Chapter 6
Supporting the Project Portfolio Selection Decision of Research and Development Investments by Means of Multi-Criteria Resource Allocation Modelling

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Abstract The healthcare industry needs to carefully balance their research and development (R&D) project portfolios in terms of the diverse benefits, risks and costs of the technology they aim to develop. Although not common in healthcare, multi-criteria portfolio selection modelling can provide a structured and transparent approach to support decision-makers to share information on the performances of their R&D projects, to negotiate the necessary trade-offs to evaluate the projects and to arrive at a decision for an R&D project portfolio that decision-makers are committed to. In this chapter we illustrate how the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) approach, assisted by the recent portfolio module of the M-MACBETH decision support system, was used to build a model to select a portfolio of robotic innovations for minimal invasive surgical interventions. We show how these projects were prioritized according to their value for money and how the value of the R&D portfolio was maximized under a budget constraint and under the presence of interdependencies between projects that could affect their benefits, risks and/or costs.

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K. Marsh et al. (eds.), *Multi-Criteria Decision Analysis to Support Healthcare Decisions*, DOI 10.1007/978-3-319-47540-0_6

6.1 Introduction

Organizations developing healthcare technologies are under a growing pressure to fulfil stricter regulatory demands on the technologies' benefits and risks in the context of increasingly cost-constrained healthcare systems (Paul et al. 2010). In order to survive, organizations are facing multiple challenges in designing technologies with a high performance, without incurring unmaintainable research and development (R&D) risks and costs. Scarce resources need to be efficiently allocated to promising R&D projects.

Selecting a portfolio of R&D projects on healthcare technology that makes the best use of available resources is complex both at the technical and social level. In order to maximize the value of the portfolio, various trade-offs need to be made among the expected benefits and risks of the technologies, as well as the risks and costs for the developing organization. Since it is not likely that one and the same manager is most knowledgeable on all benefits, risks and costs, managers are to deliberate and assess these versatile trade-offs with their stakeholders (Philips and Bana e Costa 2007). Furthermore, budget constraints and interdependencies among R&D projects may complicate these assessments when selecting multiple projects (Stummer and Steinberger 2003).

Decision analytic methods can support health managers in making complex resource allocation decisions for R&D projects. They help decision-makers in selecting the most efficient portfolio of projects from a large set of projects, while taking into account relevant constraints, preferences and uncertainties (Salo et al. 2011). Multi-criteria decision analysis (MCDA) tools for resource allocation have been shown to be specifically helpful when the projects are to be evaluated by multiple evaluation criteria (e.g. benefits and risks) and when they compete for funding in a context of limited resources (Kleinmuntz 2007).

Various MCDA techniques have been used to assess the multiple benefits and risks of new technologies in the context of the healthcare system (Diaby et al. 2013; Marsh et al. 2014) and to prioritize the value of these technologies (Thokala and Duenas 2012). In particular the MCDA models based on the principles of value measurement – which we will name in this article as multi-criteria value models (MCVM) – have been recommended to assess healthcare technologies (Thokala and Duenas 2012). MCVM have been shown to support health policymakers in technology selection, to analyse market access options or to compare reimbursement systems (Baltussen and Niessen 2006).

When applying MCVM in the context of resource allocation to R&D projects, the benefits and risks of the technologies are assessed from the perspective of the R&D organization. Besides the benefits and lower risks, the R&D organization strives to deliver to healthcare to achieve market success, and other risks, such as technical or market failure, can be incorporated. Also in this context, diverse MCDA techniques have been applied to assist in building multi-criteria resource allocation models (e.g. Hurson and Ricci-Xella 2002; Vetschera and de Almeida 2012; Liberatore 1987).

Multi-criteria resource allocation models extend MCVM from assessing the value of single technologies to assessing the aggregate value of multiple technologies to develop within a restricted budget. The simplest and most common MCVM for resource allocation is to use a prioritization approach in which R&D projects are ranked by their value for money, i.e. by overall value divided by cost (Philips and Bana e Costa 2007). The costs typically include the R&D investments required to develop and market the technologies. However, this prioritization approach does not necessarily ensure the maximum total value for the budget available and cannot easily assist in cases in which there are interdependencies between projects. Our recommendation is to use the prioritization and the optimization approach together. Optimization implies, in the portfolio selection context, solving a mathematical programming problem to maximize the aggregated value of the projects without exceeding the budget constraint, while considering the constraints and synergies of combinations of R&D projects (Lourenço et al. 2012).

Several software packages assist the development of multi-criteria portfolio analysis, namely, Equity and HiPriority enable a prioritization analysis, Expert Choice Resource Aligner provides the optimization approach, while Logical Decisions Portfolio and PROBE enable both prioritization and optimization approaches (Lourenço et al. 2012). Even though there is an increasing trend in the use of multi-criteria resource allocation models in several contexts (for instance, in the pharmaceutical and oil and gas industries, as well as in the public sector (Salo et al. 2011)), they have, until now, only scarcely been applied by the healthcare industry.

This chapter illustrates how a multi-criteria resource allocation model can aid decision-makers in the healthcare industry to reflect on which R&D portfolio of healthcare technologies – or in our case study, robotic innovations that enable minimally invasive surgical interventions – should be selected under a budget constraint. We applied the *Measuring Attractiveness by a Categorical Based Evaluation Technique* (MACBETH) approach to conduct the portfolio analysis (Bana e Costa et al. 2005, 2012a). MACBETH is an interactive approach for building evaluation models that asks evaluators – either a decision-maker or a group of decision-makers – to judge the difference of attractiveness between options. MACBETH has sound theoretical foundations, being based on the principles of additive value measurement, and has been used in different managerial contexts in healthcare, including for the prioritization of community care programmes in (Oliveira et al. 2012) and for hospital auditing (Bana e Costa et al. 2012b). The recent portfolio module of the M-MACBETH decision support system (Bana Consulting 2005) enables multi-criteria resource allocation modelling. Following a decision-aiding perspective, we advocate that multi-criteria resource allocation models should express the viewpoints of managers of R&D organizations, and their development can help these decision-makers to discuss, negotiate and decide with the stakeholders on the R&D projects to invest in, bearing in mind the projects' benefits, risks and costs.

6.2 Case Study and Method

6.2.1 Case Study

Minimally invasive surgery has been applied to significantly lower the patient burden of disease and to reduce length of stay in hospitals (Mack 2001). In order to extend the application of minimally invasive procedures to new interventions and more complex interventions, robotic innovations are desired (Mack 2001; Gomes 2011). Nevertheless, the adoption of the currently available robotic systems has often failed due to unmet user needs in healthcare and to their high costs (BenMessaoud et al. 2011). For selecting a best portfolio of R&D projects for robotic systems, decision-makers need to consider multiple objectives, which include to maximize the benefits and to minimize the risks of the robotic innovations simultaneously for patients (BenMessaoud et al. 2011) and for healthcare professionals (Vander Schatte et al. 2009) and to minimize the costs for healthcare (Barbash and Glied 2010). Trade-offs among these (often) conflicting objectives need to be considered, as well as the costs to develop and market these innovations.

6.2.2 Resource Allocation Modelling on Robotic Innovations with MACBETH

Within MCDA, MACBETH is an interactive approach for building a model of quantitative values that requires only qualitative judgements of difference in value (Bana e Costa et al. 2012a). Central in this approach stands a questioning protocol in which the evaluator (a decision-maker or a decision-advising group) qualitatively pairwise compares projects, using a semantic scale – no, very weak, weak, moderate, strong, very strong and extreme difference in attractiveness – thus avoiding the difficulty of expressing value judgements numerically (Von Winterfeldt and Edwards 1986). Using linear programming (Bana e Costa et al. 2005), MACBETH assists not only in testing the consistency of the qualitative judgements expressed but also, when consistency is achieved, in proposing numerical value scales that are in accordance with the judgements. Within ranges that are compatible with the semantic judgements provided, decision-makers can fine-tune the proposed numerical values. This MACBETH procedure is used both to value the projects regarding each of the benefit and risk criteria and to weight these criteria. Then, the overall values of the projects can be calculated by a simple additive model, that is, by multiplying the value of the project in each criterion by the respective weight and summing up these products. An explanation of the mathematical algorithms behind MACBETH can be consulted in Bana e Costa et al. (2005, 2012a).

We developed a MACBETH resource allocation model by conducting two main activities: first to build an MCVM to evaluate the value of nine potential robotic R&D projects and then to analyse which combinations of projects maximize overall value for a given budget, by using both prioritization and optimization approaches for portfolio analysis. Both activities were enabled by means of the recent portfolio module of the M-MACBETH decision support system (beta version) (Rodrigues et al. 2015), following the next model building steps.

Step 1: Identifying Evaluation Criteria

The first step consists in identifying the key aspects, i.e. the benefits and risks that will be used as the evaluation criteria, to appraise the value of the robotic innovations.

It is well known in literature (Von Winterfeldt and Edwards 1986) that the application of an additive value model requires each criterion to represent an independent evaluation axis, i.e. the (partial) value of a project on one criterion should not depend on the performance of the projects on the other criteria. Preference independency may require the restructuring of the set of evaluation criteria, namely, by merging several interdependent aspects into one covering criterion. Each evaluation criterion is to be operationalized into an attribute (Keeney 2002) or descriptor of performance (Bana e Costa et al. 1999) which can either be a continuous or a discrete set of performance levels (either quantitative or qualitative). A detailed discussion on how to build attributes or descriptors of performance is available in Keeney (2002) or Bana e Costa and Beinat (2005).

In order to compare the potential value of the nine alternative robot-assisted surgical approaches, their foreseen benefits and risks were inserted as the evaluation criteria in the decision support system M-MACBETH (version 2.4.0) (Bana Consulting 2005). These criteria were adapted from the technological success factors that explain the probability of technical and commercial success, as distinguished by Cooper and Kleinschmidt (1995). For all criteria, quantitative or qualitative descriptors of performance were defined to measure the performance of the nine robotic innovations. In each descriptor, two reference performance levels were defined: a reference of “low (or neutral)” performance and a reference of “good” performance, with the substantive meaning of, respectively, a minimally and completely satisfying performance. These references of intrinsic value help to analyse whether each robotic project has an undesirable (worse than low) or a satisfactory (from low to good) or an outstanding (better than good) performance. This analysis could also be extended to consider all the criteria together, to appraise the intrinsic overall value of a project.

Step 2: Building the Evaluation Model

In this step, value scales and weights for the evaluation criteria are defined based on the elicitation of MACBETH value judgements.

A value scale enables the conversion of performance into a value score that measures the attractiveness or desirability of that performance. Weights harmonize the value scales across all criteria and enable the aggregation of value scales in an overall value scale that numerically represents the attractiveness or desirability of the alternatives.

Using the MACBETH protocol, value scales for each evaluation criterion were constructed to convert the foreseen performances of the robotic innovations into value scores. For each criterion, the evaluator was asked to judge the difference in attractiveness between pairs of performance levels, using the semantic categories of MACBETH. The MACBETH decision support system proposed numerical value scales that were compatible with the qualitative judgements on the differences in attractiveness of the robotic R&D projects. The reference descriptors of a “low” and a “good” performance of robotic innovations in each evaluation criterion worked as anchors in these value scales, being assigned a value of, respectively, 0 and 100. The evaluator was then asked to eventually adjust and validate the numerical value scale built for each evaluation criterion.

In order to weight the criteria, the qualitative swing weighting procedure of MACBETH was followed (Bana e Costa et al. 2012a; Oliveira et al. 2015). The evaluator was asked to consider the ranges between the low and good references of performance of the robotic innovations on the evaluation criteria. “Suppose a robot is expected to have a low performance on all criteria; on which criterion would a swing from low to good performance be most attractive?” The next most attractive swing was identified, until all performance swings were ranked. Following the additive value model, the ranking of the swings corresponds with the ranking of the weights of the criteria. It is worthwhile nothing that, therefore, a change on one reference level on one criterion may provoke a change in the ranking of the weights. As stated by Philips and Bana e Costa (2007), “a major error in multi-criteria modelling is the attempt to assign weights that reflect the ‘importance’ of the criteria without reference to any considerations of ranges on the value scales and how much each one of those ranges matters to the decision maker” (Keeney 2002). Next, the evaluator was asked to pairwise compare the global attractiveness of swings using the MACBETH categories. Again, the M-MACBETH decision support system provided numerical weights compatible with the qualitative judgements given by the evaluator. These weights needed to be analysed, eventually adjusted and validated.

Either in building value or weighting scales, M-MACBETH automatically detects inconsistent judgements and suggests ways to resolve inconsistencies (see details in Bana e Costa et al. 2012a).

Step 3: Valuing the Robotic R&D Projects

This step includes the appraisal of the performance of the projects on the criteria and the calculation of their (*partial*) *value scores and overall value scores*.

The robots range from more generic robots to facilitate multiple minimally invasive procedures (e.g. robot G having the da Vinci robot as a dominant competitor) to specialized robotics for enabling a specific procedure (e.g. robot F for knee surgery). On each evaluation criterion, the performance of each robot-assisted approach was established by assigning to it one performance level of the respective descriptor; then each performance was converted into a value score using the value scale defined for the respective criterion (see step 2); finally, the weighted average of the value scores is calculated to estimate the overall value of each project across all criteria.

Step 4: Structuring the Portfolio Analysis

This step includes the definition of the portfolio baseline and the modelling of synergies across projects as well as other constraints relevant for the analysis of candidate portfolios.

Proper portfolio decision analysis demands for the specification of a baseline value, that is, a so-called "do nothing" project. Only projects that are more attractive than the "do nothing" project are worthwhile to be considered as candidates for funding. This is important because the use of distinct baselines can affect the optimal portfolio (Morton 2015). There are different procedures to set the baseline value (Liesiö and Punkka 2014). In our case study, if a robotic innovation project was assigned a lower score than the baseline project, which has a "low" performance on all criteria, then that innovation project would not deserve to be funded and, consequently, would be discarded from the portfolio analysis (Bana e Costa et al. 2006). Besides the estimation of the benefits, risks and development cost of each innovation project, the R&D budget was defined and it was observed that the sum of the development costs of all the candidate projects exceeded the budget constraint. Furthermore, an analysis was conducted on the extent to which there were synergies between projects in terms of their benefits, risks and development costs.

Step 5: Analysing Portfolios Using Prioritization and Optimization Approaches

Step 5a: Prioritizing the R&D projects based on their value for money

The nine robotic technologies were prioritized with the M-MACBETH decision support system. These priorities were derived from their potential value for money, that is, by dividing the overall value of each robot innovation (see step 3) by the investment cost required to its development. The projects were ranked in order of decreasing priorities.

Step 5b: Optimizing the R&D project portfolio

With the optimization module of M-MACBETH, a mathematical programming problem was solved that identifies the optimal portfolio, that is, subset of projects that maximizes total value given the budget constraint and existing synergies between projects. Specifically, synergies in development costs of similar robotic technologies were modelled.

6.3 Results

Step 1: Identifying Evaluation Criteria

The criteria to evaluate the innovation projects included:

1. The health gains for patients, in terms of the additional quality-adjusted life years to be gained through the surgical intervention in comparison with current practice

2. Economic benefits to healthcare, in terms of the potential costs savings in comparison with current practice
3. Fit with the existing infrastructure and skills present within the existing healthcare system
4. Fit with the technological expertise and organizational resources of the developing organization
5. Market size in terms of the size of the target patient population of the robotic surgical interventions
6. Competition in the market, in terms of the amount of competing developers

Quantitative and qualitative descriptors of performance were defined to measure the performance of the R&D projects on the criteria (see Table 6.1). Criteria 1, 2 and 5 relate to the benefits of the innovations for the healthcare market, while criteria 3 and 4 relate to the developmental risks, and criterion 6 relates to the market risk. All criteria were framed positively, in the sense that a quality descriptor describing a low risk or a high benefit represented a high performance. The more specific operationalization of the qualitative descriptors, in this case all risk-related descriptors, is to be discussed and agreed upon by the evaluators.

Table 6.1 Criteria and types of performance descriptor

Evaluation criterion	Type of criterion	Type of descriptor	Descriptor of performance
QALY gain patient	Benefit	Quantitative	Quality of life years gained
Economic advantage healthcare	Benefit	Quantitative	Amount in euros
Fit with healthcare setting	Risk	Qualitative	5 qualitative performance levels
Fit with expertise and resources company	Risk	Qualitative	5 qualitative performance levels
Market size	Benefit	Quantitative	Number of patients
Market competitiveness	Risk	Qualitative	5 qualitative performance levels

Step 2: Building the Evaluation Model

Based on MACBETH's pairwise comparisons of the attractiveness of the performance levels, a value scale was created for each evaluation criterion, with 0 and 100 always assigned to the low and good reference levels, respectively. Figure 6.1 shows as an example the value curve of the first criterion: the gain in quality-adjusted life years per patient. Note in the horizontal axis that a half-a-year gain in quality-adjusted life years per patient is considered to be a low-performance outcome for a minimally invasive robot. An increase in 2.5 quality-adjusted life years is considered to represent a good performance. The S-shape of the value curve shows that an even higher QALY gain is not expected to much stronger increase the market need for the robot in healthcare and thus does not create much more value to the developers.

The MACBETH protocol for building weights led to the set of weights depicted in the second line of Table 6.2.

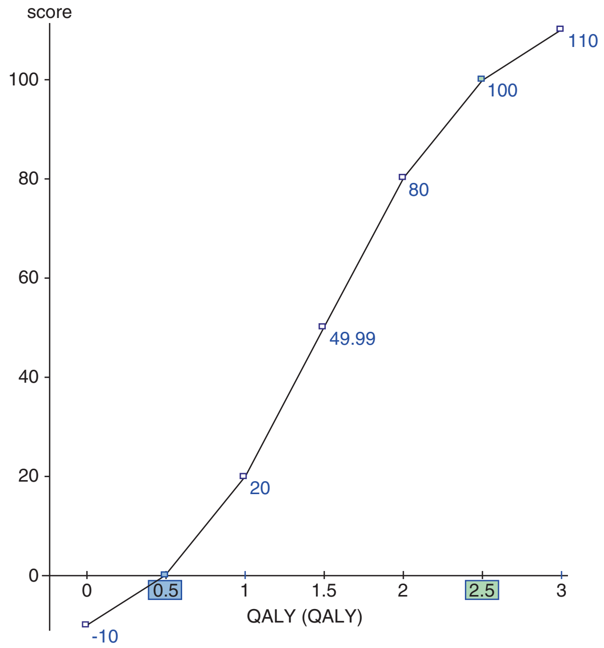

Fig. 6.1 Example of a value curve for the QALY gain criterion built in M-MACBETH

Table 6.2 Criteria weights and robot innovations' partial and overall value scores

	QALY gain	Economic benefit	Fit healthcare setting	Fit expertise and resources	Market size	Competitiveness	Overall value
Weight	*0.26*	*0.13*	*0.14*	*0.26*	*0.15*	*0.06*	
Robot A	102	−115	60	0	5	100	*27*
Robot B	27	116	120	−80	112	60	*39*
Robot C	−3	−102	0	0	11	60	*−9*
Robot D	−8	13	0	0	−6	60	*2*
Robot E	27	61	100	120	−7	−80	*54*
Robot F	14	19	100	100	−6	60	*49*
Robot G	102	−115	60	0	5	0	*21*
Robot H	6	−116	100	60	5	60	*20*
Robot I	39	47	−80	0	−6	120	*11*
Good allover reference	100	100	100	100	100	100	*100*
Low allover reference	0	0	0	0	0	0	*0*

Step 3: Valuing Alternative Robotic R&D Projects

The value scales were used to convert the performances of the robotic innovations into value scores. The performances on the criterion health gain, as estimated in step 1, were positive predictions of the gain in QALYs. These predictions were adapted from the first clinical evidence of similar robots, if available. For example, robot F is to facilitate a minimally invasive procedure for knee arthroplasty. By preventing pain and stiffness of the knee and slightly increasing the physical function of the knee, an improvement in quality of life of 0.06 was predicted during an average time span of 14 years. Resultantly, the predicted gain in health summed up to a QALY gain of 0.84. For more generic robots, the predicted QALY gain was averaged over the applicable procedures that most frequently occur in clinical practice. In this third step, the value scale helped to convert these QALY scores into partial values scores; in case of robot F, the QALY gain of 0.84 was converted in the rather low value score of 14.

Table 6.2 shows the partial and overall value scores of the nine R&D projects on the robotic surgical approaches. To appraise the overall intrinsic value of each project, Table 6.2 also includes two hypothetical robotic innovation projects, the reference good allover with "good" performance on all criteria and the reference low allover with "low" performance on all criteria, obviously with overall scores of 100 and 0, respectively. One can observe in Table 6.2 that several robots have a low or very poor performance on multiple criteria (leading to negative scores).

Step 4: Structuring the Portfolio Model

Investment synergies were incorporated in the portfolio model between two R&D projects: robots A and G. Both robots are more generic robots aiming to facilitate multiple minimally invasive procedures. Synergies are generated as the development of the two robots use a similar core technology. Accordingly, investment in this core technology would simultaneously benefit the two robots, only if both robots are included in the R&D portfolio.

Zero overall value and cost were inserted in M-MACBETH to establish the baseline for portfolio analysis, from which robot C was excluded due to its negative overall value score. This rejection of a project with negative overall value corresponded to the use of a "multi-criteria screening criterion", as defined by Bana e Costa et al. (2006).

Step 5a: Prioritizing the R&D Projects Based on Their Value for Money

The calculated overall values of the nine surgical approaches and the estimated development costs to deliver these products can be plotted in a cumulative cost versus cumulative value graph, by increasing order of the respective value for money ratios (Fig. 6.2). Each point in the graph represents a portfolio of projects, with increasing number of projects from left to right. The curve linking the points is the frontier of convex efficient portfolios, when neglecting interactions between projects. Under these conditions, for a maximum available budget of ten million euros, projects F, B, E, H and A would be selected, with a total cost of 9.2 million euros.

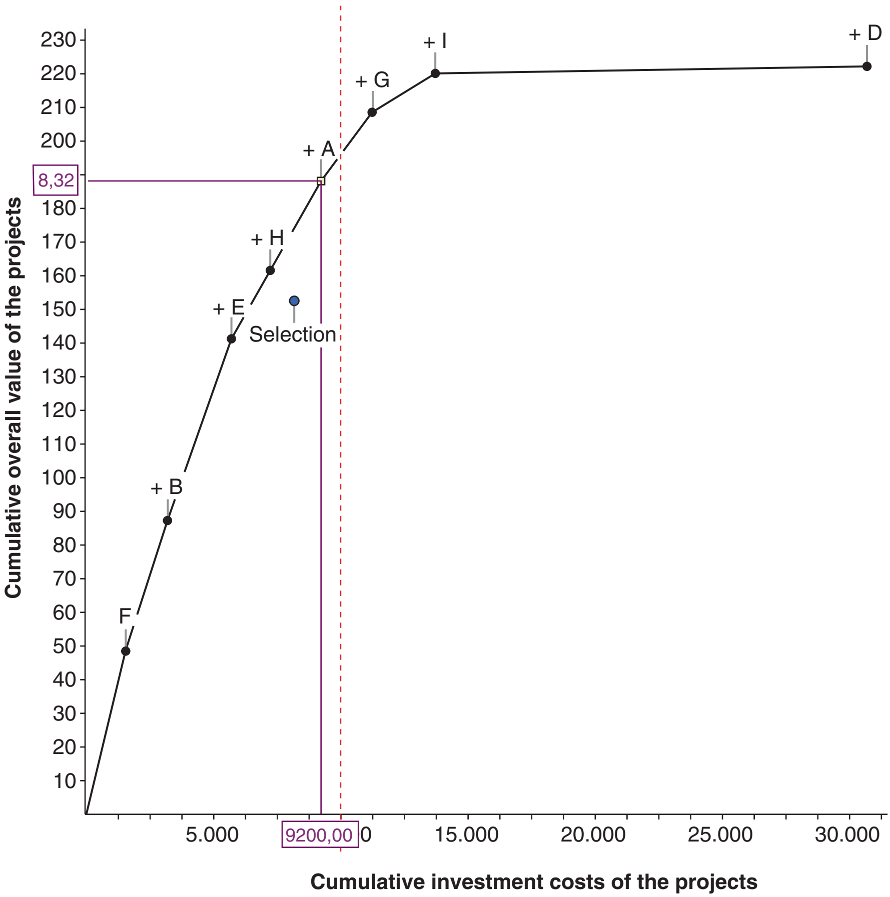

Fig. 6.2 Efficiency frontier and budget cut-off point (costs in 1000 euros units)

Step 5b: Optimizing the R&D Project Portfolio

When taking into account synergies in the development costs of robots A and G, robot G is now included and robot H is excluded from the optimal portfolio B, even though robot H has a higher overall value to cost ratio than robot G. This is shown by comparing the portfolio obtained with the prioritization approach in Fig. 6.2 with the portfolio obtained with the optimization approach in Table 6.1. Note that taken individually, one can include robots A or G in the portfolio, but when both are considered together, the costs change and robots A' and G' are the ones considered (Table 6.3).

The optimization of the project portfolio reduced the total costs from 9.2 to 9.1 million euros, while the aggregated value of the portfolio very slightly increased from 188 to 189 overall value units.

Table 6.3 Value for money of the R&D projects and portfolio

	Value	Cost	Value/cost ratio	In portfolio B
Robot A	27	2000	1.33	No
Robot B	*39*	*1700*	*2.28*	*Yes*
Robot E	*54*	*2500*	*2.17*	*Yes*
Robot F	*49*	*1500*	*3.24*	*Yes*
Robot G	21	2000	1.03	No
Robot H	20	1500	1.35	No
Robot I	11	2500	0.45	No
Robot A' (synergy)	*27*	*1700*	*1.33*	*Yes*
Robot G' (synergy)	*21*	*1700*	*1.03*	*Yes*
Aggregated value portfolio				*189*
Aggregated costs portfolio				*9100*

6.4 Lessons Learned and Discussion

The case study presented illustrates how a multi-criteria resource allocation model can support R&D investment decisions for multiple healthcare innovations. In multi-criteria portfolio analysis, candidate R&D projects can be selected for the R&D portfolio based on their foreseen values and costs. The number of candidate R&D projects can be reduced when minimum levels of performance levels for each benefit or maximum acceptable risks are demanded for the inclusion of a project in the portfolio. In our case, one R&D project was excluded due to its less than "low" overall value. Those performance thresholds are particularly relevant in case the amount of possible portfolios is high. In practice, the number of feasible portfolios can be enormous, exceeding by far the number of feasible portfolios in our illustration (Ghasemzadeh and Archer 2000). Of the appropriate candidate R&D projects to consider for the portfolio, the (convex) efficiency frontier graphically depicts these projects in order of descending priority, when priority is captured by the value for money ratio. For a preliminary analysis of portfolio by applying the prioritization approach, R&D project portfolios can be analysed following the order in the efficiency frontier, from left to right, until the available budget is exhausted.

Nonetheless, the prioritization approach does not necessarily ensure that the optimal portfolio is selected, that is, the subset of projects that maximizes cumulative value although respecting the budget constraint. Moreover, only the optimization approach enables to take into account the presence of synergies between projects. Note that the prioritization approach can lead leaving a significant part of the available budget unexploited when the budget cut-off point is further off from the total budget. In our illustration, altering the preliminary portfolio increased the total value that could be delivered for the total budget and diminished the portfolio costs, due to investment synergies between two R&D projects. These two projects aimed to develop robots that were based on a similar core technology, which generated cost savings. In general, interdependencies among projects can affect not only costs but also benefits and/or risks of the R&D projects (Eilat et al. 2006). Examples of cost interdependencies are the sharing of project resources that translate into overhead cost reductions for the single projects. Examples of benefit interdependencies are the use of competing technologies for which joint project benefits are reduced or the existence of complementary technologies in which one project can be developed only if another one is selected as well. An example of interdependent developmental risks is the existence of a critical mass of resource capital that can increase the likelihood of success of the R&D projects, which translates into lower project risks (Eilat et al. 2006). Due to these interdependencies among projects, proper tools to simultaneously analyse the value, costs and risks of combinations of R&D projects in alternative portfolios is necessary. Optimization modules can assist in proposing changes to the portfolio to maximize the overall value without exceeding the budget constraint (Lourenço et al. 2012). However, it should be noted that, contrary to the prioritization approach, the optimization approach does not guaranty the stability of the selected portfolio when an increase in the available budget is considered. That is why the combined use of the two approaches is recommended.

The combined approach illustrated provides a structured and transparent approach to support decision-makers to share information on the benefits, risks and costs of R&D projects competing for scarce financial resources, to negotiate the necessary trade-offs and to arrive at a decision for an R&D project portfolio the decision-makers are committed to. For our illustration, researchers constructed the multi-criteria resource allocation model being informed by literature and expert opinions. In empirical applications, it is a good practice to involve a constituency of (internal) stakeholders that need to be engaged to successfully realize the R&D projects. In fact, the adequate involvement of multiple stakeholders is paramount in constructing the value tree to capture the versatility of all relevant benefits, risks and costs (Montibeller et al. 2009). Moreover, stakeholders may have conflicting interests. Showing the decision-makers the consequences of changing the portfolio can support key stakeholders to discuss and negotiate the portfolios and to select a portfolio they are willing to engage to (Ghasemzadeh and Archer 2000). Philips and Bana e Costa (2007) have been successful in using a decision conferencing approach in multi-criteria portfolio analysis in real cases, showing that decision conferences can support communication between the stakeholders to develop a shared understanding of the issues involved in portfolio analysis and to make smarter decisions.

The R&D project portfolio analysis can be more advanced by analysing the uncertainty in the appraisal of value of the portfolio. In our illustration, we have implicitly dealt with this uncertainty, by including success factors that predict the probability of achieving commercial success as evaluation criteria and adapting these factors to the healthcare context. Accordingly, a higher score on these success factors predicts a higher probability of market success. There are other ways to deal with these uncertainties in development – for instance, to include as a risk criterion the probability that the benefits will not fully be achieved (Philips and Bana e Costa 2007) or the probability of success (e.g. Liberatore 1987). Or more generally, methods for uncertainty analysis can be applied (Broekhuizen et al. 2015). In optimizing the portfolio of R&D projects, sensitivity analyses can be conducted, or the robustness of the selected portfolio can be tested (Lourenço et al. 2012). A fuzzy approach has also been applied (Carlsson et al. 2007). For the case in our illustration, uncertainty analysis on the benefits would be a valuable addition, considering the contradictory findings on health gains evoked by the literature on the impacts of existing robotics for minimally invasive interventions.

Another elaboration of the multi-criteria resource allocation model described in this study would be the separate analysis and visualization of the individual benefits and risks of the portfolio to the developing organization. Furthermore, high- and low-risk projects could be balanced, minimum levels of benefit for different target groups of patients could be ensured, or other combinations can be optimized that make sense to the organization. With these elaborations, multi-criteria resource allocation modelling can be tailored to provide decision-makers the specific information they desire about R&D projects to facilitate the R&D project portfolio selection decision.

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