Strategic Planning of BMW's Global Production Network

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We developed a strategic-planning model to optimize BMW's allocation of various products to global production sites over a 12-year planning horizon. It includes the supply of materials as well as the distribution of finished cars to the global markets. It determines the investments needed in the three production departments, body assembly, paint shop, and final assembly, for every site and the financial impact on cash flows. The model has improved the transparency and flexibility of BMW's strategic-planning process.

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A car manufacturer's decisions on investing in production capacity are critical. A great part of the capacity is product specific, for example, the assembly lines for bodies. The installed capacity must be sufficient for the whole life cycle of the product, six to eight years, because expanding capacity later is very expensive. On the other hand, low utilization of capacity threatens the profitability of the product. Although the time to market for new products has dropped remarkably, it still takes several years from the investment decision to start serial production. Thus, a firm's decisions on very large capital investments affect its competitiveness for the next 10 years.

A car manufacturer's situation for strategic planning is complicated by market trends, currently the market's increasing dynamics and globalization of the supply chain, including sales markets, production sites, and suppliers. Competition forces car manufacturers to launch new car models frequently to provide new functions for customers, new concepts, such as sports activity vehicles, new materials, such as aluminium, and future electronic components, such as dynamic stability control (DSC) or BMW's integrated driving system, I-Drive. Customers want individual configuration, particularly for premium cars. Besides the classical markets in Europe, North America, and

Japan, new markets are emerging, such as Eastern Europe and China. The product life cycles in these new markets are likely to be different from those in the established markets. Possibly, manufacturers can sell discontinued models in new markets. Locating production sites throughout the globe brings production closer to such markets, permitting firms to benefit from the individual advantages of certain countries, for example, investment incentives and low costs for labor.

Strategic Planning at BMW

The BMW Group, with its head office in Munich, Germany, manufactures and sells BMW, MINI, and Rolls Royce cars. Its products cover the full range of size classes and car types but consist exclusively of premium-class cars. In 2004, it sold 1.25 million cars. Currently, BMW produces cars in eight plants in Germany, the United Kingdom, the United States, and South Africa, and its external partner, Magna Steyr, has a plant in Austria (Figure 1). Moreover, it manufactures engines at four further sites, and completely knocked down (CKD) assembly takes place at six sites. The product program is expanding steadily.
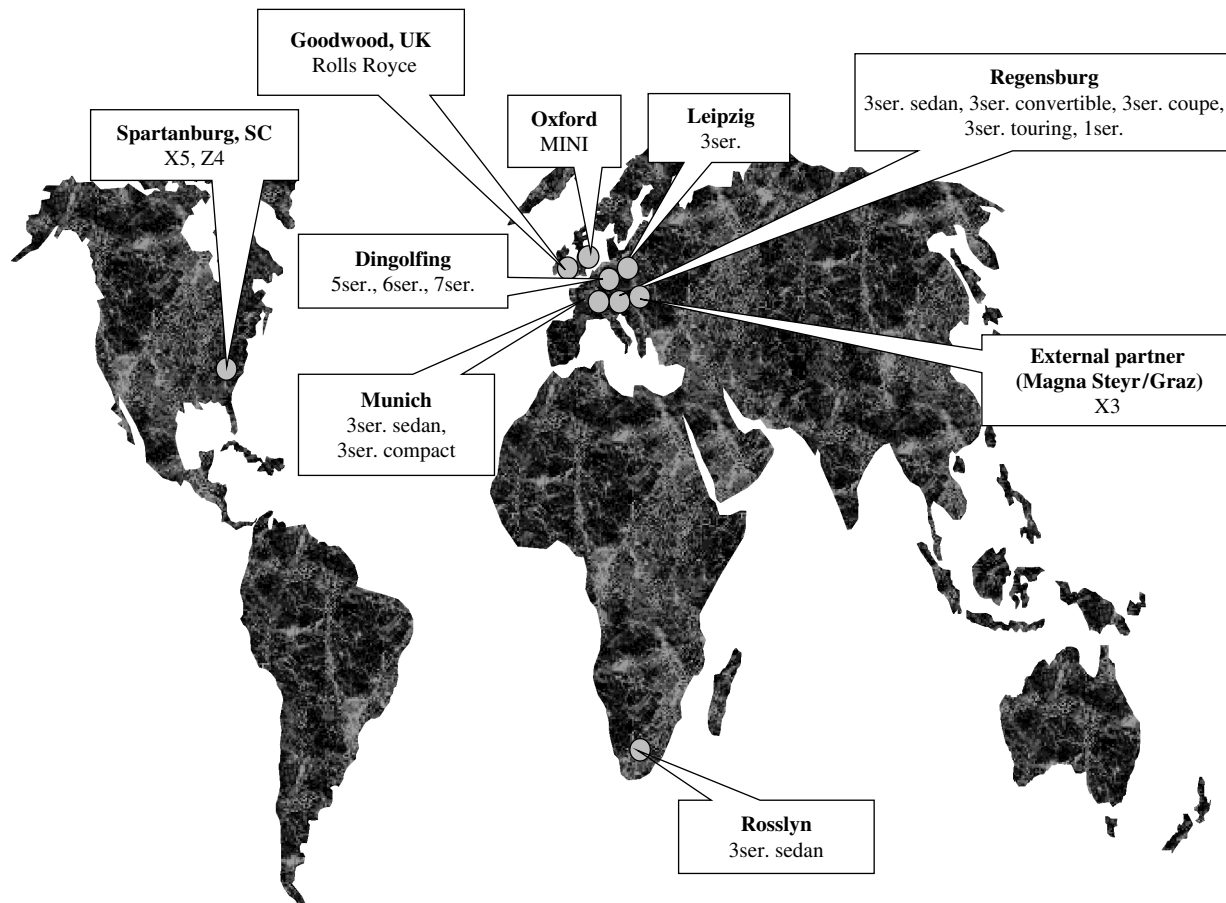
Figure 1: The BMW Group manufactures cars in eight of its own plants in Germany, the United Kingdom, the United States, and South Africa, and its external partner, Magna Steyr, manufactures cars in Austria. In addition, there are seven CKD plants not shown in this figure.

In the last three years (2001 to 2004), nine new models have been launched, among them the 6 series with a coupé and a convertible, the X3, a sports activity vehicle, the Mini convertible and, most recently, the 1 series. This dynamic development will certainly continue in the future.

The Initial Situation

For BMW, long-term strategic planning of products and production is a fundamental task. BMW had a well-elaborated strategic-planning process when we started our project in 2000. In this planning process, the horizon extends to 12 years, divided into yearly periods, so that it contains the full life cycle of the products starting in the next five years. Planners aggregate the products to the level of the derivatives

of the product series, for example, sedan, coupé, touring car, or convertible. They revise the 12-year plans several times a year, and the board of directors must approve of the results.

Naturally, within the planning process, BMW plans its products and sales before planning production capacities. In these two initial steps, which we do not consider in detail, the firm decides on the set of future products and, for each existing or future product, the year or even the month of start-up and shutdown, and estimated sales figures during its life cycle, for different geographical markets. The results of these steps and the flexibility reserves the firm considers necessary based on its experience are available as data for the third step, plant loading, in which planners allocate the products to the plants and determine the
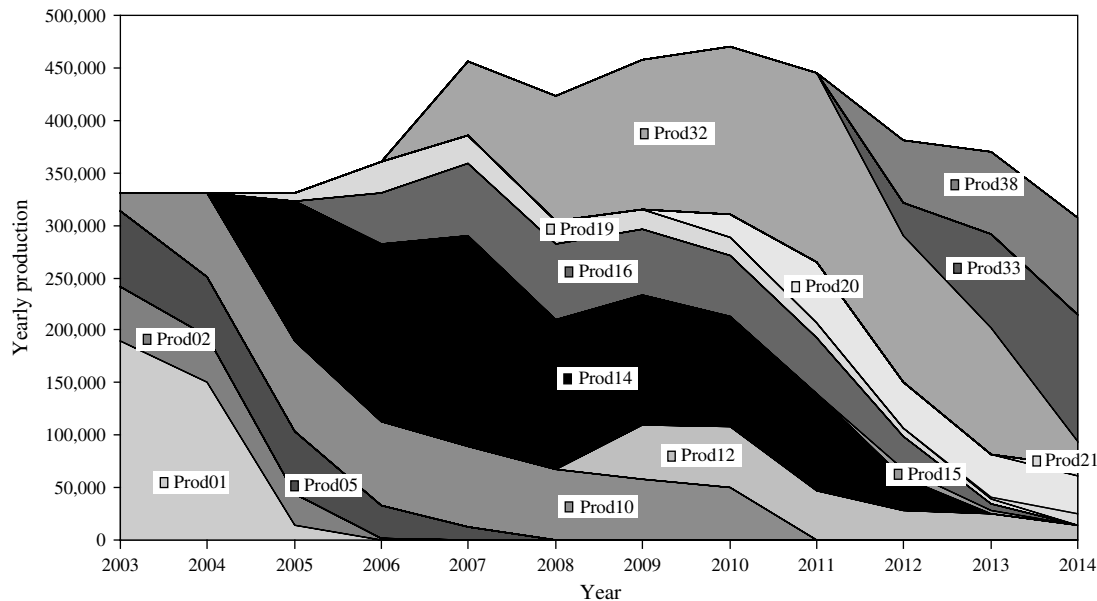
Figure 2: Planners produce a load plan of this type for every plant. It depicts the development of the load over the planning horizon, composed of the volumes of the various products, represented by different shades of gray. It clearly shows the life cycle of each product and its varying production volume. The load line during the first three years is flat because existing capacity is limited and can be increased only after the lead time of three years.

required production capacities. We focus on this third planning step.

Originally, planners performed this step manually using Excel sheets that expressed the load and the capacity per plant as the number of cars produced per day and the number producible per day summed up over all products. They transformed the resulting load plans for all the plants into diagrams (Figure 2).

Planners' allocation of products to plants was restricted for technical reasons, by the personnel skills available at every location, and because of general policy. For only a few products were there alternative production locations, from which planners either made an appropriate choice or tried each one. They had a further degree of freedom for "split products," those produced at two or more plants, for which they decided the volume to be produced at each plant, usually to utilize the plants properly.

Weaknesses
BMW's traditional load planning approach had deficiencies:

(1) The mainly manual planning procedure required a great deal of effort, limiting the comparison

of different strategies and the performance of sensitivity analyses with varying data.

(2) A one-dimensional calculation of capacity at each plant was not adequate. Planners needed to consider separately capacity for assembling bodies, which is dedicated to single products, and capacity for the paint shop and final assembly line, which all products share. Each of these stages is a potential bottleneck.

(3) In allocating products to the global production sites, planners did not consider the effects on the global supply chain, in particular the flow of materials from the suppliers to the plant and the flow of finished cars to the markets. Even the BMW engine plants were not included in the load planning but were planned afterwards in a separate department starting from the results for the car plants. For this process, planners often need iterations with coordination between the departments.

(4) Planners had no clear objective for free decisions, in particular for allocating the production volume of split products, and hence they did no optimization. They also had to evaluate the economics of load plans in an additional separate step.

When BMW realized the deficiencies of its planning process, in particular the effort it required, it initiated a project to improve its strategic load planning. BMW employees who were PhD students worked on the project in cooperation with faculty members of the department of production and logistics of the University of Augsburg. In a first phase, Peter Henrich (2002) studied the interfaces between the load planning and the overall strategic planning and the implications for a quantitative model within this planning process. He developed a mixed-integer programming (MIP) model and implemented it in a commercial software system. In a second phase, Sonja Ferber (2005) extended the model to include investment decisions and their impact on plant capacities and the financial variables.

Literature Review

Goetschalckx (2002) surveyed the rich body of literature on models for designing global supply chains. Some theoretical models focus on a single one of the aspects important to BMW. Arntzen et al. (1995), in a paper on the electronics industry, and Papageorgiou et al. (2001), in a paper on the pharmaceutical industry, addressed practical issues relevant to strategic planning at BMW. Meyr (2004) provided an overview of operational planning in the German automotive industry.

Number of Periods

Single-period models are appropriate for decisions on the immediate reoptimization of parts of the supply chain, for example, new distribution centers or new machines for installation in a factory. Typical models of this type are the classical production-distribution models (Geoffrion and Powers 1995). Cohen and Moon (1991) developed a single-period model for allocating products to plants so as to minimize the variable costs for supply, production, and distribution and the fixed costs for each allocation.

However, we needed a long planning horizon divided into years for two reasons (Goetschalckx and Fleischmann 2005): (1) We have to plan the development of the supply chain over the planning horizon, starting from its present state, and not just plan for one optimal future state, and (2) The timely allocation of investments is important for any objective function based on discounted cash flows, such as net present value. Inventory carried from period to period, however, as is usual in operational planning models, has no importance for strategic planning with yearly periods. In operational linear programming (LP) models, as used for master planning (Fleischmann and Meyr 2003), end-of-period stocks above the minimum (zero or a given safety stock) occur only if forced by a peak demand above the capacity limit in a future period. Even though this seasonal inventory makes no sense for yearly periods, several models include it (Goetschalckx 2002, Papageorgiou et al. 2001). Canel and Khumawala (1997), Huchzermeier and Cohen (1996), and Papageorgiou et al. (2001) considered developing supply chains over long planning horizons. Arntzen et al. (1995), in spite of their multiperiod model, considered only a static supply chain, with many details, such as a multistage bill of materials and duration of processing and shipment operations. Their periods are essentially seasonal periods, and their model is in the spirit of the single-period strategic models. The so-called capacity-expansion models focus on long-term development of a plant or a supply chain (Li and Tirupati 1994) and optimize decisions about when and how much to invest in which type of capacities. However, in BMW's case, the type of equipment, dedicated for a single product or flexible for several products, is fixed by corporate strategy. Moreover, capacity-expansion models assume a continuous expansion of capacity, while BMW can expand capacity only in big steps.

Volume Flexibility

For BMW, flexibility of production capacities with regard to future unknown demand is a central issue. Therefore, corporate policy defines a mandatory flexibility reserve, that is, the difference between expected demand and available capacity, for every product and for every production department in a plant. Jordan and Graves (1995) and Graves and Tomlin (2003) show for single-stage and multistage production systems, respectively, that the flexibility of a supply chain with multiple production sites essentially depends on how the firm allocates products to the sites. They develop flexibility measures and rules on the structure of good allocations but refrain from optimizing the allocation. We could use their results to select

reasonable potential allocations for the load-planning model and to evaluate the resulting load plan, but we have not done so.

New Products
In the planning models, the given (estimated) demand per product and year drives production and distribution activities and installation of capacities. However, the actual logic for new products is inverse (Goetschalckx and Fleischmann 2005): The firm creates demand for a particular new product only by deciding to launch it. Demand starts in the year of the launch and develops over the product's life cycle. Therefore, models based on given demand can support the decision on where to produce a new product but not on when to launch it. To make that decision, the model must allocate the demand over the life cycle to the years. Popp (1983) developed this type of model. All other models, as far as they consider new products, are based on given demand like ours, for example, Papageorgiou et al. (2001).

Uncertainty
The development of market demand, prices, cost factors, and exchange rates over a long-term planning horizon is highly uncertain. Some authors propose stochastic optimization models to deal with the uncertainty. Huchzermeier and Cohen (1996) considered stochastic exchange rates with a known multivariate (dependent) probability distribution. They defined a stochastic dynamic program, changing the configuration of the supply chain based on current exchange rates. The value function of the new configuration consists of switching costs plus the optimal objective value of a single-period operational supply chain model. Santoso et al. (2003) adapted the Kleywegt et al. (2002) sample average approximation method to strategic supply chain models with any kind of uncertain data. The method requires a known probability distribution of the data, from which it derives a large sample of n scenarios, each with probability $1/n$. However, we could make no serious assumptions about the probability distribution of the future demand of new products over a 12-year planning horizon. We therefore fell back on the classical scenario technique.

Objective Function
To model the design of a multiperiod supply chain with investment decisions, the appropriate objective function is the net present value (NPV) of the yearly cash flows (Goetschalckx 2002, Huchzermeier and Cohen 1996, Papageorgiou et al. 2001, and Popp 1983). In their model, Canel and Khumawala (1997) did not discount the revenues and costs and completely allocated the investment expenses as cost to the year of installation. For a long planning horizon, evaluating investments in this way is not appropriate. For a global supply chain, one must take into account duties and exchange rates, and in addition, to determine after-tax cash flows, one must include the transfer payments between producing countries, selling countries, and the holding company. Goetschalckx, Papageorgiou et al., Popp, and Canel and Khumawala all included these elements. Huchzermeier and Cohen did not include transfer payments and allocated profits only to the producing countries.

A Basic Supply Chain Model
To improve BMW's load planning, it was necessary to:

(1) consider the impact of the load planning on the entire supply chain from the suppliers to the customers,

(2) develop a quantitative optimization model with a clearly defined objective function, and

(3) implement the model in an easy-to-use software system.

To integrate the new load-planning model into BMW's existing strategic-planning process, we had to extend the existing load planning beyond the borders of the department in charge and obtain the cooperation of other departments, such as procurement, engine plants, and distribution logistics.

We had to take into account the implications of corporate strategic planning, in particular product planning, as before. Incorporating strategic decisions concerning the product program into the optimization model, as some authors suggested (Papageorgiou et al. 2001, Popp 1983), is not adequate in the automotive industry. There, product policy is the key issue for competitiveness and depends on many qualitative factors. But a load-planning model can be used to support a decision about a new product by showing the consequences for the supply chain.

Henrich (2002) formalized the overall strategic-planning process and the interfaces with strategic load planning. He defined a number of partial strategies, such as the location strategy, the allocation strategy, the capacity and flexibility strategy, and the make-or-buy strategy, and he described characteristics of these strategies for a premium car manufacturer as opposed to a mass product manufacturer. For instance, in determining its location strategy, BMW must consider whether qualified personnel are available in a foreign country and the positive effect on its image of production in Germany ("made in Germany"). In determining its allocation strategy, BMW's objective of making highly customized cars to order requires flexible assembly lines that can be used mostly for all products of a plant, whereas a manufacturer of mass products uses dedicated assembly lines for every product with few variants and thus increases productivity and reduces costs. Allocating several products to one plant makes it easier to balance its utilization, and producing large-volume products in several plants gives the firm the flexibility to cope with varying demand. Capacity of the installed machines should be greater than the expected demand so that the firm has the flexibility to meet the actual demand by the choice of the appropriate working time. The BMW Group has clearly defined rules on how to determine the flexibility reserve.

In our new planning model (Appendix), we considered the same set of assembly plants and products and the same 12-year planning horizon as BMW did in its original model. The new model is an optimization model of the MIP type with two kinds of decision variables, binary allocation variables indicating whether a certain product is produced in a certain plant, and continuous flow variables that represent the yearly quantities in supply, production, and distribution. The overall strategy restricts the possible allocations: The production site for products already in serial production or starting up in the near future is fixed. For other products, the model can choose a single location from a few alternatives, or for the split products, it can choose several locations, say, two out of four alternatives. For split products, the different plants may start producing the product in different

years. But in any case, the first start-up year of a product is determined by when its first demand occurs in the demand data.

The production variables represent the number of cars produced per year, per plant, and per product. They are restricted by the available capacity in each department. Each product has a separate body-assembly capacity, whereas the capacities of the paint shop and the final assembly are shared by all products in a plant. We reduced the capacity figures we used in the model to account for BMW's general flexibility reserve.

We represented the distribution of finished cars by aggregating the global markets into eight or 10 sales regions, so that we could calculate the transport cost and the duties with appropriate exactness. We broke down the demand per product by sales regions using fixed proportions based on the expected regional sales performance.

To model the supply of materials, we aggregated both materials and suppliers into material classes and supply regions. For instance, we considered two classes, steel parts and assembly parts, sufficient for most applications. The engine variants (four, six, eight, or 12 cylinders; gasoline or diesel) are additional material classes, and the BMW engine plants are additional suppliers. To avoid bill-of-material data, we set the quantity unit for materials equal to the amount necessary for one car of a certain type. However, for engines we had to take into account that customers can choose among motor types for their cars. We used coefficients for the proportions of the various engine types demanded for each product. BMW can procure materials from different supply regions or engine plants, but some countries impose local content conditions on plants so that they must purchase a minimum amount of materials from suppliers in the country. Supply regions with restricted sources may have upper limits.

The objective function of our first model consists of only the variable costs for supply, production, and distribution. The cost coefficients per car are expressed in Euros, using estimates of future exchange rates. Because the given demand must be satisfied with products at fixed sales prices, the total revenue is fixed. To calculate the NPV of the investments, planners must consider capital expenditures

for machines and production sites separately outside the model, but they can use the costs resulting from the model as components of the cash flows (Henrich 2002).

Our MIP model (Appendix) is, for fixed allocation variables, a multicommodity network-flow model, as is typical for optimizing aggregated flows in supply networks. Analysts can model and solve this type of planning problem using the software SNO (Strategic Network Optimization), a module of Oracle's JD Edwards supply chain management solutions (Fleischmann and Meyr 2003, Meyr et al. 2005). SNO permits direct graphical construction of the supply network on several aggregation levels, enables expression of BMW's restrictions on product allocation, and uses ILOG/CPLEX as the linear-programming solver. Henrich (2002) implemented BMW's load-planning model in SNO and linked it with a database containing the relevant strategic planning data. The typical model comprises nine plants, about 40 products, six supply regions, two material classes, seven engine types, 10 sales regions, and 12 years. In 2002, the computation time for the solver was a few minutes. BMW used the model for several special projects, for example, to support a decision about allocating a new product, comparing three alternatives: production in Germany or in the United States or in both countries (Henrich 2002).

An Extended Model

In a second project, which BMW initiated in 2002, we extended the model (1) to incorporate investment decisions and their financial impact, and (2) to consider capacities and flexibility reserve in greater detail. Modeling the various investments in the three stages (body assembly, paint shop, and final assembly) turned out to be too complex for the SNO software. Therefore, we developed the new model in ILOG OPL Studio, an environment for developing LP and MIP models using the solver CPLEX (ILOG 2004). This software permits implementation of any kind of LP or MIP model, but it can be used only by experts in operations research. BMW intends to supplement the model with a customized graphical user interface, which still has to be developed.

Investment Planning

In allocating a new product to a certain plant, BMW must make product-specific investments, mainly in the body-assembly department, and to a lesser extent, in the paint shop and final-assembly departments. It may also have to make structural investments for additional space, for buildings, and for expanding equipment that the new product shares with existing products. Typically such expansions are possible only in discrete steps, for example, by adding a spray robot or assembly line. Engineers work out the technical configuration of the machines, such as the degree of automation and the pace, considering BMW's high quality requirements, and provide such data for load planning. The configuration may depend on the manufacturing location. For instance, high levels of automation are profitable only in countries with high labor costs; in countries with low labor costs, production will be less automated. For some operations, however, BMW can achieve the precision it requires only with automation.

The financial variables related to an investment are the capital expenditure and the contribution to revenue and cost. Together, these variables form the cash flow that can be attributed to the investment, and the net present value (NPV) of this cash flow is the usual criterion for evaluating the investment. In our load-planning problem, the revenue is fixed, because sales prices are fixed. Therefore, the objective is to minimize the NPV of the sum of all capital expenditures and costs. A critical question is whether to calculate cash flow before or after tax. The large variations in taxation from country to country are a strong argument for considering tax in global strategic planning. However, in calculating taxes in an international enterprise, we must also consider internal transfer prices and payments. Because incorporating these complexities would have overloaded our planning model, we decided to work with cash flow before tax. Nevertheless, our model can incorporate the impact of tax approximately.

BMW's strategy is self-financing, that is, it obtains operating investments mainly from cash flow. Therefore, its yearly cash flow determines its yearly investment budget, which is the upper limit for investment expenditures. The financial department estimates the investment budget for the 12 years of

Years before and after the start-up	−3	−2	−1	0	1	2
Product-specific investment (%)	4	21	45	22	6	2
Structural investment (%)	—	20	35	45	—	—

Table 1: BMW typically has to pay investment expenditures over several years before machine start-up. For product-specific investments, some expenditures arise in the years after the start-up to pay for product changes.

the planning horizon. In the load-planning model, we consider only investments for allocating new products to plants. BMW may also need to replace equipment, for example, spray units after 20 years. We account for such investments by reducing the investment budget accordingly.

When installing complex machines, BMW has to pay investment expenditures over several years before and after the start-up (Table 1).

The structure of the investments differs for the three production departments:

In the body department, BMW needs a new specialized assembly line for each innovative product. If a plant reaches its limit in production capacity, it can install a second line if it has the space. The expenditure consists of a fixed amount per line plus a variable amount that depends on the maximal number of cars per year (or per day) to be produced on this line. The variable amount is approximately linear. In addition, BMW may make structural investments for new buildings if the number of products in a plant exceeds its limit.

In the paint-shop department, which all the plant's products share, investments are mainly structural. If production volume increases, BMW may need to invest in additional capacity in one or two steps at the most during the planning horizon. But BMW also makes smaller product-specific investments, for example, fixed-cost expenditures for transmission equipment or expenditures that are proportional to the maximal number of cars per year, for example, for equipment for fastening the cars.

In the final-assembly department, BMW uses multiproduct lines that can also handle customized variants of a product. The pace is slower for such flexible lines than it is for the dedicated lines of mass-product manufacturers. In this department, most investments

are structural, with product-specific investments for tools, containers, and mounting and measuring equipment, with fixed plus variable expenditures.

Capacities

Because future demand is uncertain, the BMW Group established general guidelines on flexibility reserves to ensure that installed capacities are highly flexible in production volume. These guidelines are obligatory for strategic planning of capacities, and they reflect the way BMW deals with long-term demand uncertainties. They are incorporated into the load-planning model. For a production line, we distinguish between the maximal capacity (per week or per year) based on running continuously seven days a week, 24 hours a day, and the normal capacity under normal working conditions. Maximal capacity is a technical characteristic of the production line, whereas normal capacity depends on the working-time strategy, which differs for various production stages and from country to country. We express normal capacity as a percentage of the maximal capacity. Moreover, BMW requires a minimal utilization for any production line.

Reducing the maximal capacity by the flexibility reserve (a percentage) yields the disposable capacity. In load planning, any utilization between the minimal and the disposable capacity is feasible, but utilization above the normal capacity creates costs for overtime (Figure 3). In reality, the various types of overtime, such as prolongation of a shift, weekend shifts, night shifts, or regular third shifts, have different costs. BMW uses the various types of overtime
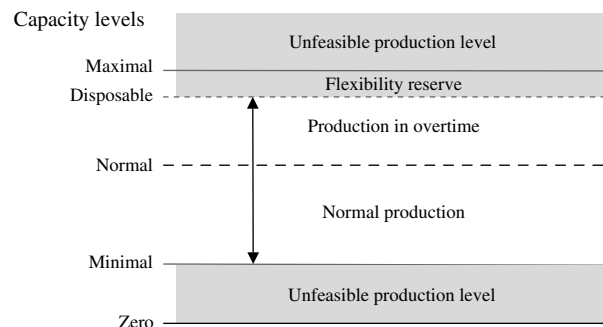

Figure 3: The strategic load plan can use the capacity of a production department between the minimal level and the disposable level, which falls short of the maximal technical capacity by the amount of the flexibility reserve.

in order of increasing cost. But for strategic planning, using an average cost for overtime is sufficient.

Incorporating Tax

To incorporate cash flows after taxes in planning investments, an international group of companies like the BMW Group must consider the taxation systems of different countries, internal transfer prices, and the payments between the producing companies, the selling companies, and the holding company. We have not yet done this in our model. But using some simplifying assumptions about transfer payments and taxation, similar to those Papageorgiou et al. (2001) use, we can determine after-tax cash flows by making simple changes to the cost and investment data.

ASSUMPTION 1. *National producing companies sell the total production volume to the holding company, which is true for the BMW Group with a few exceptions. The transfer price is based on the costs for materials, production, and depreciation plus a fixed margin, ρ_c, if production takes place in country c.*

ASSUMPTION 2. *National selling companies buy the products from the holding company and sell them to the customers in their country at fixed prices. The internal transfer price is equal to the external sales price minus a fixed margin. As a consequence, in our model with fixed sales volumes in every country and in every year, the revenue after tax for both the holding and the selling companies is fixed and we therefore omit it from consideration.*

ASSUMPTION 3. *The holding company pays the distribution cost from the production site to the selling company.*

ASSUMPTION 4. *There are fixed tax rates ψ_c on the profit in country c and ψ_0 for the holding company.*

Given Assumptions 1 and 4, any cost of supply and production in country c, say cost_c, causes the producing company to pay a tax $\psi_c \rho_c \text{cost}_c$, whereas the tax of the holding company is reduced by $\psi_0(1 + \rho_c)\text{cost}_c$. Therefore, all cost coefficients for supply and production have to be multiplied by the factor $(1 + \psi_c \rho_c - \psi_0(1 + \rho_c))$.

The distribution cost affects only the tax for the holding company. Therefore, we must multiply the distribution cost coefficients by $(1 - \psi_0)$.

To calculate the depreciation of investments, in every country c, a time profile is valid, say $\xi_{c\delta}$, similar to the time profile of the investment expenditures η_δ (Table 1), where δ is the year relative to the start-up year. The tax effect of the depreciation is the same as that for the cost. Therefore, for after-tax cash flows, we must modify any investment profile η_δ into $\eta_\delta + \xi_{c\delta}[\psi_c \rho_c - \psi_0(1 + \rho_c)]$.

A Case Study

BMW used our planning model in a real application for strategic planning. For reasons of confidentiality, we have altered the data and include only a subset of 36 products and six production sites in this case study (Figure 4).

We performed all the computations on a 1.6 GHz processor using ILOG OPL Studio with the CPLEX solver. Initially, the MIP model included about 60,000 variables and 145,000 constraints. The number of integer variables depends on the number of alternative production sites per product, and it was up to 2,000. However, the number of true binary decisions is much smaller, because demand data determines the time of each product start-up: For products produced at only one site, the model must determine the production site for only the start-up year, but for the split products it must determine the production sites for every year from the start-up year on. CPLEX's powerful preprocessor detects these relationships and reduces the size of the MIP model to 5,200 variables, 4,100 constraints, and about 400 binary variables. All computation runs reached the optimal solution within four minutes.

To evaluate the results of the new planning model, we use, as a benchmark, the current load plan that planners determined for 2005 to 2016 in strategic planning. They allocated 32 products to single production sites and four split products to several sites:

Products 7, 8, and 30 to two sites each; and
Product 29 to four sites.

In the first run of our model, we fixed this allocation and optimized the production volume per site and the investments. We used the result as the reference strategy in the following runs. We defined an alternative strategy (Strategy 1) by adding further potential allocations (Table 2), introducing more split products, and increasing the maximal number of sites for some split products. We did not choose potential
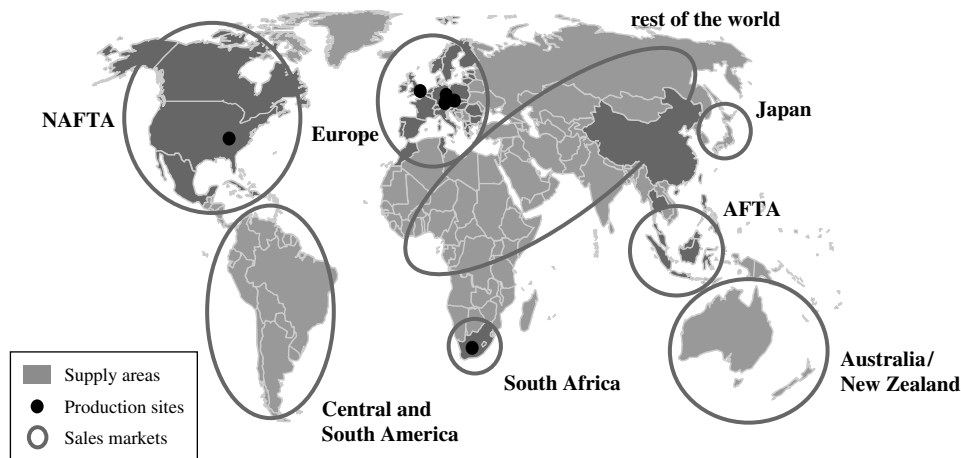
Figure 4: In our case study, we considered six production sites in Europe, the United States, and South Africa. Materials come from five areas: Europe, the countries of the North American Free Trade Agreement (NAFTA), the Asean Free Trade Area (AFTA), China, and South Africa. We aggregated the global sales markets into the eight circled areas.

allocations arbitrarily, but we considered the technical possibilities and the overall strategic objectives. Compared with the reference strategy, Strategy 1 includes 35 additional potential allocations for the nonsplit products and seven instead of four split products:

Product 7: up to two sites out of three possibilities;
Products 8, 17, and 30: up to two sites out of four possibilities;

Products 23 and 28: up to two sites out of five possibilities; and

Product 29: up to four sites out of four possibilities.

Optimizing the allocations, production volumes, and investments leads to a load plan that differs essentially from the reference strategy: It shifts all nonsplit products, except for those in current series production, to other sites. The plan allocates the Split Product 7

		Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Maximal number of plants
	Product 01			x				1
	...	...	...	...	...	...	...	...
	Product 24					x		1
	Product 25		x	x		x		1
	Product 26	x	x	x		x		1
	Product 27			x				1
Split products	Product 28	x	x	x	x		x	2
	Product 29	x		x	x		x	4
	Product 30	x		x	x		x	2
	Product 31	x	x					1
	Product 32	x	x	x	x			1
	Product 33	x		x				1
	Product 34	x	x	x	x	x		1
	Product 35		x	x				1
	Product 36	x	x	x	x	x		1

Table 2: In this extract from the matrix of potential product-plant allocations indicated by x, Product 24 is completely fixed in Plant 5, because it is already being produced in series there, Products 25 and 26 are nonsplit products but have several potential production sites, and Products 28 to 30 are split products.
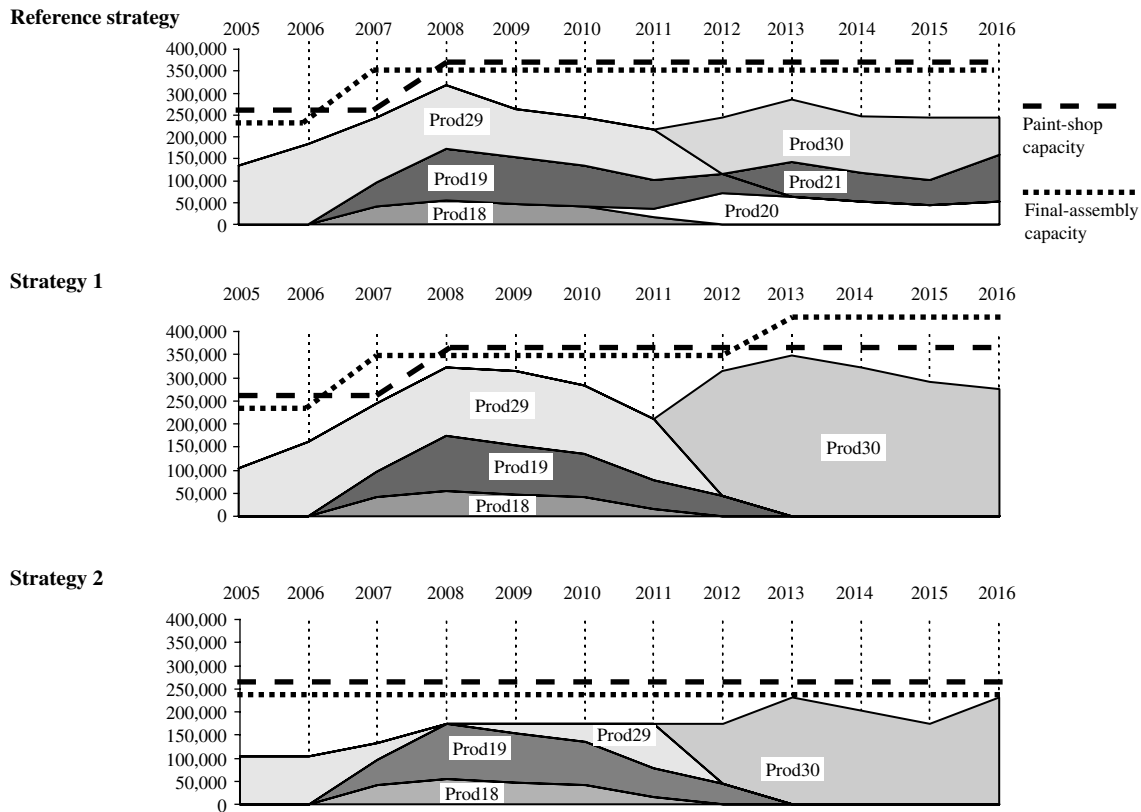
Figure 5: We investigated three strategies that led to different load plans and required capacities, shown here for Plant 4. In the starting year 2005, the capacities, measured in cars per year, are equal to the current level in every strategy. The reference strategy and Strategy 1 expand the final-assembly capacity in 2007 and the paint-shop capacity in 2008. Strategy 1 plans a further expansion of final assembly in 2013. By allocating Products 29 and 30 partly to other plants, Strategy 2 avoids investments in Plant 4.

only to one site and thus avoids making large product-specific investments for a small volume product. In Strategy 1, Plant 4 produces the Split Product 30 in greater volume than it did in the reference strategy, and it drops the nonsplit Products 20 and 21, which move to other sites (Figure 5). To provide for Plant 4's higher total volume, the plan includes an additional investment in the final assembly lines in 2013. The objective function value, that is, the discounted cash flows over the planning horizon for operational costs and investments, decreases from the reference strategy to Strategy 1 by 9.3 billion €, that is, by about seven percent (Table 3). The main contribution to this decrease comes from savings on materials cost, which is also the dominant part of the absolute objective function value. The reallocation of products also saves

on costs for production and distribution, whereas the cost of overtime increases slightly to enable higher utilization of plant capacity. Increasing capacity utilization also made future investments in the paint shop necessary and lower investments in body assembly and final assembly.

We optimized the load plans with regard to economic criteria only. Managers must approve any results of the model in subsequent steps, taking into account qualitative aspects, such as supplier relationships and development policies for sites and personnel.

In our analysis of the Strategy 1 results, we found that the allocation of Product 30 was critical, and therefore we investigated the effect of splitting it over three instead of two sites in a further optimization

| | Differences from the reference strategy in million € | | | |
| | Expected demand | | Increased demand | |
	Strategy 1	Strategy 2	Strategy 1	Strategy 2
Supply and materials cost	−9.044	−9.074	−9.041	−9.071
Production cost	−202	−83	−213	−92
Overtime cost	63	−7	67	−27
Distribution cost	−154	−220	−123	−196
Total costs	−9.338	−9.384	−9.310	−9.386
Investments in body assembly	−51	93	−51	69
Investments in paint shop	154	−13	241	65
Investments in final assembly	−66	−103	−66	−50
Total investments	36	−23	124	83
Total cash flow	−9.301	−9.407	−9.186	−9.303

Table 3: The increasing number of potential product-plant allocations from the reference strategy to Strategies 1 and 2 implies a decrease in the objective function value, the NPV of costs, and investments over 12 years. If the demand for Product 30 in Europe exceeds the expected demand by 30 percent (the last two columns), this advantage diminishes slightly.

run (Strategy 2). The optimal load plan makes use of this possibility, proposing a start-up in 2011 in Plant 6 only, followed by start-ups in Plants 3 and 4 in 2012. Furthermore, it moves most of Split Product 29 from Plant 4 to other sites (Figure 5). Thus, Plant 4 can keep its production volume at the normal working-time level until 2012 and avoid any capacity expansion. Compared to Strategy 1, Strategy 2's objective function value drops by 100 million €, but product-specific investments (body assembly) increase and structural investments (paint shop and final assembly) decrease.

To compare the volume flexibility of the two strategies, we increased the estimated demand for Product 30 in the European market by 30 percent but left the product allocation fixed. The advantages of both strategies against the reference strategy diminish slightly, but the distance between Strategy 1 and Strategy 2 increases. Strategy 2 demonstrates its higher flexibility by increasing its advantage in production and overtime costs. The main difference from the scenarios based on expected demand is the increase in structural investments in the paint shop and final assembly.

Conclusions

We improved long-term load planning, an essential step in BMW's strategic-planning process, by extending it to an integral view of the global supply chain. The new model optimizes the allocation of products to production sites and investments in additional capacity, taking into account corporate-policy restrictions. The model makes the planning process more transparent, and it has been accepted by the many departments concerned, which provide the necessary data. We modeled operations in the supply chain and cash flows in appropriate detail to include the essential effects of product-allocation decisions and to permit optimization with a standard MIP solver. The optimization model produces load plans for various scenarios quickly. It reduces planning effort and allows planners to investigate various scenarios more frequently than they could in the past. All in all, the model greatly improves the decision support for BMW's overall strategic planning. Based on our early tests of the new model, we can realistically expect a reduction in investments and costs for materials, production, and distribution of about five to seven percent.

BMW intends to imbed the new MIP model in a graphical user interface, which still needs to be developed. Planners with little knowledge of operations research will then be able to use the model.

Appendix. MIP Formulations

The Basic Supply Chain Model

The data from the preceding strategic-planning steps are as follows:

$i \in I$ set of plants.

$j \in J$ set of products.

$r \in R$ set of sales regions.

$t = 1, \ldots, 12$ years.

a_{ij} matrix of possible allocations ($a_{ij} = 1$ if product j may be manufactured in plant i, $a_{ij} = 0$ otherwise).

l_{jt} maximum number of plants for product j in year t.

d_{jrt} demand for product j in sales region r in year t.

k^B_{ijt} body-assembly capacity for product j in plant i.

k^P_{it}, k^A_{it} paint-shop and assembly capacities in plant i,

where demands and capacities are measured in cars per year.

The decision variables for production

$Z_{ijt} = 1$ if product j is allocated to plant i in year t, 0 otherwise, and

X_{ijt} number of cars to be produced,

must satisfy the constraints

$$Z_{ijt} \le a_{ij} \quad \text{for all } i, j, t, \tag{1}$$

$$\sum_i Z_{ijt} \le l_{jt} \quad \text{for all } j, t, \tag{2}$$

$$Z_{ij,t-1} \le Z_{ijt} \quad \text{for all } i, j, t, \tag{3}$$

$$X_{ijt} \le k_{ijt}^B Z_{ijt} \quad \text{for all } i, j, t, \tag{4}$$

$$\sum_j X_{ijt} \le \min(k_{it}^P, k_{it}^A) \quad \text{for all } i, t. \tag{5}$$

The distribution of finished cars is described by the decision variables

X_{irjt}^D cars of product j distributed from plant i to sales region r in year t

and the flow conservation constraints

$$\sum_i X_{irjt}^D = d_{rjt} \quad \text{for all } r, j, t, \tag{6}$$

$$\sum_r X_{irjt}^D = X_{ijt} \quad \text{for all } i, j, t. \tag{7}$$

The supply of materials is modeled by means of the data,

$m \in M$ material classes and engine types,

β_{mj} proportion of cars of product j with engine type m,

$q_{simj}^{\min}, q_{simj}^{\max}$ minimal, maximal proportion of material class m from supplier s for product j in plant i,

and the decision variables

X_{simjt}^S amount of material class m for product j supplied from supply region s to plant i in year t,

which are restricted by

$$\sum_s X_{simjt}^S$$

$$= \begin{cases} X_{ijt} & \text{for all } i, j, t \text{ and } m \ne \text{engine,} \\ \beta_{mj} X_{ijt} & \text{for all } i, j, t \text{ and } m = \text{engine type,} \end{cases} \tag{8}$$

$$q_{simj}^{\min} X_{ijt} \le X_{simjt}^S \le q_{simj}^{\max} X_{ijt} \quad \text{for all } s, i, m, j, t. \tag{9}$$

The objective is to minimize all variable costs along the supply chain. With the cost coefficients per car

c_{simjt}^S cost for supplying material m from supply region s to plant i,

c_{ijt} production cost,

c_{irjt}^D distribution cost for the transport from plant i to sales region r plus duties,

the total cost in year t is

$$\text{cost}_t = \sum_{s,i,m,j,} c_{simjt}^S X_{simjt}^S + \sum_{i,j,t} c_{ijt} X_{ijt} + \sum_{i,r,j,t} c_{irjt}^D X_{irjt}^D \tag{10}$$

and the objective function is

$$\text{minimize} \sum_t \text{cost}_t. \tag{11}$$

Investment Planning

Let the index d denote the production departments B (body assembly), P (paint shop), and A (final assembly). The following additional integer variables are used for structural investments:

Y_{it}^d number of capacity expansion steps in department d effective in year t, which can be restricted to the values 0, 1, and 2.

In addition, we introduce the binary variable

$\bar{Z}_{ij\tau} = 1$, if a second body assembly line for product j is available in year τ, 0 otherwise, with

$$\bar{Z}_{ij\tau} \le Z_{ijt} \quad \text{for all } i, j, t. \tag{12}$$

All other product-specific investments are triggered by the allocation variables Z_{ijt}. The objective function (11) is now replaced by the NPV of costs and investment expenditures,

$$\text{minimize} \sum_t (1+\rho)^{1-t} (\text{cost}_t + \text{inv}_t), \tag{13}$$

where ρ is the interest rate. The calculation of the total expenditures in year t, inv_t, must take into account the time profile of the investments (Table 1). Hence, a distinction is necessary between the year t where a cash flow occurs and the start-up year τ. If a product-specific investment in year τ causes a fixed expenditure f_{ij} with time profile $\vartheta_\delta = $ proportion in year $\tau + \delta$ ($\delta = 0, \pm1, \pm2, \ldots$), then it contributes $\vartheta_{t-\tau} f_{ij}$ to the cash flow in year t.

The start-up occurs in year τ if and only if $Z_{ij\tau} - Z_{ij,\tau-1} = 1$. Analogously, structural investments in year τ are indicated by $Y_{i\tau}^d - Y_{i,\tau-1}^d > 0$. The variable part of a product-specific investment is more difficult to express: We need the auxiliary variables

$X_{ij}^{\max}$ maximal amount of product j produced in plant i, and

$X_{ij\tau}^{\mathrm{inv}} = X_{ij}^{\max}$ in the start-up year τ, 0 otherwise,

which are restricted by

$$X_{ij}^{\max} \geq X_{ijt} \quad \text{for all } i, j, t, \qquad (14)$$

$$X_{ij\tau}^{\mathrm{inv}} \geq X_{ij}^{\max} + (Z_{ij\tau} - Z_{ij,\tau-1} - 1)M, \qquad (15)$$

where M is an upper bound to $X_{ij}^{\max}$, say $M = \max_t d_{jt}$. The last term in (15) is zero in the start-up year and negative otherwise. The investment data are

b_t budget for year t,

and for department d in plant i,

g_i^d fixed expenditure for structural investment,

f_{ij}^d fixed expenditure for product-specific investment,

p_{ij}^d variable product-specific investment per car,

$\eta_{i\delta}^d$ time profile of structural investment, and

$\vartheta_{ij\delta}^d$ time profile of product-specific investment,

where δ is the year of expenditure relative to the start-up year. The total investment expenditure is now

$$\begin{aligned}
\mathrm{inv}_t = &\sum_{d,i,\tau} \eta_{i,t-\tau}^d g_i^d (Y_{i\tau}^d - Y_{i,\tau-1}^d) \\
&+ \sum_{d,i,j,\tau} \vartheta_{ij,t-\tau}^d \left[f_{ij,t-\tau}^d (Z_{ij\tau} - Z_{ij,\tau-1}) + p_{ij}^d X_{ij\tau}^{\mathrm{inv}} \right] \\
&+ \sum_{i,j,\tau} \vartheta_{ij,t-\tau}^R f_{ij}^R (\bar{Z}_{ij\tau} - \bar{Z}_{ij,\tau-1}) \quad \text{for all } t \quad (16)
\end{aligned}$$

with the constraint

$$\mathrm{inv}_t \leq b_t \quad \text{for all } t. \qquad (17)$$

Extended Capacity Restrictions
With the additional variables

X_{ijt}^{OB} number of cars produced in overtime in body assembly, and

X_{it}^{Od} number of cars produced in overtime in departments $d = P, A$,

and data (Figure 4),

c_{it}^{Od} additional cost for overtime production per car in plant i, department d,

k_{ij}^B maximal capacity of a body-assembly line,

k_i^d, k_i^{d+} maximal present capacity, increase by expansion step in departments $d = P, A$,

λ_i^d flexibility reserve in department d of plant i,

μ_i^d proportion of normal capacity in department d of plant i,

$k_{it}^{\min}$ minimal load in plant i in year t,

the capacity constraints (4) and (5) are replaced by the restrictions of the maximal capacity

$$X_{ijt} \leq (1 - \lambda_i^B) k_{ij}^B (Z_{ijt} + \bar{Z}_{ijt}) \quad \text{for all } i, j, t, \qquad (18)$$

$$\sum_j X_{ijt} \leq (1 - \lambda_i^d)(k_i^d + k_i^{d+} Y_{it}^d)$$
$$\text{for all } i, t \text{ and } d = P, A, \qquad (19)$$

the normal capacity,

$$X_{ijt} - X_{ijt}^{OB} \leq \mu_i^B k_{ij}^B (Z_{ijt} + \bar{Z}_{ijt}) \quad \text{for all } i, j, t, \qquad (20)$$

$$\sum_j X_{ijt} - X_{it}^{Od} \leq \mu_i^d (k_i^d + k_i^{d+} Y_{it}^d)$$
$$\text{for all } i, t \text{ and } d = P, A, \qquad (21)$$

and the minimal load,

$$\sum_j X_{ijt} \geq k_{it}^{\min} \quad \text{for all } i, t. \qquad (22)$$

Furthermore, structural investments in the body-assembly department are necessary if the number of products in plant i exceeds

$n_i^{\max}$ maximal number of products in plant i,

hence the constraint

$$\sum_j Z_{ijt} \leq n_i^{\max} + y_{it}^R \quad \text{for all } i, t. \qquad (23)$$

Finally, the cost for overtime in year t,

$$\sum_i \left(\sum_j c_{it}^{OB} X_{ijt}^{OB} + c_{it}^{OP} X_{it}^{OP} + c_{it}^{OA} X_{it}^{OA} \right),$$

has to be added to the total cost (10).

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llka Schulte, General Manager, BMW Group, BMW AG, D-80788 München, Germany, writes: "The development of the production network optimization model was very successful and we will continue to use it as an important tool to configure our future production network. At the highest level, the model allowed us to understand the relationships among the different cost drivers and the investment decisions within the production network. Furthermore, the integration of these investment decisions into the network optimization model had a decisive impact on the allocation of models into the plants. I was very impressed that the work on the optimization model considered scientific as well as practical issues. The mathematical model formulation required a deep understanding of the functional interrelationships between the parameters, as well as close collaboration of all the involved departments to create the database. In this way, the model was successfully established as an accepted tool in the interdepartmental planning process."