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Geleitwort

Die „Practice meets Science“-Initiative des Bundesverbandes Materialwirtschaft, Einkauf und Logistik e.V. (BME) steht für den konstruktiven, offenen Austausch zwischen Praktikern und Wissenschaftlern. Dabei unterstützt der Verband aktiv das Aufspüren von Trends und Innovationen, das Erarbeiten von Erfolgsansätzen, das Vermitteln von Erprobtem und das Vernetzen interessierter Menschen und ihrer Ideen. Für den Austausch bietet der BME mit seiner fast 60-jährigen Erfahrung seinen rund 8.000 Mitgliedern und einer breiten Fachöffentlichkeit eine ideale Plattform.

Die wissenschaftliche Auseinandersetzung mit den Themen Beschaffung und Logistik, verbunden mit der Förderung des wissenschaftlichen Nachwuchses, ist eine wichtige Säule des BME. Hier gilt es, Anreize für Arbeiten zum Thema Supply Management zu setzen. Seit 1988 zeichnet der Verband Verfasser der besten Habilitationsschriften und Dissertationen mit dem „BME-Wissenschaftspreis“ aus. Herausragende Studienabschlussarbeiten werden seit 2003 mit den „BME-Hochschulpreis für Beschaffung und Logistik“ prämiert. Der „BME-Preis Trendscouting“ für Abschlussarbeiten zum Themenbereich Logistik wird seit 2007 vergeben.

Mit seiner BME-Buchreihe „Advanced Studies in Supply Management“ macht der Verband wichtige wissenschaftliche Erkenntnisse rund um aktuelle und vieldiskutierte Managementmethoden transparent und stellt diese einer breiten Öffentlichkeit zur Verfügung. Ich freue mich sehr, dass auch der fünfte Band wieder interessante Lösungsansätze für aktuelle Herausforderungen aufzeigt. Beispielhaft nenne ich hier Aufsätze zur Entwicklung innovativer Supply-Chain-Management-Konzepte, zum Risk Pooling in Business Logistics und zur Flexibilisierung von Frachtraten in langfristigen Luftfrachtverträgen. Interessante Lösungsansätze für Praktiker in den Unternehmen bieten u. a. Beiträge zur nachhaltigen Rohstoffbeschaffung, zum Risikomanagement in Beschaffung und Distribution sowie zur Verteilung von Koalitionsgewinnen in Beschaffungskooperationen.

Mein herzlicher Dank gilt den Autoren für ihre Beiträge sowie insbesondere den Professoren Ronald Bogaschewsky, Michael Eßig, Rainer Lasch und Wolfgang Stölzle für ihre langjährige fachliche Unterstützung und ihr großes Engagement.

Frankfurt, im März 2012

Dr. Holger Hildebrandt
Hauptgeschäftsführer
Bundesverband Materialwirtschaft, Einkauf und Logistik e.V.

Vorwort

Das vorliegende Buch ist der fünfte Band der im Jahre 2008 gestarteten Buchreihe „Advanced Studies in Supply Management“, in der jährlich die wissenschaftlichen Fortschritte in diesem Forschungsfeld dargelegt werden. Zugleich handelt es sich um den Tagungsband des „5. Wissenschaftlichen Symposiums Supply Management“, das im Frühjahr 2012 durchgeführt wurde. Diese jährlich ausgerichtete Tagung wird vom Bundesverband Materialwirtschaft, Einkauf und Logistik e. V. (BME) veranstaltet, der auch die Buchreihe herausgibt. Inhaltlich verantwortlich für die Durchführung der Symposien und die hieraus resultierenden Schriften ist der Wissenschaftliche Beirat des Bundesvorstands des BME.

Die hohe Bedeutung der Bereiche Beschaffung, Einkauf, Materialwirtschaft, Logistik und Supply Chain Management spiegelt sich in den zunehmend intensiven Forschungsanstrengungen der – theoriegeleiteten wie der anwendungsnahen – Wissenschaft wider. Mit dem Wissenschaftlichen Symposium Supply Management konnte hierfür eine adäquate und inzwischen etablierte Diskussions- und Präsentationsplattform im europäischen Raum geschaffen werden.

Alle in diesem Band aufgenommenen, in primär wissenschaftlich und stärker anwendungsnah differenzierten Beiträge mussten sich einem Double-blind-Review-Verfahren unterziehen und wurden von unabhängigen Gutachtern eingehend geprüft. Diesen gilt unser Dank für die gewissenhafte Erstellung der Gutachten und die auf diesem Wege bereitgestellten Verbesserungsvorschläge für die Beiträge. Zahlreiche Einreichungen wurden abgelehnt, da sie den rigorosen Ansprüchen der Gutachter nicht genügten. Aufgenommen wurden zudem die drei Arbeiten, die sich für das Finale des „BME-Wissenschaftspreises“ aus einer großen Anzahl Einreichungen qualifizieren konnten. Der Jury des „BME-Wissenschaftspreises“ gilt ebenfalls unser Dank für die geleisteten Begutachtungen. Ein herzliches Dankeschön geht an Ulrike Müller, die wiederum in höchstem Maße zuverlässig und sehr sorgfältig das gesamte Projekt Wissenschaftliches Symposium samt Tagungsband betreute.

Es war und ist erklärtes Ziel, ausschließlich exzellente Forschungsergebnisse sowie innovative Beiträge mit hoher Praxisrelevanz auf dem Wissenschaftlichen Symposium zu präsentieren und im Tagungsband zu publizieren. Der vorliegende Band zeigt die große Breite und erhebliche Tiefe der Erkenntnisse im Bereich Supply Management auf. Es ist dem Wissenschaftlichen Beirat und dem BME ein besonderes Anliegen, diese Arbeiten weiterhin intensiv zu fördern.

Im Januar 2012

Prof. Dr. Ronald Bogaschewsky, Würzburg
Prof. Dr. Michael Eßig, München
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Prof. Dr. Wolfgang Stölzle, St. Gallen

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Teil A

Wissenschaftliche Forschungsbeiträge

Multi-Period Supplier Selection and Supplier Development under Dynamic and Uncertain Demand

Frank Meisel

Abstract

Supplier selection and supplier development are important activities of companies for establishing effective and reliable sources for materials and components. A large number of studies provide decision support for supplier selection but a lack of planning tools is observed for supplier development. This paper provides a combined approach for selecting suppliers and for scheduling development projects in a multi-period time horizon. The purpose of development projects is to adapt the production capacities of suppliers to demand forecasts and to lower variable procurement cost. The planning problem is described through a mathematical model. Decision support techniques are presented where rolling-horizon planning and simulation are used for capturing the dynamics of markets and the probabilistic outcome of development activities. The approach is capable of adapting supplier capacity for growing markets and declining markets as is required when demand changes with the life-cycle stage of a product. Experiments show that the methods discover profitable supplier bases and deliver effective project schedules for supplier development.

1 Introduction

In dynamic markets, companies have to adapt their supply chain portfolio frequently in order to stay competitive (Seifert and Langenberg, 2011). The overall goal is to establish and adapt procurement, production, and distribution capabilities at competitive cost for meeting market demands at a desired quality and service level (Li et al., 2007). Changes in the demand for a product correspond typically to the stages of the product life-cycle, see Fig. 1(left). In the life-cycle, a low demand is observed during the introduction stage. It grows until reaching the maturity stage before turning into a phase of decline. Unfortunately, the idealized demand curve will not be observed in a real-world situation due to random disturbances and unforeseeable events like the

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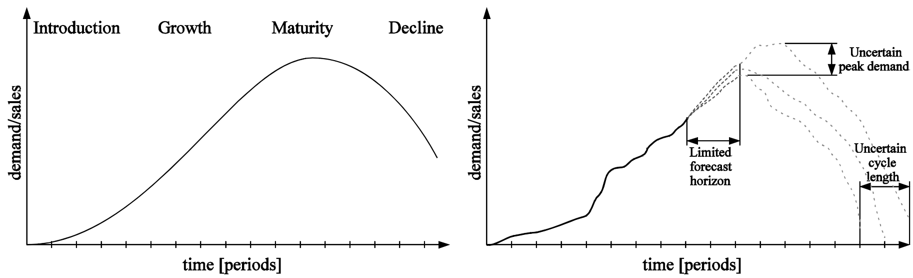
entry of new competitors. For this reason, a precise period demand is often known for a limited forecast horizon only, where the peak demand is generally uncertain, and also the overall cycle length is unknown at the begin of a venture, see Fig. 1 (right). Such a non-stationary and volatile demand forces companies to adapt the capabilities of their supplier base flexibly in the short and medium run.

Figure 1: *Idealized product life-cycle (left) and dynamic market with volatile demand (right)*



Instruments for adapting supplier capabilities are (i) to revise the supplier base by replacing suppliers that do not meet the requirements of the buying company any more and (ii) to improve the performance of existing suppliers through supplier development initiatives. Supplier development is a viable option if the current supplier base of a company shows potential for performance improvement and if switching suppliers requires considerable investments for finding new sources of supply and for enabling new suppliers to provide the desired goods. Supplier development furthermore supports establishing long-term relationships that create strategic benefits for the buying company and the suppliers too (Wagner, 2011).

Supplier development can be defined as any effort of a buying company to improve the capabilities of its suppliers for meeting the companies supply needs in the short and the long run (Krause and Ellram, 1997a). It comprises a wide range of activities like technology transfer (Simons et al., 1991), certification programs (Krause and Ellram, 1997b), or knowledge transfer (Modi and Mabert, 2007) for improving the operational processes and the quality of sourced components (Wagner, 2006). Common to all such activities is that the buying company has to provide resources and investments for conducting development programs, see Talluri et al. (2010). Clearly, companies strive for an efficient supplier development, which means that capacities are developed effectively at low cost, see Simons et al. (1991). Nevertheless, as shown in Talluri et al. (2010), there is a lack of decision support tools for the optimization of supplier development activities.

The contribution of this paper is to provide modeling and decision support methods for supplier selection and supplier development in dynamic markets. Here, supplier development comprises the selection and scheduling of development projects in the course of time. Development projects are joint activities of a buying company and a supplier that require spending resources (investments) and whose successful realization improves the production capacity of the supplier as well as the procurement cost at which the buying company sources goods. The goal of the supplier development is to maximize the profit of the company within a given time horizon by carefully initiating the right development projects at the right time. Uncertain outcome of development activities and even failures of development projects are handled by means of scenario techniques. Due to the unknown project outcomes, development activities are initiated on a rolling time horizon by taking into account the realized benefits of previously conducted projects. The presented approach can be applied in companies that strive for a long-term cooperation with their suppliers to improve their competitiveness. It is capable of supporting both, companies that use a single sourcing strategy or companies that aim for multiple sourcing. Potential fields of application are found in the automotive industry or in producers of machinery or electronics, which are some of the industries that actively conduct supplier development, cf. Wagner (2006).

The paper is organized as follows. In the next section, we review the literature on supplier evaluation, selection, and development. Section 3 describes the considered planning problem in detail and presents a model that captures the planning task. Solution methods for making the supplier selection, supplier development, and ordering decisions are presented in Section 4. Computational results are presented in Section 5. Section 6 concludes the paper.

2 Literature

The problem addressed in this paper is related to the fields of supplier evaluation, supplier selection, and supplier development. These three topics have received considerable attention from research.

2.1 Studies on Supplier Evaluation and Selection

The recent literature on supplier evaluation and selection is surveyed in Ho et al. (2010). The reviewed studies consider supplier selection as a multi-criteria decision making process where cost, quality, distance, technological capabilities, and further criteria are used for identifying the right supplier base for a company. Methods used most often are Data Envelopment Analysis (DEA) and Analytic Hierarchy Process (AHP), see e.g. Braglia and Petroni (2000) and Akarte et al. (2001). DEA and AHP are combined in the recent study of Zeydan et al. (2011), where suppliers are selected for an automotive company in Turkey with respect to qualitative and quantitative criteria. An AHP approach for the fast changing fashion market is presented in Chan and Chan

(2010), where next to cost and capacity also lead times and order flexibility are of high importance. Mathematical programming techniques are applied when supplier selection is treated as a facility location problem within strategic supply network design, see the survey of Melo et al. (2009). In such approaches, supplier selection decisions can be combined with decisions regarding capacity installation, inventory holding, and order sizing, e.g. Cakravastia et al. (2002), Melo et al. (2006), and Keskin et al. (2010). Fazlollahtabar et al. (2011) combine AHP and mathematical programming to determine priority values for selecting suppliers and to quantify the cost and service levels that result from placing orders at the selected suppliers. Also Wu et al. (2011) combine these two approaches, where AHP is extended towards a deeper consideration of interrelated selection criteria like quality, time, and flexibility. Solution methods for supplier selection models comprise, for example, exact methods like Benders Decomposition (Cordeau et al., 2006), meta-heuristics like Genetic Algorithms (Wang and Shu, 2007), and simulation based approaches (Ding et al., 2005). Several studies address supplier selection and evaluation as a multi-period problem to adapt the supplier base according to changing customer demand or to changing preferences of the buying company, e.g. Sucky (2007) and Osman and Demirli (2010). The problem size considered in the studies varies strongly. It ranges from case studies with four suppliers (e.g. Ding et al., 2005) to studies with 30 to 40 suppliers (e.g. Cordeau et al., 2006; Osman and Demirli, 2010). In the latter studies, methods are developed for reducing the number of supplier combinations that need to be inspected within a solution process. Supplier selection taking the product life-cycle into account is considered in Narasimhan et al. (2006) and Chang et al. (2006). However, these studies propose to revise the supplier base when market conditions change. Developing selected suppliers is out of scope.

2.2 Studies on Supplier Development

Supplier development has been investigated numerously too. An overview of the recent literature in this field is provided by Chidambaranathan et al. (2009) and Wagner (2011), showing that the majority of papers present empirical studies based on surveys. Krause and Ellram (1997a,b) conducted a survey to identify critical factors of a successful supplier development. It is found that successful cooperations show a considerable commitment to supplier certification, mutual visits of representatives, training and education of supplier personnel as well as to investments in supplier operations. According to the survey of Modi and Mabert (2007), evaluation and certification programs seem to have a stronger impact on the success of a development initiative than knowledge transfer activities like training of personnel. Wagner (2006) conducted a survey to identify the type of supplier development activities in various industries. It is found that companies prefer to give process-oriented support like machine set-up advices or quality management practice but they are often reluctant to a direct investment into suppliers.

It has been noted by Talluri et al. (2010) that, in contrast to the large number of empirical studies on supplier development, formal decision models do almost not exist in this field. The authors provide a decision support approach for allocating an investment volume of a company among its suppliers such that a target return is achieved at minimum risk. The decision fields considered in this paper are not considered in their study. To the best of our knowledge, selective investments into structured development projects and the combination of supplier selection and multi-period supplier development have not been addressed in the literature before.

3 Problem Description

3.1 Planning Situation

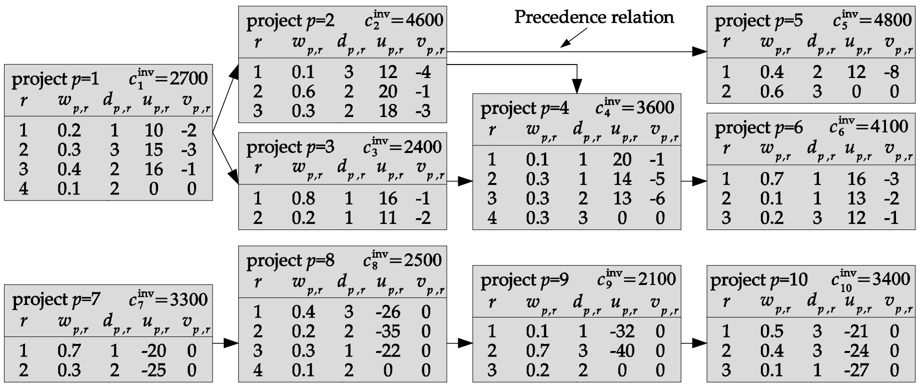
We consider a company that sources a component from suppliers and produces a final product which is sold to customers in a dynamic and uncertain market. The task is to select the suppliers from which the component is sourced and to schedule development projects for improving the capabilities of these suppliers such that the market demand is fulfilled most profitably. The notation used for modeling this management task is summarized in Tab. 1.

Let H denote the planning horizon for which the activities of the company have to be planned. The planning horizon is subdivided into periods. Customer demand a_t of period $t \in H$ and sales price p_t per unit of the final product are stochastic values that become known in the course of time. We assume that the company can forecast these values for h periods in advance. This means, in period t, reliable demand quantities and prices are known for periods t,t+1,…t+h. Let S denote the set of potential suppliers from which the company has to select its supplier base. A selected supplier $s \in S$ provides an initial production capacity b_s^0 at time 0, which changes by g_s^t units in subsequent periods $t \in H$. The capacity change represents the supplier's ability to improve its performance within certain bounds without the help of the buying company. The initial procurement cost rate at which the buying company can source the component from the supplier is denoted c_s^0. It includes all relevant cost like the variable production cost of the supplier and the transportation cost for shipping the component from the supplier to the company.

Table 1: *Parameters and variables*

Market Environment:	
H	planning horizon, i.e. a finite set of consecutive time periods
a_t	customer demand in period $t \in H$
p_t	sales price per unit of the final product in period t
h	forecast horizon, number of periods for which a reliable forecast of demand and price exists
α	discount rate
Suppliers:	
S	set of potential suppliers
b_s^0	initial production capacity of supplier $s \in S$, measured in equivalent final product units
g_s^t	self-induced capacity change of supplier s in period $t \in H$
c_s^{fix}	fixed cost for employing supplier s
c_s^0	initial variable procurement cost rate for sourcing components from supplier s
c_s^{maint}	maintenance cost per capacity unit and period for supplier s
Development projects:	
P_s	set of development projects for supplier $s \in S$
R_p	set of potential realizations (scenarios) of project p
$\bar{R}_p$	set of successful realizations of project p, $\bar{R}_p = \{r \in R_p \mid (u_{p,r} \neq 0) \vee (v_{p,r} \neq 0)\}$
c_p^{inv}	investment cost of project p, i.e. the budget that is spent for conducting the project
$w_{p,r}$	occurrence probability of realization $r \in R_p$ of project p
$d_{p,r}$	duration for implementing project p under realization r
$u_{p,r}$	capacity change realized through project p under realization r
$v_{p,r}$	change in variable cost realized through project p under realization r
W_p	set of predecessor projects of project p
Decision Variables:	
y_s	binary, 1 if supplier s is selected as a sourcing partner, 0 otherwise
z_p^t	binary, 1 if project p is started in period t, 0 otherwise
x_s^t	quantity ordered from supplier s in period t
Dependent Variables:	
$k_{p,r}^t$	binary, 1 if project p is finished at the begin of period t under realization $r \in R_p$, 0 otherwise
b_s^t	production capacity of supplier s in period t, measured in equivalent final product units
c_s^t	variable procurement cost rate for sourcing components from supplier s in period t
NPV	net present value of a solution

Figure 2: *Representation of development projects*



Within the planning horizon, the buying company can intensify the cooperation with a selected supplier s by conducting development projects from set P_s. Such development allows to further adapt the supplier's production capacity and to lower the procurement cost. The projects are characterized by the required investment and by their potential benefits regarding capacity and cost improvement. This way, a generally applicable planning approach is derived, no matter which activities (training of personnel, process optimization, technology improvement, or the like) the projects actually comprise. Initiating a project p incurs investment cost c_p^{inv}, which represents the budget available for conducting the project. The success of project p, the duration for implementing it as well as its impact on supplier capacity and procurement cost are typically uncertain. This is modeled through a set R_p of potential realizations (or scenarios) that could occur for project p. The occurrence probability of realization $r \in R_p$ is denoted by $w_{p,r}$. If realization r takes place for project p, implementing the project takes $d_{p,r}$ periods. Realization r effects a change in the production capacity of supplier s by $u_{p,r}$ capacity units as well as a decrease of the variable procurement cost rate by $v_{p,r}$. Figure 2 exemplarily illustrates ten projects that can be conducted for a supplier. It shows for each project the investment cost and the parameters of the project realizations. For example, the realization $r = 1$ of project $p = 2$ occurs with a probability of $w_{2,1} = 0.1$ (10 %). Under this realization, conducting the project takes $d_{2,1} = 3$ time periods and the project effects an increase of the production capacity of supplier s by $a_{2,1} = 12$ units as well as a decrease of the variable procurement cost rate by $v_{2,1} = -4$. Failing of a development project is represented by realizations that do not create any benefit (i.e., $u_{p,r} = v_{p,r} = 0$), see realization $r = 4$ of project $p = 1$. Realizations with negative values of $u_{p,r}$ are used for representing so-called downsizing projects. These projects aim at reducing supplier capacity to save maintenance cost in a declining market. In Fig. 2, projects $p = 7$ to $p = 10$ represent a program for such a downsizing. Note that $u_{p,r}$ and $v_{p,r}$ refer to absolute changes of capacity and variable cost in this study. However, realizations that effect relative changes (like a 10 % reduction in variable procurement cost) could be incorporated as well. Interdependencies among projects are represented by precedence relations. We denote by W_p the set of predecessor projects that must be accomplished successfully before project p can be started. The network structure in Fig. 2 illustrates such precedence relations. For example, starting project $p = 4$ requires that projects 2 and 3 have been completed, i.e. $W_4 = \{2,3\}$.

The buying company has to make three decisions:

- A long-term decision covering the whole planning horizon is to select the supplier base that is used by the company. This decision is made once at the beginning of the planning horizon.
- A medium-term decision covering several subsequent periods is to select the development projects that are initiated for the suppliers. The decision is made once at the beginning of every period in the planning horizon. This allows taking into account the forecast of demand and price for the coming h periods as well as the realized effects of previously conducted projects.
- A short-term decision is to allocate customer demand to the suppliers in a period or, in other words, the determination of the order size placed by the buying company at a supplier. The decision is made at the beginning of a period and takes into account the capacities of suppliers and their variable procurement cost.

The company aims at maximizing the net present value (*NPV*), which is the sum of discounted cash flows of revenues and costs over all periods of the planning horizon. Revenues depend on the sales prices in the periods and on the fulfilled demand volume. Note that demand is not served completely (i.e. lost sales occur) if the supplier development does not establish sufficient capacity. Considered costs are the fixed cost c_s^{fix} for selecting supplier s, the investment cost c_p^{inv} for conducting development project p, the variable procurement cost c_s^t of supplier s in period t, and maintenance cost c_s^{maint} for the capacity installed at supplier s. Maintenance cost occur per period and per installed capacity unit independent of the utilization of the capacity. They make building excessive supplier capacity economically unattractive and enforce an active reduction of capacity in a declining market.

The parameters of suppliers and development projects give a tendency regarding their attractiveness for the buying company. For suppliers, the chance of being taken up in the supplier base increases with lower fixed cost, a low initial procurement cost rate, a low maintenance cost rate, and a high initial production capacity. Development projects are attractive if they show low investment cost, high probability for a successful realization, short implementation time, and significant capacity and cost effects. Nevertheless, the overall contribution of a supplier is revealed in the course of time only. This is because development projects and demand allocation decisions can outweigh the initial performance parameters of suppliers, and, thus, the best supplier base cannot be determined a priori just from considering the mentioned characteristics. The same holds for development projects, where precedence relations and stochastic project outcomes make it difficult to find a good development strategy without proper decision support. Furthermore, since the space of supplier selections and project schedules grows exponentially with the number of available suppliers and projects, a formalized decision support seems reasonable for supporting managers when tackling the complex problem of joint supplier selection and development.

The following assumptions are made in this study:

- The set of potential suppliers is known together with the possible development projects and their probabilistic realizations.
- Each project p that is performed ends in one realization $r \in R_p$. The particular realization that takes place for a project is unknown to the decision maker at the point in time when the project is initiated and becomes known to the decision maker at the end of the realization process, i.e. $d_{p,r}$ periods after starting the project. We refer to this realization as the occurring realization. It determines the benefits that are achieved through the project. Projects that fail can be repeated.
- The demand of a period is satisfied through the suppliers' period capacity. Producing and stock-keeping components for meeting demand in future periods is not considered. Demand that cannot be satisfied in a period is lost.
- Order quantities and customer demand are measured in equivalent units of the final product that is sold by the company. Hence, there is no transformation necessary between supplier capacities, production and order quantities, and final product demand of customers.

3.2 Optimization Model

The decisions that must be made by the company are represented by the following decision variables. The selection of supplier $s \in S$ is represented by the binary decision variable y_s , which is set to 1 if s is selected and 0 otherwise. The scheduling of development projects is modeled by binary variables z_p^t, set to 1 if project p is initiated at the begin of period t and 0 otherwise. The allocation of period demand to suppliers is represented by non-zero variables x_s^t, which correspond to the amount of the component that is procured from supplier s in period t.

Further dependent variables are introduced that model the effects of the scheduled development projects. We denote by b_s^t the production capacity of supplier s in period t that results from successfully finished development projects. Accordingly, c_s^t denotes the variable procurement cost rate of supplier s in period t. A further variable is used for modeling the stochasticity of project realizations. A project p that is scheduled at time t' will end in one of its realizations $r \in R_p$ at time $t' + d_{p,r}$. At this point in time, the capacity and cost changes take place at the corresponding supplier. To account for these effects, a binary variable $k_{p,r}^{t}$ is introduced, where $k_{p,r}^{t}$ takes value 1 if project p finishes with realization r at the begin of period t.

A formal description of the planning problem is provided by model (1)-(11).

$$max \rightarrow NPV = \sum_{t\in H} \sum_{s\in S} \left(p_t \cdot x_s^t - c_s^t \cdot x_s^t - \sum_{p\in P_s} z_p^t \cdot c_p^{\text{inv}} - c_s^{\text{maint}} \cdot b_s^t \right) \cdot (1+\alpha)^{-t} - \sum_{s\in S} c_s^{\text{fix}} \cdot y_s \qquad (1)$$

The objective function (1) is to minimize the net present value of discounted revenues and period cost together with the fixed cost for selecting suppliers at the begin of the planning horizon. Here, α denotes the discount rate which is used for taking the time preference of the decision maker into account.

Constraints (2) to (5) guarantee a feasible scheduling of development projects. Constraint (2) ensures that development projects are scheduled for selected suppliers only. From (3), all predecessor projects $p' \in W_p$ must have been accomplished successfully if project p is started in period t. Here, $\bar{R}_p \subseteq R_p$ denotes the set of successful realizations of project p', i.e. all realizations where a capacity or cost effect is achieved. Failed project realizations are excluded from this set. Constraint (4) avoids that successfully completed projects are restarted. Repetitions of failed projects are allowed to strive again for a successful completion. Finally, Constraint (5) guarantees that a project is not started if it is already running at time t. This is done by enforcing that the number of project starts is not larger than the number of times the project ended.

$$z_p^t \leq y_s \qquad \forall\, s \in S, p \in P_s, t \in H \qquad (2)$$

$$z_p^t \leq \sum_{t'=0}^{t} \sum_{r\in \bar{R}_{p'}} k_{p',r}^{t'} \qquad \forall\, s \in S, p \in P_s, t \in H, p' \in W_p \qquad (3)$$

$$z_p^t \leq 1 - \sum_{t'=0}^{t} \sum_{r\in \bar{R}_p} k_{p,r}^{t'} \qquad \forall\, s \in S, p \in P_s, t \in H \qquad (4)$$

$$z_p^t \leq 1 - \sum_{t'=0}^{t-1} z_p^{t'} + \sum_{t'=0}^{t} \sum_{r\in R_p} k_{p,r}^{t'} \qquad \forall\, s \in S, p \in P_s, t \in H \qquad (5)$$

The order quantities are restricted in (6) and (7). Constraint (6) ensures that components are sourced from selected suppliers only and that the period capacity of a supplier is not exceeded. Constraint (7) ensures that the quantity produced by suppliers and sold to customers in a period does not exceed the period demand. Note that (7) does not enforce meeting the customer demand completely, because, in case of insufficiently developed suppliers, available capacity does not allow fulfilling all demand. Since supplier capacity is measured in equivalent units of the final product, no transformation between order quantities x_s^t and customer demand a_t is needed in (7).

$$x_s^t \leq b_s^t \cdot y_s \qquad \forall\, s \in S, t \in H \qquad (6)$$

$$\sum_{s \in S} x_s^t \leq a_t \qquad \forall\, t \in H \qquad (7)$$

The benefits of successful projects are determined in (8) and (9). Constraint (8) derives the production capacity of supplier s in period t from the supplier's capacity in period t−1 plus its self-induced capacity change and the capacity change from projects that are realized at the begin of period t. Accordingly, (9) determines the variable procurement cost rates of suppliers in each period. Domains of decision variables are defined in (10) and (11).

$$b_s^t = b_s^{t-1} + g_s^t + \sum_{p \in P_s} \sum_{r \in \bar{R}_p} k_{p,r}^t \cdot u_{p,r} \qquad \forall\, s \in S, t \in H \backslash \{0\} \qquad (8)$$

$$c_s^t = c_s^{t-1} + \sum_{p \in P_s} \sum_{r \in \bar{R}_p} k_{p,r}^t \cdot v_{p,r} \qquad \forall\, s \in S, t \in H \backslash \{0\} \qquad (9)$$

$$y_s, z_p^t, k_{p,r}^t \in \{0,1\} \qquad \forall\, s \in S, t \in H, p \in P_s, r \in R_p \qquad (10)$$

$$x_s^t, b_s^t, c_s^t \geq 0 \qquad \forall\, s \in S, t \in H \qquad (11)$$

4 Decision Making

Model (1)-(11) catches the planning problem that is faced by the company. Unfortunately, the structure of the problem prevents identifying the best decisions by solving the model directly. A technical issue is the nonlinearity of (1) and (6) (supplier capacity b_s^t and variable cost c_s^t are dependent on the decisions made), from which the model cannot be tackled by mixed-integer programming solvers. A practical difficulty is that the decisions have to be made under a limited availability of demand forecasts and with respect to the stochastic realization of projects. The actual realization of a project and its resulting benefit are unknown until it has been conducted. Hence, the setting of variables $k_{p,r}^t$ cannot be determined within the model. This impedes scheduling the development projects for all periods at the begin of the planning horizon, i.e. when the suppliers are selected. To circumvent this difficulty, decision making is decomposed as follows: Supplier selection is made at the begin of the planning horizon, where simulation is used to measure the performance of a supplier base in an uncertain market environment. Development projects are scheduled on a rolling time horizon by taking into account the available demand forecasts and the effects of already completed projects. The used solution techniques are described in detail in Sections 4.1 to 4.3.

4.1 Supplier Selection

The selection of suppliers has to be made at the begin of the planning horizon, although its performance is observed during the course of time when suppliers are developed and customer demand and sales prices become known. In this situation, a company can use simulation for evaluating the performance of a selection.

A supplier selection is a subset of the suppliers in set S. The power set $\wp(S)$ contains all possible subsets of S. The size of $\wp(S)$ grows exponentially with the number of suppliers. Nevertheless, if only few suppliers are available, which is likely the case when specific components in high tech businesses like the automotive industry are to be sourced, and if solution time is a less critical factor, which is generally the case for strategic-tactical planning, $\wp(S)$ can be searched completely to find the best supplier selection. The performance of a selection $S' \in \wp(S)$ is evaluated by simulating the development process over the periods of the planning horizon. This is done by applying the project scheduling and the demand allocation techniques of Sections 4.2 and 4.3 together with various demand scenarios and sales price scenarios. Let $\widetilde{D}$ be a set of demand scenarios (each scenario is a setting of demand values $a_t \; \forall t \in H$) and let $\tilde{P}$ be a set of price scenarios (settings of sales prices $p_t \; \forall t \in H$). For each combination of a demand scenario from $\widetilde{D}$ and a price scenario from $\tilde{P}$, we simulate the supplier development process to estimate the *NPV* that is achieved by supplier selection S' under the influence of stochastic project realizations. Multiple simulation runs are conducted to obtain statistically valid results. For a risk-neutral decision maker, the best performing supplier selection S' is the one with highest average *NPV*. This selection represents the outcome of the decision process and serves as the supplier base of the buying company. An outline of the described procedure is provided in Fig. 3.

Figure 3: *Procedure for the identification of the most profitable supplier selection*

SELECT_SUPPLIERS(set of potential suppliers S, demand scenarios $\widetilde{D}$, price scenarios $\tilde{P}$)

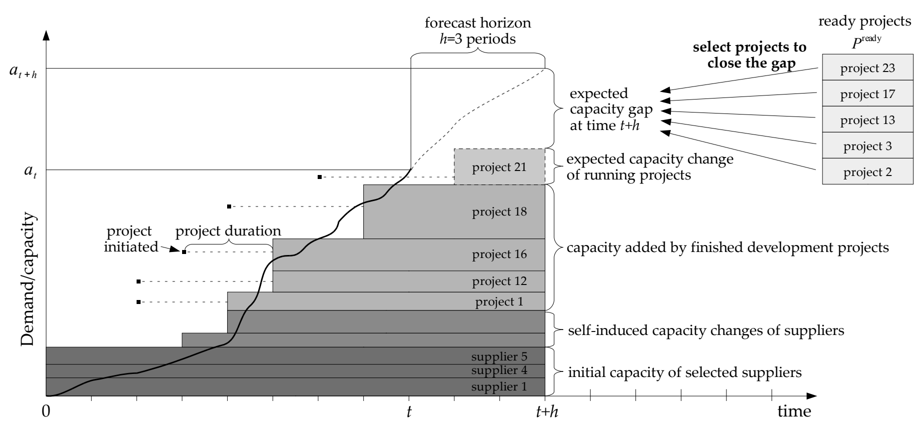
for each supplier set S' in the power set $\wp(S)$ **do**
    for each demand vector from set $\widetilde{D}$ **and each** price vector from set $\tilde{P}$ **do**
        simulate the dynamic supplier development and demand fulfillment process;
    calculate average *NPV* observed over all demand and price scenarios and all simulation runs;
    if S' shows a higher average *NPV* than the best so far known supplier selection **then**
        store S' as the best performing subset of suppliers;
return the best performing subset of suppliers;

4.2 Scheduling of Development Projects

The selection of the development projects that are started at the begin of a planning period is made once in every period $t \in H$. Scheduling projects in such a rolling-horizon fashion enables a company to take the actual capacities and cost rates of suppliers, the expected impact of currently running projects, and the available forecast of customer demand and sales prices into account.

Let P^{ready} be the set of all projects that are ready for being started at the begin of period t. It contains projects, for which (i) the corresponding supplier has been selected in the first phase of the decision making process, (ii) all predecessor projects have been completed successfully at or before time t, (iii) that were not finished successfully before, and (iv) that are not currently running. In other words, projects $p \in P^{\text{ready}}$ respect Constraints (2) to (5). From set P^{ready}, those projects have to be selected that are started at the begin of the current planning period t. In this study, we strive for identifying a selection of ready projects that brings the expected supplier capacity in period t+h close to the demand forecast a_{t+h}. The strategy promises to fulfill future customer demand with respect to a medium-term trend. This avoids a shortsighted focusing on the current market situation and, at the same time, a speculative long-term supplier development which exceeds the reliable forecast horizon. The planning situation is illustrated in Fig. 4.

Figure 4: *Planning situation for development project selection in period t*



Note that in a market with a very short peak season, it may be preferable not to strive for closing the capacity gap completely. This is the case, especially if cost for building up capacity and for later reducing this capacity again outweighs the additionally generated revenue. Unfortunately, due to the uncertainty in terms of unknown length of the product life cycle, the random disturbances in period demand and the restricted forecast horizon, it is extremely difficult to identify a point in time when building up of capacity should be stopped prematurely. Such strategies, including termination of already started projects, are therefore not considered in this study. Hence, the presented approach is a heuristic method for planning supplier development.

The first planning step is to determine the gap between the expected supplier capacity in period *t+h* and the customer demand a_{t+h}. For this purpose, the expected supplier capacity of period *t+h* is determined as the current supplier capacity in period *t* plus the supplier's self-induced capacity change in periods *t+1* to *t+h* as well as the expected capacity change of already running development projects. Let P^{running} be the set of all projects that are running at the begin of period *t*. Let t_p^{start} be the point in time at which project $p \in P^{\text{running}}$ has been started. Since *p* is running in period *t*, it only contributes to the capacity of period *t+h*, if a successful realization $r \in \bar{R}_p$ occurs that ends in the interval (*t*,*t+h*]. Hence, the expected capacity change $E(u)_p^{t+h}$ of a running project *p* until time *t+h* is

$$E(u)_p^{t+h} = \sum_{r \in \bar{R}_p | t_p^{\text{start}} + d_{p,r} \in (t,t+h]} w_{p,r} \cdot u_{p,r} \qquad \forall\, p \in P^{\text{running}} \quad (12)$$

For ready projects $p \in P^{\text{ready}}$ the expected contribution to the supplier capacity in period *t+h* is determined similarly. Since $t_p^{\text{start}} = t$ for newly started projects from P^{ready}, the relevant realizations that could have an effect up to time *t+h* are those with a duration $d_{p,r}$ of at most *h* time periods. Hence, the expected capacity change of a ready project $p \in P^{\text{ready}}$ is

$$E(u)_p^{t+h} = \sum_{r \in \bar{R}_p | d_{p,r} \leq h} w_{p,r} \cdot u_{p,r} \qquad \forall\, p \in P^{\text{ready}} \quad (13)$$

Having determined the expected capacity change of projects, the task is to select a subset of projects $\bar{P}^{\text{ready}} \subseteq P^{\text{ready}}$ that closely approaches the expected capacity in period *t+h* to the future demand a_{t+h}. I.e., $\bar{P}^{\text{ready}}$ needs to be determined such that

$$min \rightarrow \left| a_{t+h} - \sum_{s \in S'} b_s^t - \sum_{s \in S'} \sum_{t'=t+1}^{t+h} g_s^{t'} - \sum_{p \in P^{\text{running}}} E(u)_p^{t+h} - \sum_{p \in P^{\text{ready}}} E(u)_p^{t+h} \right| \qquad (14)$$

is minimized. Three selection rules are presented here for determining set $\bar{P}^{\text{ready}}$. The rules represent project selection criteria that aim at minimizing the project investment cost, at minimizing the resulting procurement cost, or at maximizing the probability of successful project completion. It is assumed that these three criteria are of particular interest for a decision maker in a practical application. A computational study is later conducted to compare these policies.

4.2.1 Rule *Min-Invest*

Rule '*Min-Invest*' aims at keeping investment cost low when selecting projects for closing the capacity gap. Recall that c_p^{inv}denotes the investment cost of a project p. Then, $c_p^{\mathrm{inv}}/E(u)_p^{t+h}$ is the expected investment per capacity unit of project $p \in P^{\mathrm{ready}}$. The projects in P^{ready} are sorted in increasing order of this measure. Starting from the project with the lowest expected investment cost rate, projects are successively added to $\bar{P}^{\mathrm{ready}}$ if they contribute to the minimization of (14). All projects that eventually entered set $\bar{P}^{\mathrm{ready}}$ are started at the begin of period t. Note that in a declining market with demand a_{t+h} below the available capacity, projects are selected that reduce capacity. In such a situation, the rule selects projects with negative expected capacity change ($E(u)_p^{t+h} < 0$) as is the case for downsizing projects. In doing so, the rule reacts adaptive no matter whether demand grows, declines, or stagnates.

4.2.2 Rule *Min-Var-Cost*

Rule '*Min-Var-Cost*' aims at selecting projects that lead to a strong reduction of variable procurement cost. For projects p of suppliers s, let

$$E(v)_p^{t+h} = \sum_{r \in \bar{R}_p | d_{p,r} \leq h} w_{p,r} \cdot v_{p,r} \cdot \left(b_s^t + \sum_{t'=t+1}^{t+h} g_s^{t'} + u_{p,r} \right) \qquad \forall\, p \in P^{\mathrm{ready}} \quad (15)$$

be the expected saving in variable cost in period t+h. Since the change in the variable cost rate applies to each capacity unit of the supplier, the savings are weighted with the current capacity b_s^t plus the self-induced capacity changes $g_s^{t'}$ in periods up to t+h plus the capacity change $u_{p,r}$ of project realization r. Note also that $E(v)_p^{t+h}$ takes a negative value, because cost savings are modeled by parameters $v_{p,r} < 0$. Thus, the lower $E(v)_p^{t+h}$ is, the more effective p is. For this reason, rule *Min-Var-Cost* sorts projects in P^{ready} by increasing order of this measure. Starting from the project with the lowest value $E(v)_p^{t+h}$, projects are successively added to $\bar{P}^{\mathrm{ready}}$ if they contribute to the minimization of (14). All projects that eventually entered set $\bar{P}^{\mathrm{ready}}$ are started at the begin of period t. Recall that in declining markets, projects must be selected that reduce capacity. Generally, realizations of such projects do not reduce procurement cost, which leads to a value $E(v)_p^{t+h} = 0$. Therefore, in declining markets, *Min-Var-Cost* cannot make a qualified selection and we fall back to rule *Min-Invest* in such a situation.

4.2.3 Rule *Max-Succ-Prob*

Rule '*Max-Succ-Prob*' simply selects those projects that show the highest probability for being successfully finished until time t+h. The extent of cost and capacity effects of the selected projects is ignored. Hence, rule *Max-Succ-Prob* sorts projects $p \in P^{\mathrm{ready}}$ by decreasing value $\sum_{r \in \bar{R}_p | d_{p,r} \leq h} w_{p,r}$. Starting from the project with the highest probability for a successful implementation, projects are added successively to $\bar{P}^{\mathrm{ready}}$ if they contribute to the minimization of (14). All projects that eventually entered set $\bar{P}^{\text{ready}}$ are started at the begin of period t. An outline of the project selection procedure is provided in Fig. 5.

Figure 5: *Procedure for selecting development projects*

SELECT_PROJECTS (suppliers base S',running projects P^{running},demand a_{t+h}, selection rule *rule*)

1: determine set P^{ready} of projects that meet preconditions for being started;

2: $\bar{P}^{ready} \leftarrow \emptyset$; ▹ Initialize set of selected projects.

3: **if** rule = *Min-Invest* **then** sort projects $p \in P^{\text{ready}}$ by increasing value $c_p^{\text{inv}}/E(u)_p^{t+h}$;

4: **if** rule = *Min-Var-Cost* **then** sort projects $p \in P^{\text{ready}}$ by increasing value $E(v)_p^{t+h}$;

5: **if** rule = *Max-Succ-Prob* **then** sort projects $p \in P^{\text{ready}}$ by decreasing value $\sum_{r \in \bar{R}_p | d_{p,r} \leq h} w_{p,r}$;

7: **for each** project p in the sorted project list **do**

8: **if** p contributes to the minimization of (14) **do** $\bar{P}^{\text{ready}} \leftarrow \bar{P}^{\text{ready}} \cup \{p\}$;

9: **return** selected projects $\bar{P}^{\text{ready}}$;

4.3 Demand Allocation

The third decision domain is to allocate customer demand to the selected suppliers. This decision is made once at the beginning of each period $t \in H$. The quantities ordered at the suppliers are not allowed to overshoot the supplier capacities or the observed period demand, see Constraints (6) and (7). The goal is to maximize the period profit. Since building up inventory for future periods is not considered in this study, the customer demand a_t is fulfilled through the available production capacities b_s^t of the supplier base S'. In case of insufficient production capacity ($a_t > \sum_{s \in S'} b_s^t$) period demand cannot be fulfilled completely. For this reason, the objective (1) includes revenue next to total cost. The described allocation problem can be solved to optimality in two steps. First, the suppliers in S' are sorted in increasing order of their current variable procurement cost rate c_s^t. Second, starting from the supplier with lowest cost rate, the period demand a_t is allocated with respect to the capacities b_s^t. An outline of this procedure is provided in Fig. 6.

Figure 6: *Procedure for allocating period demand to suppliers.*

ALLOCATE_DEMAND (supplier base S', period demand a_t)

1: **for each** supplier s in S' **do** $x_s^t \leftarrow 0$; ▹ Initialize order quantities.

2: sort suppliers in S' by increasing variable cost rate c_s^t;

3: **for each** supplier s in the sorted supplier list **do**

4: $x_s^t \leftarrow min\{a_t, b_s^t\}$; ▹ Allocate remaining demand up to supplier's capacity.

5: $a_t \leftarrow a_t - x_s^t$; ▹ Reduce remaining demand by ordered amount.

6: **return** order sizes x^t.

5 Computational Experiments

We conduct computational experiments to identify the best performing subset of suppliers and the best supplier development policy for a set of test scenarios as well as for assessing the sensitivity of solutions when problem parameters change. The generation of test data is described next. Computational results are described afterwards.

5.1 Test Scenarios

We generate a hypothetical data set for assessing the planning methodology. The set contains ten test instances with five suppliers each. Parameters of the suppliers are determined randomly. The initial capacity b_s^0 of supplier $s \in S$, its fixed cost c_s^{fix}, its initial variable procurement cost rate c_s^0, and its maintenance cost rate c_s^{maint} are drawn from uniform distributions in the interval U[10,20], U[10 000,100 000], U[100,150], and U[25,50], respectively. Self-induced capacity changes of suppliers are not considered in further detail ($g_s^t = 0$). Development projects are generated as follows. For each supplier $s \in S$, between 10 and 24 projects are created for increasing the supplier's production capacity. The projects are grouped in two to three development programs with random precedence relations inserted among the projects belonging to a same program. The investment cost c_p^{inv} of projects are drawn from U[1000,5000]. Each project receives two to four possible realizations. The duration $d_{p,r}$ (measured in periods) of project p under realization $r \in R_p$ is drawn from U[1,3]. Capacity change $u_{p,r}$ of realization r and the reduction in variable cost $v_{p,r}$ are drawn from U[10,20] and U[−10,−1], respectively. Realizations that represent the failing of a project are defined through $u_{p,r} = v_{p,r} = 0$. The occurrence probabilities $w_{p,r}$ are distributed randomly among the realizations of a project such that $\sum_{r \in R_p} w_{p,r} = 1$ holds $\forall\, s \in S, p \in P_s$. The generation process is repeated to create projects and programs for decreasing the production capacity in a declining market. These project receive realizations where $u_{p,r}$ is drawn from U[−50,−20] and $v_{p,r}$ is set to 0.