To take maximum advantage of a new ingot mold stripping facility, which was installed in 1984 at the Bethlehem Plant, we developed a two-phase, computer-based procedure for selecting optimal ingot dimensions and internal ingot mold dimensions. Phase 1 generated feasible ingot and internal ingot mold dimensions consistent with the new stripper's capability and with foundry, steelmaking, metallurgical, mill, and shipping yard constraints. Phase 2 then used a set-covering approach to select the optimal ingot and internal ingot mold sizes from among the feasible sizes. Based on model results and following trial mill tests, full production use of new mold sizes has affected the entire plant operation, resulting in over $8 million annual realized savings.

Bethlehem Steel Corporation is the second largest steel producer in America with major steel producing plants in Bethlehem, Johnstown, and Steelton, Pennsylvania, and at Sparrows Point, Maryland, and Burns Harbor, Indiana. Continuous casting is a steelmaking technology that greatly reduces costs and that has been adopted in Japan and Europe and more recently in the United States to replace the traditional ingot-based steelmaking technology. While using continuous casters (instead of ingot-based steelmaking) improves yield, productivity, and product quality,
these benefits demand a considerable investment — the installation of a continuous caster can easily cost between $200 and $300 million.

Although Bethlehem Steel is committed to modernizing its steelmaking facilities (four continuous casters have been installed at its plants, including three since 1982), for the foreseeable future, it plans to continue producing structural steel at its Bethlehem Plant without a continuous caster. Therefore, to remain competitive in the structural shapes market, it must optimize the operation of the ingot-based Bethlehem Plant. At the heart of the operation are the ingot molds used to produce the steel ingots that are processed into structural shapes. The size and shape of the ingots directly affect the efficiency of both upstream and downstream operations. At a modest cost, compared to a new continuous caster, a new ingot stripping facility to remove molds from ingots together with optimally designed ingots and molds provided a major improvement in efficiencies.

The installation of a new ingot mold stripping facility provided us with the opportunity to develop a robust computer-based procedure for designing and selecting optimal ingots and ingot molds.

The Ingot Mold Stripper Project

In 1980, to remedy the deteriorated condition of its existing ingot mold stripper, the Bethlehem Plant proposed that a new facility be built because the cost of rebuilding the obsolete, existing facility was prohibitive. In 1981, management approved the construction of a new facility capable of handling taller ingots; that is, solid rectangular-shaped steel blocks. The new facility was justified on the basis of projected benefits from reduced equipment maintenance costs and improved material flow resulting in fuel savings. The justification for the stripper did not quantify any projected benefits from redesigned ingot molds other than from raising the height of several of the current mold sizes.

Bethlehem’s management realized that management science experts within the corporation could help design the ingot molds, and they formed an interdisciplinary team to do it. The systems analysis group within Bethlehem’s research department developed a two-phase, computer-based model for selecting optimal ingot dimensions and internal ingot mold dimensions. At the same time, both the plant and the research department were performing steel deformation studies, examining the way the shape and size of the ingot is transformed by sets of horizontal and vertical rolls into a structural shape, for example, an I-beam. The interdisciplinary team of plant and research personnel incorporated into the optimization model (1) the new results from the steel deformation studies, (2) the enhanced capabilities of the new stripper, and (3) all relevant foundry, steelmaking, metallurgical, mill, and shipping yard constraints.

Material Flow

The Bethlehem Plant is a fully integrated steel plant. Blast furnaces are used to convert iron ore, coke, and other raw materials into molten iron. The molten iron is supplied to the steelmaking division where basic oxygen furnaces refine the iron into steel. Molten steel from the
basic oxygen furnaces is poured into ladles, and from there the metal is poured into various size ingot molds (cast iron containers open at both ends), which sit on flat iron bases called stool plates, which in turn sit on flatbed railroad cars. The molds are then transferred by rail to an ingot stripper where, after the steel ingots have solidified sufficiently, the molds are stripped from (lifted off) the ingots by large cranes. The molds are then shipped to storage until needed again. The ingots are transferred to furnaces called soaking pits, where they are heated by a mixture of gases to a uniform temperature before being rolled on the mills into a variety of structural steel shapes (wide-flange beams, standard beams (I-beams), H-piling, sheet piling, channels, angles, and several specialty shapes). After rolling, the products are transferred to hot beds (storage areas where they cool), cut to the lengths specified by customers, and shipped. Figure 1 depicts a generic material flow for an ingot-based steel rolling mill complex.

There are two structural complexes (series of mills) at the plant that are different in the way they convert ingots into finished shapes. The larger of the two, known as the 48-inch mill, was built in 1907 and modified and upgraded through the years. It was one of the first mills of its type to be built in the United States. Despite its age, this mill can produce quality wide-flange beams, large H-piling sections, and large standard beams — some of the largest and heaviest (730 lbs./ft.) structural products of any structural rolling mill in the world. The 48" mill rolls finished products directly from ingots, using three in-line mills (blooming mill, roughing mill, and finishing mill). It bypasses such intermediate steps as rolling the ingot into smaller rectangular sizes called blooms, which must then be
reheated in furnaces before they can be rolled into their finished shapes. The 48" mill rolls an ingot of a given cross-section and weight into a long length (200 feet) of finished product, for example, an I-beam. A very specific ingot size and ingot weight must be provided for each customer order to produce the desired finished product. The majority of the rolled products (over 100 distinct products) from the 48" mill are cut to customer ordered lengths immediately following the finishing mill. They are then straightened, inspected, and grouped into customer orders ready for shipment.

The second complex of rolling mills, known as the combination mill, was built in 1967. It can produce a wide variety of high quality medium-to-light-weight wide-flange beams and standard beams, as well as channels, angles, interlocking sheet piling, and miscellaneous shapes. Material flow on this mill is different from that on the 48" mill, in that ingots from the soaking pits are first rolled in a series of blooming mills into rectangular blooms of a multitude of dimensions, for example, 12" x 20", 6" x 12", 8" x 14", and of various lengths. About 50 bloom sizes are used by the combination mill to produce over 100 distinct products. The blooms must be heated in a reheat furnace prior to being rolled on the combination mill. The products from this mill are cut to individual customer lengths after they have been cooled and straightened. Although the constraints on ingot size are less severe for the combination mill (almost any bloom size can be produced from any ingot size within reason), nevertheless, optimizing the ingot sizes improves yield and productivity.

**The Problem**

As can be seen from the description of the material flow, either the molds themselves or the ingots they produce affect virtually every operation in the entire plant. Therefore, any changes in the design of the molds that affect ingot shape must be considered very carefully.

The internal dimensions of a mold determine the dimensions of the ingots that are produced from it. Ingots produced from molds of the same size will have the same bottom dimensions and shape but can differ in height and top dimensions (Figure 2). Furthermore, each ingot can be used to produce several different finished products depending on how it is processed in the mill. Therefore, one mold size can be used to produce a variety of finished products.

Important parameters in mold design that will determine the shape of the

![Figure 2: A structural product is made from a fixed volume of steel; therefore, the cross-section area of the mold determines the height of the ingot.](image-url)
The inside walls of the mold are tapered, resulting in smaller top ingot dimensions, and corrugated to make for easier removal of the ingot. The thickness of the mold wall decreases as the height of the mold increases. This influences the number of ingots the mold can produce before it has to be scrapped, for example, 60 ingots/mold.

Within Bethlehem Steel, engineers study the way steel is transformed as it is processed through a mill. For a particular finished product, for example, a wide-flange product, they can determine the best ingot size (cross-section) to use to produce it. The best ingot size is one that will produce a high quality finished product while minimizing the amount of yield loss (unusable material called crop ends) that must be removed from its ends after its cross-section is reduced in the blooming mills. At first glance, it appears that optimal ingot sizes can be determined merely by studying, one at a time, all the finished products on a mill. However, this approach would result in a collection of customized ingots, each requiring its own unique internal ingot mold dimensions and corresponding mold size. Since the two rolling mill complexes at the Bethlehem Plant produce more than 200 distinct finished products, the number of mold sizes needed to produce the "customized" ingots for these products could conceivably exceed 200.

When our study began, the Bethlehem Plant was using about a dozen ingot mold sizes. The steelmaking and foundry departments were responsible for the inventory and material handling of ingot molds and knew, based on past experience, that any increase in the number of distinct mold sizes would result in a significant increase in inventory and material-handling costs and in logistical problems. At an ingot-based operation, the cost of molds is a major expense.

Therefore, we developed a two-phase, computer-based procedure for selecting optimal ingot dimensions and internal ingot mold dimensions in order to (1) take maximum advantage of the enhanced capabilities of the new stripper — it could handle ingots of increased height and weight, (2) avoid violating any foundry, steelmaking, metallurgical, mill, and shipping yard constraints, and (3) incorporate recent research and plant technology results related to improving yield and quality. Only nominal improvement would have been realized if the old mold sizes had been retained and their height increased. Phase 1 of this procedure generated feasible ingot and internal ingot mold dimensions consistent with conditions (1), (2), and (3). Phase 2 then used a set-covering approach to select from among the feasible sizes generated the ingot dimensions and the internal ingot mold dimensions that minimize the number of distinct mold sizes required to produce the finished products. Also, phase 2 selects, from among the solutions for the minimum number of mold sizes, the one that achieves the secondary objective of either minimizing product yield loss or maximizing mill productivity for the Bethlehem Plant's product-mix distribution.
By decomposing the formulation into two phases, many math programming constraints were implicitly handled in phase 1. This reduced the size and complexity of phase 2 without sacrificing the accuracy of the overall problem formulation. As discussed in Vasko, Wolf, and Stott [1987], this resulted in a very robust procedure that could easily handle changes in both constraint parameters and logic associated with generating feasible ingot sizes.

In phase 2 the first priority was to minimize the number of mold sizes because the inventory investment, material-handling, and logistical considerations associated with an additional mold size outweigh the potential yield or productivity benefits from increasing the number of mold sizes.

Assumptions, Constraints, and Parameters

A large number of parameters and constraints influence the generation of feasible ingot sizes and internal ingot mold sizes. The information that resulted from the 1983 studies was used in phase 1 of our model to generate feasible mold sizes. A strength of using our phase 2 mathematical programming structure, which selects the optimal mold sizes from the feasible sizes that have been generated, is that the algorithm to solve the problem is not affected by this new information. We analyzed a large number of scenarios based on different parameter settings. The major parameters, considerations, assumptions, and constraints used in the model follow:

- The first objective criterion — While satisfying all constraints, the primary objective is to minimize the number of distinct mold sizes required to produce the finished products;
- The second objective criterion — Either to maximize mill productivity, that is, to minimize total blooming mill passes, or to minimize product yield loss;
- The structural tons of finished product projected for 1987;
- The set of finished products that can be made from the designed ingots;
- The maximum ingot weight limited by crane capacity;
- The maximum aspect ratio — A measure of how rectangular an ingot is, that is, the bottom ingot width divided by the bottom ingot thickness;
- The acceptable mold-pour height range — The minimum and maximum allowable ingot heights (if an ingot is too tall for a particular finished product, the product will not fit on the hot bed when it is rolled [Figure 2])
- The ingot taper — The slope of the vertical sides of the ingot (Figure 2), for example, 1.0 percent, 1.5 percent, 2.0 percent; the greater the taper, the easier it is to remove the mold from the ingot but the harder it is to roll the ingot through the mill;
- The maximum hot bed length — Maximum allowable length finished product prior to cutting it to customer lengths;
Pass reduction logic — How much reduction in cross-section is achieved each time the ingot passes through the blooming mill rolls; that is, the specifics of how the ingot’s cross-section is compressed, its length increased, and its shape transformed into an I-beam;

— The logic necessary to calculate loss in yield — The amount of material lost when the ingot is processed through the mills;

— The minimum dimensions of the top of the ingot — Must be large enough to fill out the required cross-section into the shape pass at the blooming mill for the finished product being produced;

— Guaranteed sidework (making the ingot width large enough so that adequate width reduction occurs in the mill) — An adequate amount of sidework is required to insure both surface and internal product quality, and the yield at the blooming mill is heavily influenced by the amount of sidework done there;

— Maximum dimensions of the bottom — These constraints ensure that the crane tongs at the soaking pit will be able to handle the ingots safely, the ingots can fit into the blooming mill, and ingot pouring platform limitations are not violated;

— Ingot dimension tolerances — Tolerance allowed for minimum and maximum ingot width and thickness;

— The pour height tolerance allows ingots for a particular finished product that are poured slightly below minimum pour height in a given mold size to still be considered feasible in that mold size;

— The finished product length tolerance allows ingots for a particular finished product to be produced from a mold size even if the maximum finished product length is not quite attained, for example, the tolerance permits a length of 198 feet instead of 200 feet.

Determining Feasible Mold Sizes — Phase 1 Logic

Given the input information, Phase 1 calculates all the feasible ingot dimensions and corresponding mold sizes that can be used to produce each finished product. Phase 1 is composed of three procedures, Genmolds, Feasrange, and Creatematrix, discussed in detail in Vasko [1983]:

Genmolds (generation of feasible mold sizes) calculates a set of ingot sizes and corresponding inside mold dimensions tailored to each particular product. Specifically, given a finished product, the method calculates the ingot weight for that product that corresponds to the maximum attainable product length on the hot bed without violating any constraints; for example, maximum ingot weight and hot bed length. Then, given the ingot weight and minimum allowable ingot top cross-sectional dimensions, Genmolds calculates the corresponding ingot height for any taper. If the height falls within the feasible range, it stores the ingot dimensions, since they are feasible. If, on the other hand, the height exceeds the feasible range, the ingot dimensions are not feasible and are not retained. The application-specific pass reduction logic is used to increase the cross-sectional dimensions of the ingot and recalculate the ingot.
height. For an ingot with a fixed weight, the height decreases as the cross-sectional area increases. Genmolds continues this procedure until it achieves the maximum cross-sectional dimensions or until the ingot height falls below the minimum acceptable height.

Feasrange (determination of feasible parameter ranges) uses the same logic as Genmolds to calculate ingot bottom cross-sectional areas corresponding to minimum and maximum ingot heights for each finished product (see Figure 2). The area associated with the maximum ingot height is the minimum feasible area for that product, and the area associated with the minimum ingot height is the maximum feasible area for that product. These areas are needed by Creatematrix to determine which finished products can be produced from which ingot molds.

Creatematrix (create matrix of feasible product-ingot pairs) determines whether other products can be produced from each set of feasible inside mold dimensions that were determined in Genmolds for a particular finished product. It does so largely by comparing the areas calculated in Feasrange. For example, suppose we have a mold size with bottom inside area of $A_M$, and we want to determine whether a finished product with minimum bottom area $A_s$ and maximum bottom area $A_B$ can be produced from an ingot poured into this mold size; then, given that all other constraints are not violated, such as minimum cross-sectional ingot dimensions, this mold size will be feasible for this product if

$A_s \leq A_M \leq A_B$.

If $A_M > A_B$, then the ingot height is less than the minimum feasible height. On the other hand, if $A_M < A_s$, then the ingot height is greater than the maximum feasible height. The output of Creatematrix includes a list of all feasible pairings of mold sizes with finished products.

Optimal Mold Sizes — Phase 2 Formulation

The output from phase 1 is used to determine the coefficients for the mathematical programming formulation which comprises Phase 2 (see appendix for math formulation). This formulation, called the

Any increase in the number of distinct mold sizes would result in a significant increase in inventory and material-handling costs and in logistical problems.

Ingot size selection problem (ISSP), is a preemptive, zero-one, linear goal program in which the first objective minimizes the number of mold sizes and the second objective minimizes total annual crop weight for all products produced. The constraints ensure that mold sizes are selected such that each finished product has at least one feasible ingot size associated with it.

Optimal Mold Sizes: Phase 2 Solution Procedures

The ISSP can be solved by first solving a minimum cardinality set-covering problem (MCSCP) (see Vasko, Wolf, and Stott [1987] for references), and then solving a generalized K-median problem [Mavrides 1979]. Specifically, the solution to the MCSCP determines the minimum number
of molds, call it \( K \). Then, a \( K \)-median problem is solved to find the feasible set of \( K \) mold sizes that minimizes crop weight. Both the set-covering problem [Karp 1972] and the \( K \)-median problem [Garey and Johnson 1979] are NP-complete.

Alternately, the ISSP has an equivalent formulation as an uncapacitated facility location problem (UFLP). This well-known problem, also referred to as the lock-box location problem, has been studied by numerous researchers; see Vasko, Wolf and Stott [1987] for references.

The procedures developed to solve the UFLP typically have been tested only on small problems and resort to branch-and-bound techniques to guarantee a global optimum. Computationally, Erlenkotter's [1978] dual-based procedure DUALOC appears to be one of the best, based on his results for relatively small test problems. The ISSP is equivalent to a special case of the UFLP (see the appendix).

Having obtained DUALOC from D. Erlenkotter, we tried to use it to solve ISSPs. Although DUALOC performed very well for an exact procedure, it required up to 15 CPU minutes or more (we terminated DUALOC after 15 CPU minutes) to solve ISSPs on an IBM 3032 (see Vasko [1983], Table 3). Since we were interested in analyzing a large number of different scenarios — for example, different tapers, minimum pour heights, mill configurations that influence allowable ingot dimensions, and so forth — and since ISSPs typically involve about 130 set-covering constraints (one for each finished product) and 600 integer variables (one for each candidate mold size), we wanted to use an efficient heuristic, that is, a heuristic that would require only a few CPU seconds to solve an ISSP.

As part of his PhD dissertation [1983], Vasko developed a hybrid heuristic, OPTSOL, that performs better than the standard greedy-type heuristics for solving the MCSCP [Vasko and Wilson 1986]; we used OPTSOL to solve the MCSCP part of ISSP. Once the MCSCP has been solved, a good solution to the second priority \( K \)-median problem can be found quickly by using a neighborhood search technique [Lin 1975]. In general, the neighborhood search technique starts with the OPTSOL solution to the MCSCP and removes mold sizes in the solution one at a time and tries to replace the mold size removed with one that improves the second objective function. OPTSOLI is a straightforward extension of OPTSOL that we used to solve the ISSP.

OPTSOLI was constructed as follows:

1. Execute OPTSOL to solve the MCSCP.
2. Perform a 1-opt-type neighborhood search on the OPTSOL solution in order to locally optimize the second objective function.

For this particular application, OPTSOLI provided the opportunity to evaluate a large number of design and operating scenarios quickly (several CPU seconds on an IBM 3032). Because of the magnitude of the decision, we used DUALOC to confirm the final mold specifications.

Analyses and Results

From June 1983 through February 1984, we performed extensive computer analyses using our two-phase, computer-based procedure for selecting optimal
We analyzed a large number of scenarios based on different parameter settings. We performed analyses to determine trade-offs among ingot taper, maximum finished product length, pour height range, minimum and maximum ingot dimensions for each finished product, predicted yield loss, and ingot-to-bloom reduction logic.

Our analyses progressed through five major stages, and we analyzed more than 50 scenarios. The difference among stages was the availability of new, more refined input information for phase 1 of the program. At each stage, we studied several scenarios that explored the importance of the following key parameters: maximum hot bed length, pour height range, and taper.

Stage 1 contained the following:
- The preliminary logic for determining feasible ingot sizes for each finished product,
- The initial estimates for the minimum dimensions of ingot tops,
- A secondary optimization criterion to minimize total blooming mill passes,
- Mill yield estimates, and
- Maximum ingot dimensions based on crane tong openings and stool plate dimensions, but not explicitly on mill roll opening or width considerations.

Stage 2 included the same components as stage 1 except for the following:
- A revised logic for determining feasible ingot sizes for each finished product, and
- A revision of minimum top ingot dimensions.

Stage 3 included the same components as stage 2 except for:
- New (larger) minimum ingot dimensions that ensure that a certain minimum amount of ingot reduction would occur in the mill — a quality consideration.

Stage 4 included the same components as stage 3 except that:
- Revised maximum ingot dimensions explicitly reflect the maximum mill roll opening, and
- The minimum amount of ingot reduction was revised to accommodate new maximum ingot dimensions for each finished product.

Stage 5 included the same components as stage 4 except that:
- The minimum top ingot dimensions were revised,
- The secondary optimization criterion was changed to minimize product yield loss while insuring acceptable mill productivity,
- Yield values were generated that are based, in part, on logic to calculate shear crop weights (waste removed after blooming mill operation), and
- Maximum ingot dimensions were revised.

After we analyzed each set of scenarios using the two-phase computer model, we
met with representatives of the appropriate plant departments and with steel deformation specialists from the research department to discuss the results. We generated a report for each scenario that grouped all the finished products by their optimal internal mold dimensions. We were interested only in the dimensions of the insides of the molds because these are the dimensions that determine the shapes of the ingots. For each finished product possible refinements to the input data. In particular, studies indicated that taper should be increased (over the taper of the then current mold sizes) in order to improve removal of the mold from the ingot. However, as the ingot taper is increased, the number of mold sizes required increases because of the interaction of taper with the following: minimum allowable top ingot dimensions, pour height range, and hot bed length limitation. Also, it is more difficult for the mill to roll the ingot. Those reviewing these results typically made two types of suggestions: that a particular constraint should be looked at more closely to determine if it could be loosened, and that perhaps some plant constraints needed refinement or others had not been identified. In both cases, the result was that the appropriate plant or research personnel investigated the situation and reported back to the group.

This report was extremely helpful in enabling the group analyzing the results to identify how the various constraints affected the solution. For example, although the steelmaking department wanted to limit the range of pour heights as much as possible, the number of mold sizes required increases as the range of pour heights decreases. Also, sensitivity analyses of key parameters — taper, for example — were helpful in suggesting

The ingots produced from the trial molds consistently improved mill yield and product quality.

and each scenario studied, the report lists the ingot size chosen by the model, the maximum allowable bottom ingot dimensions and the actual bottom ingot dimensions, the minimum allowable top ingot dimensions and the actual top ingot dimensions, the then current ingot size used, the finished product length on the hot bed, the height of the ingot, the mill yield, and productivity measures (blooming mill passes and annual number of ingots required to meet demand).

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Based on the results of these investigations, additional scenarios were formulated and analyzed. This evolutionary process lasted from June 1983 through February 1984.

Based on model results, we selected a trial mold size. At the end of November 1983, after the foundry produced a set of trial molds, we began mill trials. The ingots produced from these molds consistently improved mill yield and product quality. These results helped to validate the new input logic that was being used in phase 1 to design feasible ingot and mold sizes.

The Recommendation

In February 1984, we finally found a scenario that satisfied all plant departments. In March 1984, the plant accepted
our recommendation to replace the seven existing mold sizes with six new optimally-designed mold sizes (which included the trial mold size) based on a conservative analysis that predicted economic benefits of $1.8 million annually in savings due to improved yield and productivity, and savings due to reduced mold investment. Our recommendation for new ingot and mold sizes was well received and approved by plant management for a number of reasons.

Two plant departments were primarily affected by the recommendation for new ingot and mold sizes—the steelmaking division and the rolling mills division. Input to the computer model was based on recent mill studies aimed at improving quality and yield in the mills; therefore, the model results were implicitly geared to improve the performance of the mill division. On the other hand, the steelmaking division was responsible for the inventory, material handling, and logistical problems associated with maintaining ingot molds. The final mold recommendation was a "win-win" situation for both divisions in that it both reduced the number of mold sizes that had to be maintained and also improved product performance (yield and quality) through the mill.

The determination of an implementable final recommendation was made possible in part by the cooperation and willingness to compromise by the plant and research departments; and the existence of a two-phase computer model that served as an impartial referee for generating and evaluating alternative design and operating scenarios. Specifically, it enabled us to quickly model complex design and operating scenarios by modifying only phase 1 without having to alter the mathematical programming formulation and solution procedure (phase 2) that efficiently evaluated these scenarios to minimize the number of distinct ingot mold sizes required and improve product performance through the mill. Also important were the easy-to-understand reports that pointed out which constraints were binding and which were loose. In addition, the projected benefits to the plant were $1.8 million annually, even with the most conservative worst-case estimate; and the trial mold size had been tested successfully by the mill for three months.

The plant decided to phase in the new mold sizes, one size at a time, as the existing molds were scrapped due to wear, cracking, and so forth. Since the average life of the existing molds, measured by the number of ingots it could produce before being scrapped, was 60 to 70 pours, phasing in the new molds was expected to take several years.

Mold Trials and Phase-In

The plant's original plan was to conduct extensive mill trials on one new mold size at a time.

The plant's original plan was to conduct extensive mill trials on one new mold size at a time, starting with the largest size since our computer analyses predicted the largest benefits for that size. The mill trials were necessary to verify projected yield improvements for
all finished products that could be rolled from that mold size.

In order to evaluate each new mold size as comprehensively as possible, enough molds to hold a heat's worth of steel were required (approximately 15 molds for the largest size). Starting with the optimal internal ingot mold dimensions, along with input from plant technology engineers who had determined the main mechanism of failure for the existing mold sizes, the foundry prepared blueprints incorporating the optimal mold features to provide improved mold life. It takes about three months from approval of the final blueprint for a mold size until the molds are ready for mill trial; the long lead time is necessary because new foundry equipment and patterns must be made for the new molds. Each new design was scheduled to be tested for two months prior to phasing the molds into full production.

By early 1985, mill testing on the two largest new mold sizes (the second largest being the trial mold size) had been successfully completed, and these sizes were being phased into production as the existing molds were scrapped. With the mill testing and phasing-in of these first two new mold sizes, the truly conservative nature of our March 1984 worst-case benefits analysis came into focus. These molds and the ingots they produced were performing so well in terms of yield, surface quality, and internal quality that the Bethlehem Plant decided to accelerate their phase-in. By August 1985, based on the very good results for the first three ingot mold sizes and limited mill test results of the last three ingot mold sizes, the plant formally agreed (all divisions signed off) to accelerate the full production phase-in of all six new ingot mold sizes and to forego mill testing of the three smaller mold sizes. Inventory levels for the new sizes were developed in conjunction with schedules to phase-in the new sizes at optimal rates to achieve maximum benefits as rapidly as possible. By the end of 1986, the new mold sizes were being used in full production.

**Benefits Actually Realized**

With all production coming from the new mold sizes, the actual benefits are considerably better than the $1.8 million estimate:

- The annualized reduction in mold investment due to fewer mold sizes is $0.42 million per year.
- The mill yield improvement is $2.0 million per year.
- The energy savings from the new taper is $1.8 million per year.
- The reduction in product reworking saves $0.2 million per year.
- Better mold life is $1.75 million per year.
- Reduced handling costs are $0.75 million per year.
- Productivity improvement is $0.70 million per year.
- More business due to heavier and longer finished product length is $0.5 million per year.
- Total: $8.12 million per year.

This project also provided the following qualitative benefits to the plant:

- It improved communication among plant departments and between the plant and the research department.
- A multitude of ideas went into the mold designs, and everybody shared in the success.
BETHLEHEM STEEL

— It improved "customer-supplier" relationships within the plant.
— The project demonstrated that substantial savings could be achieved by changing the process.
— The model accurately traded off a multitude of design considerations and constraints and gave Bethlehem the confidence to implement a reduced set of optimally designed mold sizes.
— The project was an example of how to manage a major plant effort involving diverse expertise and many departments.

**Optsol for Assigning Metallurgical Grades**

From 1983 through 1985, Bethlehem Steel was in the process of installing, at a total cost of about half a billion dollars, a continuous slab-casting machine at its Sparrows Point Plant and a second continuous casting machine at its Burns Harbor Plant. In order to be able to utilize this equipment efficiently, Bethlehem concurrently developed production planning and control (PPC) systems to coordinate its use. Since continuous casters link steel-making directly with finishing mill operations, the PPC systems necessarily encompassed the majority of the plant functions.

Bethlehem commissioned the Systems Analysis group to develop the PPC module responsible for selecting the minimum number of metallurgical grades to produce a collection of customer orders. Conceptually, the module logic was based on the same two-phase approach we used for ingot and ingot mold design. Specifically, our minimum cardinality set-covering algorithm determines the minimum number of melting grades needed to meet current customer orders, and then the secondary objective selects the "most-desired" melt grade within that set of minimum grades [Vasko, Wolf, and Stott forthcoming]. Further, by executing the algorithm in a two-pass mode, the module is able to show-preference for priority orders. In this application, L. R. Woodyatt of the Systems Analysis group provided the metallurgical expertise. In particular, phase 1 is replaced by a table generated by a series of metallurgically based computer programs [Woodyatt 1987] that determine all feasible metallurgical grades that can be used to produce each customer order. Then in phase 2, OPTSOL, which has been embedded within the casters' PPC systems by the plant information services departments, quickly generates solutions to large-scale (up to 1,000 zero-one variables and 2,500 constraints) ISSP-type problems.

Early in 1986, Bethlehem Steel Corporation completed installation of these two continuous casting machines, and their accompanying PPC systems became operational. The OPTSOL-based grade assignment module, which is in routine use, improves caster productivity significantly and reduces semifinished inventory, when compared to the traditional method of grade assignment.

Vasko, Stott, Wolf, and Woodyatt [forthcoming] enhanced the modeling of this

The actual benefits are considerably better than the $1.8 million estimate.
Conclusions and Current Applications

A robust and innovative management science approach was implemented in a computer model and used to accomplish major process design changes at Bethlehem Steel’s Bethlehem Plant. Based on results from this computer model, new ingot mold sizes have been implemented (put in full production use) with annual benefits exceeding $8 million.

The Bethlehem Plant Foundry, which sells ingot molds to other steel companies, routinely uses our two-phase procedure for optimal ingot and ingot mold design as a marketing tool in preparing bids for mold customers. In particular, this procedure is used to suggest which mold sizes a customer should buy from Bethlehem.

The two-phase methodology, the set-covering formulation, and the solution algorithm have proven to be transportable. For example, the phase 2 optimization algorithm, OPTSOL, has been embedded as a module into slab caster production planning and control systems at Bethlehem’s Sparrows Point and Burns Harbor Plants. This module is used routinely to optimally assign metallurgical grades to customer orders, resulting in significant improvement in caster productivity and reductions in semifinished inventory. Furthermore, this approach is currently playing a major role in several of Bethlehem’s strategic planning projects.

This methodology, formulation and solution algorithm are generic and can be used to solve a large variety of set-covering type applications not only in the steel industry but in other industries as well.

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APPENDIX

Mathematical Formulation of Phase 2

Definitions

- $I$ is the set of all finished products,
- $J$ is the set of candidate mold sizes,
- $c_{ij}$ is the expected annual crop weight if mold size $j$ can be used to produce product $i$ and $c_{ij}$ is considered infinite if mold size $j$ cannot be used to produce product $i$,
- $a_{ij}$ is 1 if product $i$ and mold size $j$ form a feasible pair and 0 otherwise,
- $y_j$ is 1 if mold size $j$ is in the solution and 0 otherwise,
- $x_{ij}$ is 1 if mold size $j$ is used to produce product $i$ and 0 otherwise (although $x_{ij}$ is only constrained to be nonnegative),

The structure of the problem forces the $x_{ij}$'s to be 0 or 1 (see Erlenkotter [1978]).
**Problem 1: Ingot Size Selection Problem (ISSP)**

Minimize

\[ \sum_{j \in J} y_j, \quad (1st \ objective) \quad (1) \]

subject to

\[ \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} \leq \sum_{i \in I} f_i \quad (2nd \ objective) \quad (2) \]

Problem 2: Uncapacitated Facility Location Problem (UFLP)

Minimize

\[ \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i y_i \]

subject to constraints (3)-(6).

In this formulation, for all \( j \in J \), \( f_i > 0 \) is the fixed cost associated with facility \( j \).

Problem 3: Minimize

\[ \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in I} c_i y_i \]

subject to constraints (3)-(6).

In this formulation, \( c \) is calculated in the following manner:

\[ c_i = \max \{ c_{ij} \} \text{ where } c_{ij} \neq 0 \text{ and } c = \sum c_i. \]

**Proposition:** The pair \( X, Y \) with \( X = (x_{ij}) \), \( Y = (y_j) \) is a solution to Problem 1 if and only if it is a solution to Problem 3.

**Proof:** See Vasko, Wolf, and Stott [1987].

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### References


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*John I. Kinsey, Department Manager, Saucon Operations & Saucon Mills Department, Bethlehem Structural Products Division, Bethlehem Steel Corporation,*

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Bethlehem, Pennsylvania 18016, writes:

"The implementation of "new" ingot molds has been a true success story for the structural product line. This project required the blending of many objectives, at times conflicting, in order to provide benefits to all of the users. The basic validity of this work was proven early in the implementation and the decision was made to accelerate the phase-in to achieve maximum benefits as soon as possible.

"The overall savings to our plant will certainly be greater than the $8.12 million claimed in the paper. In addition, because of the increased taper, we have been able to strip the ingots faster and charge them into the soaking pits hotter, reducing our energy usage by 20 percent. The increase in sidework has not only reduced our rework, but also increased the overall quality of all of our shapes. This will help us to compete in the future as customer demands tighten. The return in this area should grow indefinitely.

"Equally important was the team culture which developed during this project. The analysis techniques provided objective answers for the project team's "what if" questions which promoted creative ideas and participation. We have built upon these attitudes in the ensuing years. The ultimate benefit is a more competitive product and a satisfied customer."