is to automatically reduce the number of potentially relevant interactions and to identify the most influential ones *before* an expensive expert estimation is required (see Fig. 1). Reducing the number of interactions down to a manageable amount is essential, as is illustrated in this simple numerical example: Even in the case of a comparatively small set of 20 project proposals and 5 different resources a theoretical maximum of over 5 million potential interactions – including not only pairwise but also higher order interactions – may occur. Although it seems to be rather unrealistic that a resource interaction should exist among each potential subset of projects on each resource, the number of interactions that a planner would have to assess is still likely to be extremely high, especially in business environments with a large number of project proposals.[6] We achieve

[6] For instance, the average number of projects in R&D and IT project portfolios in large and mid-sized firms, according to a cross industry study of Meskendahl et al. (2011), is 132. Obviously, the number of project proposals will typically be even much higher.

such a reduction by only considering interactions that have the potential to influence the selection decision. Therefore, at first, an optimal portfolio *PF* is computed without accounting for interactions and used as a reference portfolio in a two-step procedure (see Fig. 1) described later on.[7]

To illustrate the approach, we use and adapt a numerical example from Schniederjans and Wilson (1991) and Lee and Kim (2001) that comprises an artificial set of six projects *j* with *j* = 1…6 and four resources res_r with $r = 1...4$ (see Tab. 1 for further details).

Tab.1. Numerical Example: Projects, resources, and resource consumption matrix

		res_1	res_2	res_3	res_4	
Project	**Mandated**	**Programming (hours)**	**Analytical (hours)**	**Clerical (hours)**	**Hardware (in Units)**	**Benefits (in 1,000 $)**
1	Yes	5,000	1,500	750	60	1,500
2	No	9,000	1,100	700	20	410
3	No	1,000	1,500	450	50	210
4	No	1,000	1,700	700	40	210
5	No	1,550	1,600	650	55	950
6	No	1,700	1,450	800	50	750
Max. Available		*12,000*	*5,000*	*3,000*	*180*	
Variable Costs per Unit		*80 $*	*100 $*	*65 $*	*1,000 $*	
Budget Constraint		*1,835,000 $*				

To improve the applicability of the example, we adapted it by separately modelling hardware costs and pooled hardware resources with unit costs of 1,000 $. We further introduced variable costs for each resource and applied a budget constraint in addition to capacity constraints. The upper bound for the budget constraint is calculated by the sum of the variable costs per unit multiplied by the number of resource units available. Each project has a certain benefit and all resources have a certain capacity limit as depicted in Tab. 1. Please note that for comprehensibility reasons, we assume that resource capacities cannot be exceeded by, for example, the procurement of additional resource units from outside the company. The mandated project 1 has to be included in the portfolio.[8] Due to resource constraints, without considering any interactions, portfolio *PF* would be the optimal choice consisting of Project *1, 5,* and *6* (from now on denoted as *PF* = {*1, 5, 6*}) with a total benefit of 3,200,000 $.

Step 1: For each of the identified interactions the impact of the interaction is examined one at a time. Starting from an interaction value of 'zero' (resource consumption is unaffected by the interaction) the optimal portfolios PF_u and PF_l are calculated, including the interaction at its

[7] To calculate *PF*, we assume that all input parameters necessary for our quadratically-constrained 0-1 program are known with certainty.

[8] Relaxing the contingency restrictions from the example of Lee and Kim (2001) enabled us to better illustrate the functionalities of our approach.

corresponding lower and upper bounds. The selection of these bounds determines the impact up to which an interaction is evaluated in our approach. On the one hand, selecting bounds that are too narrow may lead to the exclusion of potentially relevant interactions. On the other, bounds that are too large may be unable to separate potentially influential interactions from uninfluential ones effectively, so that too many interactions remain in the process to be considered adequately in the subsequent step. Our approach provides the opportunity to define these bounds individually in case a planner wishes to set these initial bounds by herself. Alternatively, we implemented a default procedure to determine first bounds as follows. Without knowledge of the strength or direction of impact (increasing or decreasing the overall resource consumption), the interactions' initial bounds may be derived automatically, relative to the unmodified sum of the resource demands for a specific resource of all the projects which participate in this particular interaction. The lower bound of an interaction represents the largest reasonable synergistic effect of a resource interaction. Therefore, we suggest setting this lower bound to the resource demand of the project (from the set of projects participating in that particular interaction), which exhibits the highest independent demand for that particular resource. Relatively speaking, the selection of a lower bound as suggested leads to a situation where the project with the largest independent demand for a resource uses its initially planned amount of the resource, and the demands for this particular resource from all other projects are reduced to zero.

Defining a comparable rational upper bound for an interaction is more difficult because, to the best of our knowledge, there is no empirical or theoretical information available to assess the potential strength of the cannibalizing effects of resource interactions. Covering a deliberately large range, we suggest using symmetric bounds in a first step. A symmetric upper bound would cover situations where a single interaction causes the project with the highest individual demand to require 100% of the initially planned amount, and all other participating projects 200% of their independently planned demands for the particular resource. Setting the upper bound this way weakly relates to a recent study of Flyvbjerg and Budzier (2011), who found that in a sample of 1,471 IT projects, one out of six IT projects exhibited a cost overrun of approximately 200 % of the initially planned costs, while the average cost overrun in the sample was 27 %.

We illustrate the calculation of the bounds with the example of resource interaction $i_1 = (res_4, \{1, 5, 6\})$ concerning resource res_4. In our example, the sum of the combined demand of the participating projects is 165 resource units of res_4 (see Fig. 2). From the aforementioned projects, the highest demand for res_4 is 60 units. According to our approach the lower bound would be 60 and the upper bound 270 resource units. Converted to a percentage measure (as depicted in Fig. 3), the bounds for interaction i_1 will thus be -0.6364 and 0.6364. Our system provides the option of adjusting the bounds and thus allows the planner to experiment with different interval lengths. After automatically calculating PF_u and PF_l, their portfolio compositions are compared to the composition of PF. If the sets of projects within PF, PF_u and PF_l are identical, the corresponding interaction has no effect on the portfolio selection decision and, thus, it is excluded from further consideration in step 2.

Fig. 2 depicts the optimal portfolio *PF* with the interaction i_1 set to zero as well as PF_u and PF_l at the interaction's upper and lower bound. For effect values of zero the optimal portfolio would consist of the projects $PF = \{1, 5, 6\}$ and for an interaction value of 0.6364 the optimal portfolio would be $PF_u = \{1, 3, 4\}$. At the lower bound l = -0.6364, the optimal portfolio composition would contain $PF_l = PF = \{1, 5, 6\}$. Because the selection decision varies for different realizations of i_1, the interaction has to be considered within step 2.

As the number of the remaining interactions after this reduction may (still) be very high, our system provides the possibility of further reducing the number of interactions. The planner may specify a maximum number of *k* projects participating in an interaction. Consequently, the system will then only identify interactions among at most *k* projects. This allows the planner to further reduce the complexity of the decision problem, especially in light of the fact that the assessment of interactions tends to become more difficult with a corresponding increase in the number of projects involved.[9]

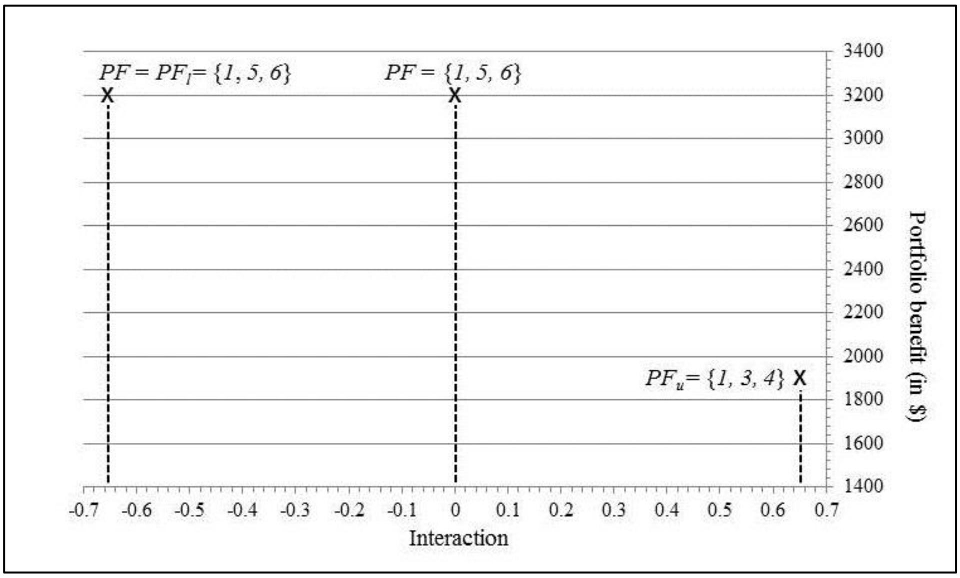

Fig.2. Example: Potential effect of interaction i_1 on the selection decision

Step 2: The interactions that have not been excluded from further consideration in Step 1 have to be prioritized according to their potential impact on the benefit of the portfolio. Therefore, we calculate the benefit difference Δv between PF_l and PF_u for each of the remaining interactions *i*. The effects of interactions with a higher Δv value entail a higher potential for suboptimal decisions and should be analyzed in greater detail (this is of special importance for situations where a cannibalizing interaction would make the reference portfolio infeasible). In our example, 45 resource interactions (from a total of 139) have an impact on the optimal portfolio selection decision[10]. Tab. 2 shows the top five interactions ranked according to their

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[9] Referring to the example in the introduction of section 3.2.2, for 20 projects, five resources and only up to three projects (k = 3) per interaction, the potential number of interactions would be reduced from over 5m to 6,650.

[10] Please note that we have limited the number of projects participating in an interaction to k = 3 projects per interaction to keep the example comprehensible.

Δv. In case of equal Δv for different interactions we use the number of involved projects as a tie-breaker, favoring lower order interactions.

Tab.2. Example: Ranking of influential interactions (top 5 out of 45)

Rank	Interaction	Δv	#Projects	Is subset of	Is superset of
1	(res_4, {$1, 5, 6$})	1,280	3	-	(res_4, {$1, 5$})* (res_4, {$1, 6$})* (res_4, {$5, 6$})*
2	(res_2, {$1, 5, 6$})	950	3	-	(res_2, {$1, 5$})* (res_2, {$1, 6$})* (res_2, {$5, 6$})*
3	(res_1, {$1, 5, 6$})	750	3	-	(res_1, {$1, 5$})
4	(res_1, {$1, 5$})	740	2	(res_1, {$1, 5, 6$}) (res_1, {$1, 2, 5$}) (res_1, {$1, 3, 5$})* (res_1, {$1, 4, 5$})*	-
5	(res_1, {$1, 2, 5$})	740	3	-	(res_1, {$1, 5$}) (res_1, {$1, 6$})*

*: interaction is among the 45 influential interactions, but is not illustrated in this table for better comprehensibility

When analyzing higher order interactions (among more than 2 projects on the same resource), the effects of the lower order interactions are included in the effect of the higher order interaction, as the analyzed effect range is naturally larger for the higher order version. In case of the numerical example mentioned above, for the interactions (res_4, {$1, 5$}) and (res_4, {$1, 5, 6$}) the analyzed bounds are [60, 170] and [60, 270], respectively. Apparently, the addition of project *6* to the interaction will automatically cause a larger range for the analysis. The lower bound nevertheless continues to make the highest demand of all single projects forming the interaction in consideration. Interactions that are related to other interactions regarding the same resource *and* that have a potential influence on the selection decision (e.g., as (res_4, {$1, 5$}) and (res_4, {$1, 5, 6$})) are marked correspondingly in the columns *'is subset of'* and *'is superset of'* in Tab. 2. Thus, when deciding which of the most influential interactions will be selected for the actual portfolio optimization, the planner can avoid the inclusion of redundant interactions. If, for example, (res_4, {$1, 5, 6$}) has been selected for further consideration, the subsets of this interaction (e.g., (res_4, {$1, 5$})) should be excluded because its effect is already contained within interaction (res_4, {$1, 5, 6$}). For better comprehensibility, Tab. 2 only depicts the top five (out of 45 identified) potentially influential interactions. Interactions for which no impact could be identified by our approach are not marked as subsets or supersets in order to reduce the table size.

3.2.3 Evaluation Phase

The thorough identification and evaluation of interactions can be a time consuming task even after having reduced the number of potential interactions in the *Identification Phase*. In the next phase we utilize the concept of *perfect information* adopted from decision theory to obtain a theoretical upper bound for the effort that should be invested in the reduction of uncertainty within the estimates for interactions. To this effect, the set of bounds defined automatically in the *Identification Phase* has to be substituted with new, more realistic lower and upper bounds l_i and u_i for each remaining interaction from the *Identification Phase*. A first (rough) estimate for these bounds will typically be derived by expert estimation, as suggested by Topilla et al. (2011), for example. To guide the estimation process, one may employ already established expert estimation methods (e.g., like the Delphi method, or group expert estimation) to provide a structured approach for this estimation. If an organization has already adopted a knowledge management approach, historical project data can serve as a baseline, or to improve on estimated data. Similarly, it would be useful to record estimates made by experts in order to inform estimates for resource interaction effects in future project selection iterations.

The lower bound represents an optimistic realization of the effect in consideration, while the upper bound represents a conservative, pessimistic realization of the interaction effect. For example, for i_1 a planner might estimate that conducting the three related projects could result in an increase of resource usage between 0 % and 60 % because of switching costs within the tasks to perform ($l_i = 0.0;\ u_i = 0.6$, see Fig. 3). Once an estimate for these two bounds is provided, the optimal portfolio composition $PF_{l,i}$ and $PF_{u,i}$ can be computed with the interaction effect being at its lower and upper bound, respectively. If the projects within these two portfolios are identical, the realization within the bounds of the corresponding interaction has no effect on the portfolio composition – and, thus, on the portfolio benefit – within the estimated interval. Consequently, no further effort should be invested in improving the initial estimation of this particular interaction effect. Naturally, a conservative planner will make use of the estimated upper bound in the portfolio selection. The corresponding interaction will *not* be subject to further expert analysis. If the portfolio compositions $PF_{l,i}$ and $PF_{u,i}$ differ, further algorithmic steps are conducted as follows: For a number of predefined discrete interval steps, the realization *s* of the corresponding interaction effect is decreased stepwise from the upper to the lower bound (as depicted in Fig. 3).

For the reference portfolio decision without further information, we use portfolio *PF* without considering interactions, as calculated in section 3.2.2. Then, for each realization *s* of the effect of the particular interaction under consideration, the optimal portfolio $PF_{i,s}$ is calculated, which represents the best selection decision assuming that the interaction effect at hand will have the realization *s* with certainty. To calculate the expected value of perfect information, we now have to calculate the benefit difference $d_{i,s}$ between the reference portfolio *PF* (without information) and the optimal portfolio $PF_{i,s}$ for each realization *s*. For this, we have to consider the following three cases (see Tab. 3):

Case 1: In case of the bounds estimated by the planner being narrower than the bounds calculated initially by the system it is possible that the interaction has no economically relevant effect within the new bounds. The portfolios *PF* and $PF_{i,s}$ are then identical, which results in a benefit difference $d_{i,s} = v(PF_{i,s}) - v(PF) = 0$. In this case, the knowledge that the realization s will occur with certainty will yield no benefit and the decision would be the same as without this information.

Case 2: Due to resource synergies, additional projects or an entirely different portfolio with a higher benefit may become feasible. In this case, the benefit difference $d_{i,s}$ will be positive and the certain knowledge of the realization of the corresponding interaction will result in a better portfolio decision ($PF_{i,s}$ instead of PF).

Case 3: In case of an interaction due to resource cannibalization, the situation may occur that for certain realizations s of the interaction the reference portfolio may not be feasible as planned initially. In this case, only a subset of projects selected within PF can be conducted due to reduced resource availability. Thus, a reduced benefit value has to be calculated for PF (in the following referred to as the reduced reference portfolio $PF^{red}_{i,s}$) under the new circumstances resulting from realization s of the interaction effect. We suggest using the subset of projects from PF which provide the highest benefits under these circumstances. In this case, we have to further distinguish between two subcases 3a and 3b.

Case 3a: If the optimal portfolio $PF_{i,s}$ only consists of projects that are a subset of PF as well, there is no benefit associated with knowing that the corresponding realization s will occur with certainty, because the selection decision is the same as without having further information on the realization of the interaction effect. Here, the potential costs associated with cancelling the corresponding project(s) as well as the potential benefits resulting from interim results, are neglected for simplicity. In this case the benefit difference $d_{i,s}$ is set to zero for the corresponding realization s.

Case 3b: If the composition of the optimal portfolio $PF_{i,s}$ differs from the reduced portfolio $PF^{red}_{i,s}$, the benefit difference between $PF^{red}_{i,s}$ and $PF_{i,s}$ may be calculated as $d_{i,s} = v(PF_{i,s}) - v(PF^{red}_{i,s})$.[11]

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[11] We assume that existing resources generate fixed costs, even if they are not used to full capacity (e.g. personnel). If this assumption is relaxed, we have to introduce penalty costs to estimate the residual value of the reduced portfolio $PF^{red}_{i,s}$ accordingly.

Tab.3. Case Overview

	Benefit v	Benefit difference	Effect
Case 1:	Projects in PF and $PF_{i,s}$ are identical	$d_{i,s} = 0$	No effect
Case 2:	$PF_{i,s}$ comprises more, or different projects with a higher overall benefit as PF	$d_{i,s} = v(PF_{i,s})- v(PF)$	Synergy
Case 3			
3a:	Projects in reduced portfolio $PF^{red}_{i,s}$ and $PF_{i,s}$ are identical, both are subsets of PF	$d_{i,s} = 0$	Cannibalization
3b:	Projects $PF_{i,s}$ are differing from projects in PF. $PF_{i,s}$ yields a higher overall benefit.	$d_{i,s} = v(PF_{i,s}) - v(PF^{red}_{i,s})$	

The choice of the underlying probability distribution for the realizations of the interval steps potentially influences the ranking of the interactions later on. Different distributions for the occurrence probabilities provide different relative weights to the value differences $d_{i,s}$ for each realization s. If information on the underlying probability distribution of a considered interaction is available, this probability distribution should be used. In cases where this information is not available, assumptions about the occurrence probabilities have to be made to be able to calculate an expected value for the amount of money-equivalent effort that should be invested by the planner towards improving the estimation accuracy for the future realization of the interaction effect i. Therefore, if the true distribution of the occurrence is unknown, we provide the option to choose between pre-implemented distributions instead. Our prototype already offers the possibility of choosing between a triangular distribution and a uniform distribution while other user defined distributions can be easily implemented. To illustrate the functionality of our approach, for comprehensibility of the numerical example we assume that each realization of s has the same occurrence probability over the specified interval (i.e., we assume a discrete uniform distribution)[12]. This allows us to calculate an expected value for the money-equivalent effort. This money-equivalent effort may be invested in activities such as the application of a more precise estimation method (e.g., Delphi method), the involvement of additional experts (internal or external), and the gathering of more precise or additional information on both the project and on the properties of the resource in question. While in reality, perfect information may rarely be obtainable, the concept presented above can be applied to generate initial evidence on the economical relevance associated with the identification and evaluation of resource interactions in IS PPS.

[12] For a triangular distribution, for example, the mode is set to the point estimate provided by the expert, while the upper and lower bounds derived by expert estimation provide the minimum and maximum values for the distribution, respectively. The probabilities for the occurrence of each realization s can then be calculated and serve as weights for the corresponding benefit differences $d_{i,s}$. To calculate the probabilities for each individual s, the interval between the bounds has to be discretized into a number of subintervals. For each subinterval, its expected value serves as the realization of the interaction under investigation for the corresponding optimization step. The area defined by the interval and the triangle defining the distribution then serves as probability for the occurrence of this realization.

Fig. 3 provides an example of this approach for interaction i_1, given an expert has selected 0.0 and 0.6 as the lower and upper bounds (and assuming the same occurrence probabilities for each realization *s*).

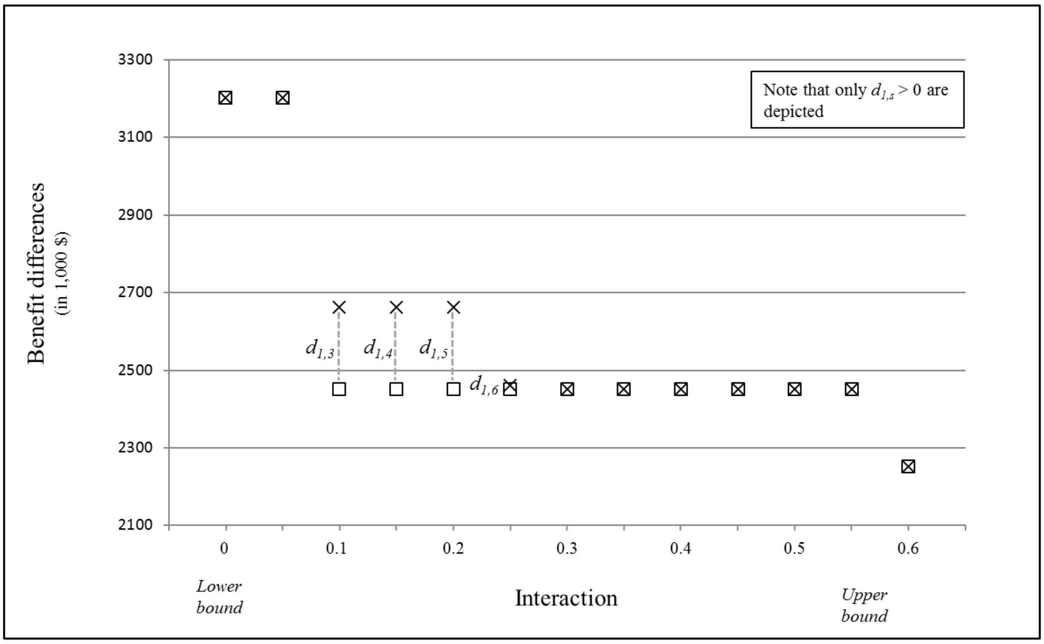

Fig.3. Example: Evaluation Phase

For our example, we separated the interval into 13 steps *s* with a step size of 0.05, each. The figure shows the value of the portfolio decision *PF* (and $PF^{red}_{i,s}$, respectively in cases where the reference portfolio *PF* is infeasible) depicted as ☐. The optimal portfolio decision $PF_{1,s}$ for each realization $s = 1\ldots13$ is depicted as **X**. The effect for the interaction i_1 is varied within the given bounds. The portfolio compositions for the realizations *s* and the resulting benefit differences are shown in Tab. 4. For interaction i_1 the expected value of the money-equivalent effort that should be invested can now be calculated and equals 49,231 $. To calculate the $d_{i,s}$ in cases where the reference portfolio *PF* becomes infeasible, we removed the project(s) with the lowest benefit from the *PF* portfolio until the resulting reduced portfolio $PF^{red}_{i,s}$ becomes feasible under the given circumstances.

Tab. 4. Numerical example – benefit differences for realizations *s*

s	***Portfolios***		$d_{1,s}$	***Case***
	Optimal Portfolio for s	*Reference/reduced reference Portfolio*		
1, 2	$PF_{1,s} = \{1, 5, 6\}$	$PF = \{1, 5, 6\}$	0	1
3	$PF_{1,s} = \{1, 3, 5\}$	$PF^{red}_{1,s} = \{1, 5\}$	210,000	3b
4, 5	$PF_{1,s} = \{1, 4, 5\}$	$PF^{red}_{1,s} = \{1, 5\}$	210,000	3b
6	$PF_{1,s} = \{1, 4, 6\}$	$PF^{red}_{1,s} = \{1, 5\}$	10,000	3b
7,…, 12	$PF_{1,s} = \{1, 5\}$	$PF^{red}_{1,s} = \{1, 5\}$	0	3a
13	$PF_{1,s} = \{1, 6\}$	$PF^{red}_{1,s} = \{1, 6\}$	0	3a

4 Discussion, Conclusion and Future Work

Based on the insights derived from the literature as well as from discussions with practitioners, we identified two problems of practical and theoretical relevance for the field of IS PPS. First, the lack of techniques featured in the literature on how to *identify* and *assess* resource interactions; second, the lack of clarity as to whether or not it pays off to identify and assess *all* possible resource interactions that may occur among a set of projects. The key contribution of our work in order to address these problems is twofold. First, we suggest a technique for identifying potential economically relevant resource interactions in a semi-automatic process. Second, we present a concept for calculating a theoretical upper bound for the effort that should be invested in improving the estimates for the interactions identified. In cases where the necessary additional effort to assess an interaction exceeds the upper bound, the interaction does not seem worthy of further investigation, whereas in other cases, a closer look appears worthwhile. To the best of our knowledge, our article is the first to utilize concepts from decision theory and, combined with a series of automated sensitivity analyses, to provide evidence on how much effort should be invested to improve the estimation quality of identified interactions.

According to our findings, it is an important task to further investigate the economic impact of resource interactions in IS PPS. Our work constitutes a starting point for further investigations into the economic benefits of considering resource interactions in IS PPS. As an ex ante evaluation (Pries-Heje and Baskerville 2008), we provide a proof of concept by implementing the approach in a software prototype. Moreover, we illustrate the operating principles of our approach by providing a numerical example.

As a first step toward examining the potential of the suggested approach for application in business practice, we held four semi-structured interviews to discuss the approach with experts from industry. The interview partners included a business executive from a medium sized IT consulting firm (portfolio size approximately 10-20 internal projects and 5-10 larger client projects per year), an IT project manager with 10 years of experience for a large IT service provider (portfolio size approximately 100 projects per year) as well as a highly experienced portfolio manager who has been in charge of the functional portfolio management in a large bank, and his counterpart at the IT department of the same bank. To validate our general decision setting, we asked each interview partner to describe their company’s current portfolio management processes. Both the consulting firm and the bank have established a recurring portfolio planning process with a one to six months’ gap between portfolio revision cycles and an ongoing project management, whereas the IT service provider has no unified resource management or portfolio management in place. Also, both the bank and the consultancy are already, to some extent, considering resource interactions in their respective selection processes. However, their identification and quantification strategies are currently based on expert knowledge and gut feeling rather than on a structured approach. After learning about the approach presented in this paper, all interview partners generally perceived it as useful. In the discussions, it emerged that certain conditions have to be met for our approach to be able to be applied in business practice. First, a certain maturity in portfolio and resource management processes is necessary to make full use of the approach. The consulting company and the bank seem to have established the necessary processes, while the IT service provider did not yet have a unified resource management or portfolio management. Second, the portfolio selection problem requires a certain degree of complexity and size to enable the leverage of the potential benefits of our approach to take effect. At the same time, if their portfolio environment is too large, companies with chronically over-utilized portfolio managers may not have the capacity to provide the additional information required for our approach. Third, the portfolio environment has to have some stability to enable a build-up of experience necessary to generate the estimates required for our approach. While this does not constitute a robust empirical validation of our approach, it provides first evidence for the usefulness and also the restrictions on its applicability.

The presented approach primarily addresses companies and organizations that already exhibit advanced portfolio management capabilities – for example, in form of a maturity level of 4 or 5 according to the Capability Maturity Model in portfolio management (Bayney and Chakravarti 2012). In addition, based on the insights derived from the literature and our discussions with experts from the field, our approach is particularly valuable for companies and organizations with a structured, periodically recurring portfolio selection process (see also, e.g., Archer and Ghasemzadeh 1999). Moreover, while our approach might provide useful insights to companies with smaller project environments, those who might benefit the most from it may be companies featuring larger project portfolios, due to the inherent combinatorial complexity resulting from larger project environments. Following the study of Meskendahl et al. (2011), those numbers are easily reached by large and mid-sized firms.

The activities associated with our approach should be viewed as one part in the context of a larger set of tasks for improving PPS in an organizational context. After evaluating and considering the identified interactions in a business context, the selected projects in the portfolio should be monitored, and success as well as failure should be documented in the context of the knowledge management functions of a PMO to improve PPS decisions and the inputs for the proposed model in future iterations.

For practitioners, the work presented here may improve the incorporation of resource interactions into their portfolio decisions in a more structured and, at the same time, pragmatic way. While a certain process maturity level is required to make full use of the insights that can be gained from the approach, it may substantially reduce the potentially high effort inherent in the identification and evaluation of economically relevant resource interactions. As an additional benefit, the structured process of information gathering may highlight the importance of at least some of the (key) resources to the organization, which may previously not have been recognized explicitly. As a result, potential bottlenecks may be identified before they occur and the procurement strategies for the corresponding resources may be improved at an early planning stage to reduce the risk of resource shortage during portfolio implementation.

For researchers, the concepts developed in this article may serve as a starting point to be incorporated into their approaches or to develop new ones that account for resource interactions in greater depth. In the following we will discuss some of the limitations of our approach and avenues for future research.

While our approach is designed to require as little information as possible from the planner, she needs to choose suitable interval bounds for initial sensitivity analyses during the Identification Phase. In future work, different sets of bounds have to be evaluated against artificial as well as real world data to identify interval lengths that are capable of including, at least, the majority of potentially relevant interactions, while at the same time minimizing both the numerical complexity and the number of sensitivity analyses that have to be conducted. If real world data were available, such bounds could be derived by applying, for example, Chebyshev's inequality (see, e.g., Greene 2008).

So far we only explore the impact of resource interactions one at a time. Although one resource interaction taken in isolation might not have any impact on the composition of an optimal portfolio within the examined bounds, a combination of resource interactions might have (see, e.g., Topilla et al. 2011). While our analysis and ranking of interactions considers interactions 'one at a time', our optimization model is capable of handling multiple resource interactions simultaneously. This provides the planner with the option to select a number of potentially influential interactions based on the results of the sensitivity analyses, and to include these into the optimization process when finally calculating the optimal project portfolio. The results and insights gathered from the analysis and evaluation of one resource interaction at a time will thereby be helpful for reducing the complexity of the interaction that shall be considered in the actual portfolio optimization. In future research, the approach could be extended to perform a series of sensitivity analyses to identify projects involved in multiple interactions at once. Thereby, highly interrelated projects could be identified. The results of the identification of such projects could be visualized, for example, by using the visual project mapping suggested by Killen and Kjaer (2012).

The objective function currently used in our formulation only reflects the benefits of the portfolio, while the costs for the resources are only considered within the constraints of our model. This objective function could equally be reformulated to represent the net benefits of the portfolio by including the resource costs as well. This would produce portfolios that do not necessarily maximize the resources' load factor, but would lead to solutions with a better cost/benefit ratio. Further, while we have focused on a single financial benefit measure in a first step, in reality different types of benefits (e.g., intangible benefits, qualitative benefits, expected financial benefits) may occur (see, e.g., Bradley 2010). As a subject for future work, the inclusion of different types of benefits could be achieved by extending the model to a multi-criteria objective function, which could lend additional realism to the model. In addition, the model could be extended by using parametric functions instead of constant cost parameters for the variable costs of the resources. This would allow the incorporation of decreasing or increasing marginal costs for specific resources in the model, instead of constant cost parameter values.

Additionally, we plan to extend our approach to consider the risks associated with resource interactions among two or more projects. In order to address risks induced by common resource usage, Monte Carlo simulation techniques could be used to simulate the impact of resource interactions on the portfolio selection decision. As part of this, an iterative simulation-optimization approach (following, e.g., Better and Glover 2006) for the construction of robust portfolios could be implemented. It would also be interesting to investigate how uncertainty in different model parameters (e.g., costs, benefits) influences the portfolio selection decision.

Another interesting subject for future research constitutes the thorough investigation of cases, where a cannibalizing interaction leads to an infeasible portfolio (as discussed in cases 3a and 3b analyzed in section 3.2.3). Currently, we calculate a residual value for the sub-portfolio of projects that may be conducted despite the resource bottleneck. In future work, it could be very interesting to analyze the effect of different penalties (e.g., residual value equals zero or below) for infeasible portfolios. The selection of different residual values would certainly have an impact on the ranking that our approach establishes for the potentially influential interactions.

The ranking of potentially relevant interactions is actually derived by using the Δv indicator, which is useful in situations where information on the probabilities of occurrence for different realizations of an interaction is not available. In situations where such information is available, however, our approach in future research should be extended to other, more elaborate ranking criteria (e.g., stochastic dominance criteria).

Finally, we have focused only on resource interactions. In future work we plan to extend the identification process to other types of interactions discussed by Aaker and Tyebjee (1978).

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