Decision Support for Bids in Process Plant Engineering

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Abstract—The intensive competition in the international market for plant engineering is characterized by high pricing pressure, increase of local content requirement and decrease of project durations. This leads to intricate logistics problems with regard to production locations and project planning. These interacting decisions are to be considered in the bidding phase of a plant project already. This paper proposes an integrated optimization model to determine the project costs as the lower limit of the bid price. Its application is illustrated by means of a case study.

Key words: plant engineering; production location; project scheduling; decision support

I. INTRODUCTION

A large-scale process plant like a refinery, or a brewery, integrates different components interconnected by process technology. A component can be a subsystem, assembly, subassembly or other major element providing a self-contained functionality (Wideman, 2006). Plant engineering is usually undertaken in form of a project with a defined due date. Due to its complexity and use of high technology, a plant project lasts three years on average and costs a minimum of 25 million Euro (Gottwald et al., 2009).

Several challenges are observed with respect to the process plant engineering industry. Plant suppliers compete for a limited number of orders with aggressive pricing leading to significant cost pressure throughout the industry. In addition, suppliers from emerging countries have become new competitors by developing their technologies with acquired know-how.

In order to realize quick amortization of investment and reduce financial risks, plant buyers are striving for shorter project durations. According to the German Engineering Association (VDMA) - the largest association representing the capital goods industry in Europe, a shortage of 30-50 percent of former project durations has been observed; however, a further reduction is expected.

The requirement of local manufacture has increased rapidly by ordering countries in recent years. In some major markets the local content requirement (LCR) reaches even 70 to 80 percent of the total plant value. The higher such a requirement is, the larger the risk of the uncontrolled drain of know-how becomes for a plant manufacturer.

In order to stay competitive, suppliers attempt to embark on strategies with respect to production location decisions: To reduce costs, plant suppliers rely on global sourcing, especially in low-wage countries. However, quality and adherence to delivery time may not be ensured with sourcing in low-wage countries. To satisfy LCR, plant suppliers need to shift their sourcing and production to the customer’s country. However, involving the local vendors in production and outsourcing of own production may lead to a drain of know-how. To avoid the drain of know-how, contractors aim at keeping their core technology home. To reduce currency risk, contractors engage in operational hedging through sourcing and production directly in countries of the weaker currency (Lowe et al., 2002). To meet the tight project due date, contractors pass on time pressure along the supply chain. Time pressure can, however, cause a lack of quality. Additionally, shorter project duration may result in higher costs.

Some of the above strategies compete with one another. Since the decision where to produce which plant component impact project costs and duration, this should be incorporated in the bidding phase of a tender already. To this end we see the integrated planning of production locations for project components and scheduling of project activities as a competitive advantage for players in the large-plant industry. Slow project execution may turn a promising investment opportunity into an expensive failure. Due to a recent study, more than 15 percent of capital projects in the process industries run 50 percent or more over budget (Scott-Young and Samson, 2008). Project scheduling literature is rich, e.g. Kolisch (1995), Neumann et al. (2003).

Clearly, the choice of production locations can significantly impact the production costs. Therefore it suggests itself that sourcing decisions with respect to project components are considered as early as possible in the project life cycle. Typically, one can choose from a small number of suppliers or joint ventures a plant supplier maintains on a strategic level. Although the location problem domain has already been addressed in the context of supply chain design by Arntzen et al. (1995), Vidal and Goetschalckx (1997), Geoffrion and Powers (1995), and Cohen and Lee (1989), a deficiency with respect to an investigation of plant engineering is noticed by Meixell and Gargeya (2005).

The logistics costs for transportation and handling of large and/or heavy components can contribute to the overall project costs significantly. Typically, minimum transportation costs are
achieved by a slow mode of transportation coming along with extensive transportation times. Neglecting location decisions and its respective transportation times in the project tender may cause the need for a faster mode of transportation in order to meet the due-date during project execution. Since violating the due-date because of a slow transportation mode is typically not an option, choosing the respective faster mode of transportation may cause significant losses solely resulting from extraordinary high logistic costs.

Thus, decisions with respect to the supply network will directly influence project lead times and project costs. In the following we discuss interrelations of constraints to be considered with respect to location choice and project scheduling. We propose a mathematical model integrating both tasks. We validate its applicability by evaluation of a CPLEX implementation, before we discuss an application case demonstrating the decision support for bidding and negotiation of a process plant project in China. We conclude with a summary of the major findings and their contributions for the large-scale process plant industry.

II. PROJECT LIFE CYCLE OF A PROCESS PLANT

For large-scale process plant projects, the project life cycle is described as follows (Helmus, 2008): As a starting point of a plant engineering project, an Invitation to Bid (ITB) is issued by the customer. On the contractor’s side the ITB is evaluated according to available technology and resources, competitor situation, profitability, risks etc. resulting in a bid/no-bid decision. The customer spends a great deal of time to satisfy the requirements of the ITB. In this phase, analysis of costs plays an important role. In order to assess the production costs for a planned plant as close as possible, so-called basic engineering is carried out. Basic engineering comprises the technical design, the determination of costs and the project scheduling. On this basis, a bid is generated.

In the negotiation phase the customer compares the bid prices provided by different bidders and negotiates the contract conditions with them (Wideman, 2004). Finally, a contract is awarded to the lowest priced bidder meeting all requirements. After the contract is assigned, the project is executed. The project is completed with acceptance after the successful test. Then the actual operation of the plant can start and the warranty is provided.

Probably most critical in the life cycle is the basic engineering. Basic engineering begins with the technical design resulting in components at several levels of breakdown. From a project point of view, the production of a plant component represents an activity. To this end a plant project can be organized as a work breakdown structure (WBS), which is defined as a system for decomposition of a project into manageable activities to provide a common framework for cost estimation, scheduling, and allocation of resources. The WBS sets up the basis for the cost estimate and project scheduling.

The objective of the cost estimating procedure is to determine the optimal bid price, which a prospective customer submits yielding the best chance for winning a contract and making a profit (Baldwin et al., 1999). Therefore, a bidder needs to be careful not to overprize the proposed project. However, the bidder must be equally careful not to underprize the project to avoid the winner’s curse; otherwise, he may make a loss rather than a profit or may have to request additional funds from the customer, which could be embarrassing and hurt the bidder’s reputation (Gido and Clements, 1999).

In order to make up leeway at forming bid price, the plant costs as the lower limit of a bid price is to be known. To calculate costs, costs should be allocated in accordance with the principle of cost causation. Direct costs describe the sum of direct labor, direct materials and direct engineering and construction expenses, which can be allocated to the various activities in the project WBS. Indirect costs, also called overheads are operating costs incurred for common or joint purpose. Typically the overhead rate for a process plant engineering project will be negotiated between the contractor and the customer before an order can be won.

In order to deal with risks, errors and omissions, it is needed to make allowances under the basic project cost estimate. Such allowances include cost escalation, exchange rate fluctuation and other contingency allowances Gido and Clements (1999). Because of keen competition, safety factors in the shape of a high mark-up, or for contingency allowances are rather small. In the short-term consideration, the lower limit of a bid price is estimated by costs directly caused by a project. Each bid price larger than this lower limit makes a contribution to cover the fixed costs and the safety factors. Therefore, we focus on direct costs to estimate the lower limit of the bid price.

In order to provide a lower bid price, plant suppliers aim to reduce costs through global sourcing. Not only the production and transportation costs but also the production and transportation duration in different countries may vary, which will result in different project completion time. Since cost estimating and scheduling are typically not carried out in an integrated way, losses may result in the implementation phase because of imprecise estimations of project costs.

Generally, the bidding phase involves high uncertainty and risk. The bid preparation requires a great deal of time and manpower effort. The costs associated with the preparation and submission of a bid may reach five percent of the total project value and the bidder shall bear all these costs (The World Bank, 2006). In spite of the high expense for generating a bid, just five to ten percent of all bids will result in contracts (Schiller, 2000).

Due to high operating expense and low chance of success, three bid types are distinguished: contact bids, standard bids and fixed bids. For the contact bid the drawing of a whole plant is required, while for the standard bid additionally information about the subsystems is needed. For the fixed bids even the components must be specified. Through selection of the bid

1The winner’s curse is a phenomenon that occurs in common-value auction. In such auctions, it has been frequently observed that winner bidders tend to underbid due to imperfect estimates of value. This substantially reduces their winnings, often leading to losses rather than profits. As mentioned by Kagel and Levin (2002), “You win, you lose money, and you curse.”
types expense of bidding is adjusted to its chance of success. It is generally concluded that the contact and the standard bid rarely result in orders directly. In the earlier phase of a project’s life cycle a contact or standard bid are issued. For the customer negotiation a fixed bid is issued (VDI, 1983).

Furthermore, the customer will set a due date for the submission of bids, so that the time available for calculation a project is limited. For very large technical projects, proposals are often due within thirty calendar days of the ITB’s issuance (Gido and Clements, 1999). In order to meet the requirements, the preparation of bids is supported by configuration software. Decision support functionality, however, is usually not yet part of such software systems.

III. INTEGRATION OF LOCATION CHOICE AND PROJECT SCHEDULING

Roughly speaking, we form two subproblems: The location problem determines the countries of production for components whereas the project scheduling problem determines the production and transportation schedule. Since the production capacity of sites is limited, the availability of sufficient production capacity is to be considered.

We may first consider the subproblem of location choice. Since the production costs of components as well as the associated transportation costs depend on the choice of location, the components are assigned to countries so that the total costs are minimized. The given LCR presents a constraint to the assignment of production countries.

An assignment also determines the production and transportation duration of each component leading from a multi-mode resource-constrained project scheduling problem (MMRCPS) to a single mode resource-constrained project scheduling problem (SMRCPSP). With the data input of durations and with the prescribed precedence relations among activities the subproblem of project scheduling is solved to determine the prospective completion time of the project. Any completion time before or equal to the project due date represents a feasible solution to the integrated problem.

Obviously, both subproblems interact with each other by means of durations, cf. Fig. 1. The choice of location determines the time needed to produce and transport a component. In this way the location decision affects the duration of the entire project. In turn, in case of a prescribed project due date, the time constrained schedule will affect the choice of locations so that shorter production durations will be favored. In order to integrate cost estimating and project scheduling, we make first the following assumptions:

- Quantity and type of the plant components are described in a bill of materials.
- Each activity in the project network diagram represents the production of a component.
- For each component the decision of make-or-buy is already made. We concern only where, i.e. in which country a component is made.
- Precedence relations of activities are known from the technical specifications.
- The production costs of the components are estimated from purchase orders, vendor quotes, cost or pricing data of subcontractors, completed projects, escalation rates, construction unit rates, or published cost information (Murphy, 2004)
- Transportation costs for components can be estimated using indicators, such as freight rates (e.g. Baltic Dry Freight Index), tanker rates and other transportation tariffs.
- The duration of each activity can be estimated from experience resulting from completed projects, similar projects or delivery time from subcontractors or vendors.
- The project due date is demanded by the customer.
- An LCR is given by the customer.

In the following a mixed integer optimization model (MIP) is proposed to minimize the total costs.

Parameter for the choice of locations are:

\[ J \quad \text{Number of activities / components } j \ (j = 1, \ldots, J) \text{ in a project} \]

\[ M \quad \text{Number of countries } m \ (m = 1, \ldots, M), \quad M \geq 2 \]

\[ V_j \quad \text{Index number of the immediate predecessors of } j, \ i \in V_j \]

\[ P_{jm} \quad \text{Production costs of the component } j \text{ in the country } m \]

\[ W_{iljm} \quad \text{Transportation costs for } i \text{ from the country } l \text{ to the country } m \text{ where } j \text{ is produced} \]

\[ G \quad \text{Estimated market value of a large-scale plant as reference to meet the expected LCR} \]

\[ Q \quad \text{The given LCR proportion, } 0 \leq Q \leq 1 \]

Parameter for the project scheduling are:

\[ EFT_{jm} \quad \text{The earliest finish time of activity } j \text{ in country } m \]

\[ LFT_{jm} \quad \text{The latest finish time of activity } j \text{ in country } m \]

\[ T \quad \text{Project due date with period } t = 1, \ldots, T \]

\[ d_{jm} \quad \text{Duration of activity } j \text{ in country } m \]

\[ g_{iljm} \quad \text{Transport duration between } j \text{ and its immediate predecessors } i, \ if \ i \text{ is produced in country } l \text{ and } j \text{ in country } m \]

\[ R \quad \text{Number of the resource types } (r = 1, \ldots, R) \]

\[ k_{jrm} \quad \text{Per period usage of resource } r \text{ required to perform activity } j \text{ in country } m \]

\[ K_{rmt} \quad \text{Per period availability of resource } r \text{ in country } m \]

The following variables are considered:

\[ \text{We do not consider the make-or-buy explicitly, but we can integrate the make-or-buy decision easily in the model. If a component can be produced in the same country } A, \text{ we can use mode 1 to represent the production of this component in country } A \text{ and mode 2 to represent the procurement of this component in country } A. \text{ Resource availability for mode 1 is the production resources. Mode 2 has no resource constraint.} \]
Fig. 1. Interdependency of location choice and project scheduling: The location problem determines the country of production for each component while the project scheduling problem determines the schedule. Both subproblems interact with each other by means of durations. The choice of locations determines the time needed to produce and transport a component. In turn, the schedule constrained by the given due date will affect the choice of locations so that shorter production times are pursued.

\[
x_{jm} = \begin{cases} 
1 & \text{if component } j \text{ is produced in country } m \\
0 & \text{otherwise}
\end{cases}
\]

\[
y_{ilm} = \begin{cases} 
1 & \text{if component } i \text{ is produced in country } l \text{ and transported to country } m, \text{ where } j \text{ is produced} \\
0 & \text{otherwise}
\end{cases}
\]

\[
z_{jmt} = \begin{cases} 
1 & \text{if component } j \text{ is produced in country } m \text{ and finished at the end of period } t \\
0 & \text{otherwise}
\end{cases}
\]

Fig. 2 depicts the model: The objective function (1) minimizes the total costs, which includes the production costs and the transportation costs. The constraints (2) to (5) are the ones applied to the location choice. (2) ensures that a component can be produced in only one country. (3) and (4) relate the two variables \(x_{il}\) and \(y_{ilm}\) to ensure that the transportation cost is that of the transportation from where component \(j\) was produced to where it is needed. \(y_{ilm}\) can be equal to one only if both variables \(x_{il}\) and \(x_{jm}\) are equal to one. (5) ensures that the local content determined by the location choice is bound by the LCR.

(6) to (9) address the project scheduling. The constraint (6) combines the project scheduling and the location choice, because the durations of production and the transport durations are dependent on the choice of location. This constraint represents the precedence relations: Activity \(j\) can be started, only if all its immediate predecessors \(i\) have been finished. (7) ensures that each activity is finished in exactly one country and in exactly one period, i.e. between the earliest finish time and the latest finish time. (8) ensures that \(z_{jmt}\) can be equal to one only if \(x_{jm}\) is equal to one. The constraint associated with (9) limits the period resource usage to the available amount in each country.

The scheduling part of the proposed model adopts the multi-mode resource-constrained project scheduling problem (MMRCPSP) (Neumann et al., 2003). A component of a large-scale plant can be produced in different countries representing different modes. However, there are differences between the original MMRCPSP formulation and the above model leading to an easier to solve problem in our case:

1) Nonrenewable resources are viewed as special cumulative resources that are depleted over time but never replenished. For nonrenewable resources, resource-feasibility solely depends on the selection of activity modes and not on the schedule. We do not consider nonrenewable resources at all.

2) In the standard MMRCPSP, modes may compete for renewable resources. In our case, resources are dedicated to countries, thus a usage of the same resource by different modes does not occur.

3) Neumann et al. (2003) model start-to-start relationships among activities in the MMRCPSP and hence define time lags between starting times of two activities. In this work, we differentiate between production and transportation times. The production time solely depends on the county chosen, whereas the transportation time depends on the country of production as well as the country of production of the successor activity. Moreover, production consumes renewable resources while transportation does not. In order to incorporate this feature, we adopt the formulation of Kolisch (1995) using finish-to-start relationships between activities.
Objective function:

\[
C_{\text{min}} = \sum_{j=1}^{J} \sum_{m=1}^{M} P_{jm} x_{jm} + \sum_{j=1}^{J} \sum_{i \in V_j} \sum_{m=1}^{M} \sum_{l=1, l \neq m}^{M} W_{ijm} y_{ijm}
\]

Subject to:

\[
\sum_{m=1}^{M} x_{jm} = 1 \quad j = 1, \ldots, J
\]  

\[
x_{il} + x_{jm} - y_{ijm} \leq 1 \quad j = 1, \ldots, J, \quad i \in V_j, \quad m = 1, \ldots, M, \quad l = 1, \ldots, M, \quad l \neq m
\]  

\[
x_{il} \geq y_{ijm} \quad j = 1, \ldots, J, \quad i \in V_j, \quad m = 1, \ldots, M, \quad l = 1, \ldots, M, \quad l \neq m
\]  

\[
\sum_{j=1}^{J} (P_{jm_0} x_{jm_0}) G^{-1} \geq Q \quad \text{with } m_0 = \text{customer country}
\]  

\[
\sum_{l=1}^{M} \sum_{t=EFT_{il}}^{LFT_{il}} t z_{ilt} \leq \sum_{m=1}^{M} \sum_{l=EFT_{jm}}^{LFT_{jm}} (t - d_{jm}) z_{jm} - \sum_{m=1}^{M} \sum_{l=1}^{M} g_{ijm} y_{ijm} \quad j = 1, \ldots, J, \quad i \in V_j
\]  

\[
\sum_{m=1}^{M} \sum_{t=EFT_{jm}}^{LFT_{jm}} z_{jmt} = 1 \quad j = 1, \ldots, J
\]  

\[
x_{jm} \geq z_{jmt} \quad j = 1, \ldots, J, \quad m = 1, \ldots, M, \quad t = EFT_{jm}, \ldots, LFT_{jm}
\]  

\[
\sum_{j=1}^{J} \sum_{r=1}^{t+d_{jm}-1} \sum_{\tau=t}^{\tau+r} z_{jmr} \leq K_{rm} \quad m = 1, \ldots, M, \quad r \in R, \quad t = 1, \ldots, T
\]  

\[
x_{jm} \in \{0, 1\} \quad j = 1, \ldots, J, \quad m = 1, \ldots, M
\]  

\[
y_{ijm} \in \{0, 1\} \quad j = 1, \ldots, J, \quad i \in V_j, \quad l, m = 1, \ldots, M
\]  

\[
z_{jmt} \in \{0, 1\} \quad j = 1, \ldots, J, \quad m = 1, \ldots, M, \quad t = EFT_{jm}, \ldots, LFT_{jm}
\]

Fig. 2. The MIP Model

IV. MODEL EVALUATION

In order to evaluate the solvability of the model, we engage in the ProGen benchmark suite developed in the field of resource-constrained project scheduling (Kolisch et al., 1995). Basically, ProGen is a generator to create benchmark instances for a broad class of resource-constrained project scheduling problems.

ProGen allows to set parameters in order to generate instances of varying characteristics:

- The number of jobs (NJ) gives the number of activities considered in the problem instance.
- The job duration (JD) specifies the average duration of jobs uniformly distributed between a minimum and a maximum value.
- The network complexity (NC) stands for the average number of direct successors of an activity; it is specified by and maximal number of successors (MaxOut).
- The number of modes (NM) specifies the maximum number of modes possible.
- The resource factor (RF) alters the average number of resources required to carry out an activity. This parameter is uniformly distributed between a prescribed minimum and maximum value.
- The resource strength (RS) expresses the relationship between the resource demand of the activities and the resource availability and therefore measures the scarcity of the resources. If RS is equal to 1, there are no resource-constrains at all, thus the optimal solution is the MPM-schedule. The smaller the value gets, the scarcer the resource becomes.

The suite comes with a number of pre-generated RCPSP instances. Since we are aiming at generating problem instances similar to the work done by Kolisch et al. (1995), we describe the relevant parameters and benchmark briefly in the following. In the single-mode cases, NJ = 30, 60, 90, 120 are considered. Parameter JD is chosen randomly between 1 and
10. Both the maximal number of predecessors (MaxIn) and the maximal number of successors (MaxOut) are set to 3. NC is set to 1.8. The NM is set to four for each activity. The RF varies between 1 and 10. A computational study shows that the increase of the resource factor results in an increase of the computation time needed, because the average portion of resources requested per activity increases. The average solution time continuously increases with decreasing RS. The hardest problems are those where the minimal resource availability is provided (Kolisch et al., 1995).

In the multi-mode cases, NM, NJ, NC and JD are the same as the single-mode case. Kolisch et al. (1995) focus on the effects of the RF and RS. The computational results show that the resource strength has the strongest impact on the solution time. Moreover, multi-mode instances in general are tractable only for a very restricted number of activities. In ProGen a maximum of 30 activities is considered for the multi-mode case.

Next to parameters we could incorporate from ProGen directly, we had to modify one parameter in accordance to the problem at hand. A third set of parameters had to be added to the problem.

a) Parameters taken from ProGen: Most parameters we take directly from the multi-mode case in ProGen and vary some of their values as can be taken from Tab. I.

<table>
<thead>
<tr>
<th>Param.</th>
<th>Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NJ</td>
<td>number of components</td>
<td>30, 60, 90, 120, 150, 180, 210</td>
</tr>
<tr>
<td>NM</td>
<td>number of countries</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>NC</td>
<td>project structure</td>
<td>3.6</td>
</tr>
<tr>
<td>ID</td>
<td>production time</td>
<td>randomly 1-10</td>
</tr>
<tr>
<td>RR</td>
<td>production resource</td>
<td>2</td>
</tr>
<tr>
<td>RF</td>
<td>resource consumption</td>
<td>randomly 1-10</td>
</tr>
<tr>
<td>RS</td>
<td>resource availability</td>
<td>0.5, 0.7, 1.0</td>
</tr>
</tbody>
</table>

Basically, we used the single-mode instances of the set of NJ = 30, 60, 90 and 120 and generated the instances with NJ = 150, 180, 210. For the instances with 30 to 120 components we set MaxIn = MaxOut = 3 like proposed by Kolisch et al. (1995). For instances between 120 and 210 components we use MaxIn = MaxOut = 6. We model the situation of two production locations, i.e. customer country and contractor country, plus a possible subcontractor from the third country. Therefore we set maximum three countries to choose from.

The resource strength has the strongest impact on solution time, indicated in the full factorial design study from Kolisch et al. (1995). If available resources are very scarce, the plant supplier faces a higher risk of a project delay. Therefore, she may make a no-bid decision, or she suggests a longer project duration than that demanded by the customer. To model this situation, we have chosen resource strengths of 0.5, 0.7 and 1.0. A parameter of 1.0 reflects the case of cost estimate class 4 and 5 where the consideration of resource availabilty hardly makes sense.

b) Modified parameters: In order to match the special problem domain in large-scale plant engineering, one modification to the source code of the ProGen program had to be made: Different countries do not compete for resources. Therefore we define for each country a resource availability separately. Thus, for each country the resources form a pool to be shared by the jobs produced in this respective country.

In the multi-mode case in ProGen, The period resource availability of each type of resource is calculated for all modes of this type of resource.

\[
\sum_{j=1}^{J} \sum_{m=1}^{M} k_{jm} \sum_{\tau=t}^{t+d-1} z_{jmr} \leq K_r \\
m = 1, \ldots, M, \quad r \in R, \quad t = 1, \ldots, T
\]

In this work, since modes represents different countries, the period resource availability is different in each country, so that we have a \( K_{rm} \) for each mode.

\[
\sum_{j=1}^{J} k_{jm} \sum_{\tau=t}^{t+d-1} z_{jmr} \leq K_{rm} \\
m = 1, \ldots, M, \quad r \in R, \quad t = 1, \ldots, T
\]

c) Added parameters: Due to the special constraints in our decision problem, we need to add some parameters:

- The Production costs in different countries;
- The Transportation costs and transportation time;
- Estimated market value of a large-scale plant;
- The Local content requirement (LCR) with values of 0.5, 0.7 and 0.9.

Our main interest refers to the size of the problem instance given by NJ. Furthermore we follow Kolisch et al. (1995) in assuming the resource strength to be responsible for the difficulty of a problem instance. Finally we are interested in the impact of the global LCR constraint on the solvability of a problem instance. We vary the parameter settings of RS, LCR and NJ (Tab. II) and generate 10 instances for each parameter setting, i.e. \( 7 \times 3 \times 3 \times 10 = 630 \) instances.

<table>
<thead>
<tr>
<th>Param.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>0.5, 0.7, 1.0</td>
</tr>
<tr>
<td>LCR</td>
<td>0.5, 0.7, 0.9</td>
</tr>
<tr>
<td>NJ</td>
<td>30, 60, 90, 120, 150, 180, 210</td>
</tr>
</tbody>
</table>

The computational results are carried out on an Intel Core 2 Duo Processor T7200 with 2.00 GHz. The results obtained by CPLEX 10.0, are presented in Tab. III . All variations of LCR for a combination of RS and NF are depicted in one line. Tab. IV summarizes all variations of RS for a combination of LCR and NJ respectively. Note, that both tables are built from the same data, just the mode of aggregation differs. For an imposed time limit of ten minutes, 514 out of the 630
problems can be solved to optimality. Further 111 problems come up with a feasible solution and a negligible deviation from the lower bound. Only for 5 problems no solution can be found within the 10 minutes interval. With the increase of activities (components), problems become more difficult. Problems with 30 activities can be solved to optimality in every case, while only 60 percent of problems with 210 activities come up with optimal solutions.

In Fig. 3 the impact of varying the amount of components, RS and LCR on the runtime is summarized. As the resource becomes scare, problems turn to be harder to solve. This is consistent with the observation of Kolisch et al. (1995). With the increase of LCR, problems become easier. The tight global LCR constraints prevents CPLEX from generating a host of feasible, but inferior solutions. The approach is well suited for a coarse grained consideration of a project’s WBS of up to a few hundred components. The solver benefits from a high LCR as well as a high availability of resources.

V. DECISION SUPPORT FOR BIDDING AND NEGOTIATION

The decision support of the developed model for bidding and negotiation is demonstrated in an application case from Bühler. The Swiss group Bühler is the world’s largest know-how center for grain processing. About 65 percent of the total global grain production is processed by Bühler plant systems. The subsidiary Bühler Braunschweig, Germany, en-
gineers brewing and malting plants throughout the world. Next to the production site in Braunschweig, Bühler runs main sites in Switzerland, China, India, Spain, South Africa and USA. Bühler aims at standardization of components with respect to the sales program. Standard components promise a unified production program which can be much more easily implemented in a globalized production environment.

Bühler uses the configuration software Navigator from Engineering Automation Systems Ltd. to support bid generation and price calculation. This configuration software allows for a technical specification and a bill of quantity. Due to the worldwide production sites of Bühler, the components of a plant can be produced in different countries at different costs. In the configuration software the production location for each component is determined either from experience or by operational rules. However, neither an optimization of costs is carried out nor production constraints are considered. Moreover, for each configuration the project schedule has to be verified manually with a significant manpower effort. Facing the shortcoming of the configuration software, Mr. Norbert Heide, senior project engineer at Bühler Braunschweig stressed, “In view of the large number of plant components, some of which being very complex, it is mandatory to have a decision support software.”

Since bids may need to be recalculated many times depending on the modified conditions in the negotiation phase, a quick scenario analysis can turn into competitive advantage for Bühler. In order to demonstrate this advantage, we present figures of an up-to-date malting plant project by way of example carried out by Bühler in China. This malting system consists of 207 components and will process 100,000 tons of malt per year. The following data enter the optimization:

- Quantity and type of the 207 plant components are described in the bill of quantity.
- The production costs of components are estimated from experience of former projects.
- Each component of the bill of quantity forms an activity in the project network.
- The prospective duration of an activity is estimated from experience.
- Precedence relations of activities are known from the technical specification.
- Transportation costs for components are known from experience and freight tariffs.
- The project due date is demanded and therefore prescribed by the customer.
- An LCR of 50 – 80 percent is requested.
- Five components carrying core technology of Bühler are to be exclusively produced in Germany.

Production locations for the remaining components are subject to optimization. Using the developed model, the problem is solved in 0.26 second using CPLEX 10 on a standard PC. The extremely quick computation time is due to the facts that no recourse constraints have been considered and that the WBS results in a project network of relatively low complexity.

As a result, 167 components are assigned to China and 40 are selected to Germany. The solution has been thoroughly validated by Bühler project managers. Possible scenarios as they may occur in the negotiation phase are depicted in Tab. V.

Five scenarios are analyzed for the project bidding phase (No. 1-3) and the project negotiation phase (No. 4-5). The cells in gray shade are prescribed by the analyst, whereas the remaining cells are determined by the MIP model. Column 2 lists the local content requirement LCR in percent. Column 3 indicates whether one important component carrying firm’s know-how is produced in Germany. Column 4 shows the deviation from duration $D$ in weeks. Column 5 lists the percentage of components produced in China in relation to the total number of components. Column 6 shows the deviation of the total costs from the minimal costs $C$ in percent.

In order to keep sensitive data with Bühler, we use $D$ to represent the project duration demanded by the potential customer. Under this constraint, the minimal costs determined for the problem instance are represented by $C$. Using this parameter setting, 85 percent of the total amount of components are chosen for production in China (No. 1). Since an important component contains core technology of Bühler, this component should be produced in Germany. Fixing this location decision while relaxing the project duration constraint, costs increase by 0.62 percent and the project duration lengthens by two weeks (No. 2). While the reasonable increase of costs seems acceptable, the extension of the project duration will hardly be tolerated by the customer. Fixing the project duration at $D$ again, the total costs now increase to 2.8 units (No. 3), i. e. $(C + C\cdot 0.028)$. This figure is accepted by Bühler as a basis of the bid price.

We assume that the customer prefers Bühler as contractor due to the reasonable price and the assured high quality. However, let us consider that the potential customer starts bargaining for an LCR of 80 percent in the negotiation phase. Consequently, the costs for Bühler increase to 3.8 units, which seems hardly acceptable (No. 4). In order to acquire the contract, Bühler asks for a leeway of additional four weeks resulting in a decrease of costs from 3.8 to 3.1 units (No. 5). In comparison to the lower limit of the bid price shown in No. 3, an increase of $3.1 - 2.8 = 0.3$ units is acceptable by Bühler in order to acquire this project. In case that the customer insists on the originally requested due date $D$, Bühler will reject the project in order to protect its know-how.

As demonstrated, the decision support tool helps a contractor to make right decisions under changing trading conditions. By means of scenario analysis the contractor keeps up a reasonable negotiation position and eventually can avoid losses due to the lack of information. The decision support for bid generation is confirmed by Mr. Heide, “Significant positive results were achieved in the saving of calculation time and manpower for the bid generation as well as in decision-making during the contract negotiation.”
TABLE V

POSSIBLE PROJECT SCENARIOS.

<table>
<thead>
<tr>
<th>No.</th>
<th>LCR (%)</th>
<th>know-how</th>
<th>deviation from duration D (week)</th>
<th>components in China (%)</th>
<th>deviation from minimal costs C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>85</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>1</td>
<td>-2</td>
<td>83</td>
<td>+0.6</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>1</td>
<td>0</td>
<td>79</td>
<td>+2.8</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>1</td>
<td>0</td>
<td>91</td>
<td>+3.8</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>1</td>
<td>+4</td>
<td>91</td>
<td>+3.1</td>
</tr>
</tbody>
</table>

VI. SUMMARY

The motivation for developing a decision support system stems from the increased demand of international plant projects in last years. Bids of projects often have to meet challenges of pricing pressure, increase of LCR, and decrease of the project duration. On the basis of the interrelation between location choice and project scheduling we have developed a mathematical model for decision-making. This approach nowadays enables Bühler to make constrained decisions in a quick and flexible way guaranteeing the minimal cost solution in each case. According to Mr. Klaus Gottwald, analyst of the German VDMA’s Large Industrial Plant Manufacturer’s Group, the findings are “not only useful for companies in the field of food plant engineering but will also provide great support for other important sectors of the large industrial plant engineering industry as, to mention only a few, the manufacturers of power stations, steel plants and construction material facilities.”

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