FOUNDRY DESIGN AND EQUIPMENT SELECTION IN DEVELOPING COUNTRIES

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PREFACE

This report is one of a series of publications which describe various studies undertaken under the sponsorship of the Technology Adaptation Program at the Massachusetts Institute of Technology.

In 1971, the United States Department of State, through the Agency for International Development, awarded the Massachusetts Institute of Technology a grant, the purpose of which was to provide support for the development at M.I.T., in conjunction with institutions in selected developing countries, of capabilities useful in the adaptation of technologies and problem-solving techniques to the needs of those countries. At M.I.T., the Technology Adaptation Program provides the means by which the long-term objective for which the A.I.D. grant was made, can be achieved.

This study investigates the issue of technical choice in industry. In recent years, development planners have become increasingly concerned with the appropriateness of technology, labor displacement and potential employment opportunities in new industrial projects. As an example of a primary industry for which local capacity should be developed in an early state of development, iron foundries have been selected for analysis. The wide range of technological alternatives for making iron castings and the great potential for employment generation in foundry operations makes this an attractive case study.

The analysis and findings of this study illustrate some of the engineering and economic constraints on the selection of appropriate technology, and provides a valuable contribution to the growing literature on technical choice. It will be of value to development planners, industrial economists and foundry engineers alike.

Fred Moavenzadeh
Program Director

ABSTRACT

An investigation of capital-labor substitution possibilities in grey iron foundries is presented. The research focuses on the problems and possibilities for foundry design in less developed countries (LDCs). A general discussion of the principal activities and technological change in foundries is followed by an exaimnation of the materials handling and moldmaking activities where substituion possibilities are greatest. A mixed integer programming model is constructed for 29 moldmaking alternatives, and simulation of representative medium and large "production" foundries in LDCs are performed. Over a wide range of alternate technical and economic assumptions, simple machine methods were preferred over both more automated and hand molding methods.

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1. INTRODUCTION

Technology transfer is the process by which technologies that have evolved in the industrialized world are transplanted to less developed countries (LDCs) with the primary objective of aiding and hastening the economic development of the region. This process to date has been hampered by inefficiencies, increasing unemployment, and the growth of "modern enclaves" that the "planners" of uncontrolled transfer of modern transportation, construction, and manufacturing technologies had not foreseen. As a result, considerable attention is being paid to the selection of appropriate (properly designed) technologies and better integrated technical development programs.

Foundries, as an example of a primary industry capable of supplying both directly, and through other manufacturers, the products needed for economic growth has been selected as a topic to investigate alternative methods of founding that could better utilize the economic resources of the LDCs. Foundries supply raw and finished goods to manufacturing, agriculture, and the consumer. Before other domestically based manufacturing industries can develop, foundry products must be available. Their importance in the early stages of development is well illustrated in the history of the industrial world. The development of modern founding arts preceded the Industrial Revolution by nearly two hundred years (45). In the U.S., the Saugus Iron Works was constructed in 1647, and provided the Massachusetts Bay Colony with eight tons of iron per week.

While numerous innovative foundry techniques have been and are currently being developed in the industrialized countries, the "traditional" casting techniques, employing sand molds, which have evolved gradually over the past several hundred years, still occupy a central position in the founding arts, and represent the technical base on which foundry industries in LDCs have been organized. The wide range of historical and modern alternatives that exist for sand casting makes it an attractive topic for investigating the issues of technical choice, and the appropriateness of specific techniques for use in the economic environments typical of LDCs.

Though foundry activities appear suitable as candidates for the investigation of these general technical and economic issues, there still remain numerous, specific technical requirements and problems which will influence real equipment selection decisions and, of necessity, limit the generality of statements concerning the appropriateness of a particular technological alternative.

Current problems encountered in U.S. foundries which influence equipment selection are:

a. Cost and supply of raw materials.

b. Shortages of skilled labor.

c. Increased quality control required for both raw materials and finished castings.

In addition, foundries in LDCs experience the following:

d. Need for efficient production for a small, dispersed market.

e. Limited equipment support and increased risk of delays resulting from breakdowns.

f. Smaller lot sizes, and greater variation in casting designs to be handled in one shop.

As the range of cast products to be produced increases, the specific requirements for materials, labor and foundry equipment vary more widely. The tremendous variation in the demand for foundry products and the supply of raw materials and labor in LDCs prevents much generalization about foundry problems. The specific requirements and problems of individual foundries have been and must continue to be treated on a case by case approach.

With these caveats in mind, this report attempts to identify some of the general issues of and possibilities for technical choice in iron foundries.

1.1 Research Objectives

This research is directed at the general issue of the appropriateness of specific foundry technologies for use in LDCs. The specific research objectives are:

1. To evaluate the capital-labor substitution possibilities in foundry operations,
2. To locate areas where substitution possibilities are great, and

3. To obtain a quantitative measure of the range of substitution possibilities in one of these areas as a function of wage and interest rates that are representative of the economic environment in LDCs.

The focus of this study has been restricted to the technical alternatives available to "organized" foundry production facilities. The small, rural foundry designs that have been presented as viable economic alternatives by groups concerned with "appropriate" or "intermediate" technologies have not been included in the discussion. In numerous communications with foundry organizations in LDCs there was no statistical or subjective evidence to support the contention that small, rural, village level foundries could play a significant rôle in the expanding metal casting industry in these countries. The argument in support of this trend is based on technological economies of scale which both reduce costs and improve the qualities of cast parts. In addition to more efficient utilization of equipment, energy resources, and skilled manpower, greater quality control in all phases of casting production, from better control of raw materials properties to more accurate regulation of the pouring temperature, is available as foundry size increases.

In addition, since the industrial sector in these countries is responsible for the rapid increase in demand for cast products, it is reasonable to anticipate that formally organized jobbing or production shops will be established or expanded to absorb this increased demand, and these foundries will inevitably be located in or near industrial centers.

This argument does not deny a potential role for rural, small scale foundries in LDCs. It just suggests that since the technical and economic requirements differ greatly, and "organized" foundries will continue to handle the bulk of the demand for cost products, they represent a more logical choice for the present survey and analysis.

1.2 Research Program

The research began with an ad hoc investigation of foundry technologies to determine where substitution possibilities exist. A number of equipment manufacturers, consultants, national and international foundry organizations were contacted for information. The organizations which contributed information to the project are presented in Appendix A. Based on the information received, the investigation focused on the material processing and handling activities in grey iron foundries. The areas for greatest substitution possibilities were identified and one of them, the moldmaking activity, was selected for further evaluation.

Unit cost comparisons and a mixed integer programming model were used to investigate the substitution possibilities in moldmaking. Alternative methods for producing "green sand" molds were assembled from data gathered from equipment manufacturers, local U.S. foundries, and consultants. Equipment costs, manpower and productivities for these methods were collected. Simulations of representative foundries permitted the investigation of the influence of wage, interest rate, and the number of production shifts on the equipment selection.

The results of the research program are presented below in the following sequence. A general discussion of foundry operations is presented to familiarize the reader with the basic processes and the terminology used in foundries. Then the areas and range of substitution possibilities are discussed. The quantitative model of moldmaking is presented with a discussion of the results, major sources of error, and alternate hypotheses.

2. SUMMARY

The principal iron foundry activities have been analyzed to determine the technical alternatives most suitable for economic conditions typical of LDCs. A general review of the technical requirements of the activities identified a number of areas in which the opportunities for capital-labor substitution are great (moldmaking, sand distribution, cleanout and cleaning operations) and others where the opportunities are more limited (pattern making, and metal melting).

Several general comments can be made about the substitution possibilities in the principal iron foundries.

Patternmaking

Patterns are a major component of the cost of finished castings. Their manufacture is primarily a machine shop activity and highly skilled workers are required. Costs are directly linked with the pattern material, which in turn is determined by the total number of molds to be produced. A new patternmaking technique, using epoxy resins for the casting shape, is currently being substituted in the U.S. for metal in many applications and has several advantages for use in LDCs. Reduced capital investment, lower skill requirements, easier machining (when necessary), and simpler repair are the major advantages over metal. We anticipate the use of epoxy patterns will expand greatly in existing and future foundries in LDCs.

Moldmaking

"Green sand" molding still dominates iron foundry operations, and will continue to do so in both the U.S. and in LDCs for the foreseeable future. The wide range of hand and machine methods make the moldmaking activity most attractive for a detailed, quantitative analysis. Chemically bonded sand methods are a potential alternative to green sand molding in areas in which the higher cost of materials is not prohibitive. Reduced skill requirements is the principal advantage of the chemically bonded sands. One major component, furfyl alcohol, can be produced by several fermentation processes from bagasse and other agricultural by-products.

Coremaking

Chemically bonded sand techniques have a much clearer advantage in coremaking than in moldmaking, though again costs will depend on the local availability of material. The principal savings over the traditional oil bonded sand technique stem from reduced skill requirements, and savings in capital investment and energy costs by eliminating the baking requirement.

Sand Handling: Reclamation, Preparation, Distribution

The choice of screen and magnetic reclamation systems is determined primarily by sand quality requirements. Simple manual or powered equipment is available and most suited to LDCs. Automated equipment would be difficult to justify under any conceivable set of conditions.

Sand preparation, or mulling, can be performed by hand when the required "green strength" is low. Higher green strengths, needed for higher quality molds, require some form of mechanical mulling.

Sand distribution can be performed by a wide range of hand and simple machine methods to replace the conveyor and hopper systems popular in U.S. foundries. Care must be taken in the foundry design to insure that the labor intensive sand handling methods do not interfere excessively with the other operations and reduce overall plant efficiency.

Metal Melting and Handling

The overriding issues in metal melting are materials and energy costs. These will dictate whether electric or cupola melting should be installed, independent of any consideration of labor cost or utilization. Technological economies of scale encourage the design of one melting facility for the entire foundry requirement.

Cupolas are somewhat more labor intensive and require lower operator and maintenance skills. While some foundries in LDCs have used novel sources of energy (an aluminum foundry in Paraguay uses alcohol supplied from an "organic" fermentation plant), the high temperatures required for iron and for steel melting restrict the opportunities for this type of innovation.

Casting Cleanout, Cleaning and Inspection

Hand and hand powered tools can perform all of the finishing operations for raw castings, and the use of sophisticated tumbling and blasting equipment in LDCs would have to be carefully justified. Some surface preparation (e.g., shot peening) and inspection (e.g., x-ray or sonic) requirements may be specified for which no labor intensive alternatives exist.

To support these qualitative judgments on technical choice, unit cost comparisons and a mixed integer programming (MIP) model of the molding activity were constructed to provide a more precise picture of the substitution possibilities, identify environments in which hand and simple machine methods are optimal, and determine the influence of the major cost components on the selection of molding equipment.

Molding Equipment Selection Model

Unit cost curves and a mixed integer programming model evaluated the capital-labor substitution possibilities for the moldmaking activity. The model focused on the range of production quantities and lot sizes anticipated for "organized", production foundries. Production levels and lot sizes for unorganized, rural, or job shops were too low to be adequately reflected in the model assumptions. The simulation illustrated several characteristics of equipment selection problems in LDCs.

1. A wide range of economic environments were tested with the basic model. Variations in the wage rate ($0 to $7.50 per hour) produced the most significant variations in equipment selected. Interest rate variation (10 to 30%) produced only small modifications in the set of optimal equipment. Double shift operation produced changes in the quantity, but not the type of equipment selected.

2. Simple machine methods, most notably based on the Matchplate process, dominated the equipment selections at low wages. Low skill requirements and pattern costs, and high overall productivity of these "modern" designs make them superior to hand methods until wage rates approach zero.

3. Employment potential increases rapidly as wages are reduced below $0.25 per hour. Unfortunately the hand techniques which offer the employment

opportunities have high skill requirements, and shadow pricing arguments will not likely improve the employment generation possibilities of this activity.

4. While the unit costs for one mold size provided information on cost trends as a function of wage, production quantity and lot size, joint production was the rule when several mold sizes were considered. This characteristic is supported by actual foundry behavior.

5. Though a preferred set of alternatives, including Matchplate molding for small sizes and operator controlled cope and drag molding for larger sizes, was indicated by the simulations, the range of price variations and limited number of mold sizes investigated prevented the identification of technically inefficient techniques.

6. Some sensitivity testing was performed on the variables that most directly influence molding costs. Increasing the total production quantity did not significantly influence the overall capital-labor substitution possibilities. Reducing the lot size caused the pattern costs to gradually dominate the equipment selection. Increasing the productivity of the hand methods, and alternately increasing the capital costs of the machine methods did nothing to enhance the selection of the former. Two alternate shadow pricing schedules for the various skill levels also did not improve the position of hand methods.

Limitations of the Model

1. The large degree of variability in patternmaking costs is the principal constraint on the precision of the model. At small lot sizes (production quantities per pattern), increases in this variability caused by the numerous technical alternatives available, make any general analytic judgments on substitution possibilities impossible. In this "job shop" environment, we anticipate hand and simple machine methods will dominate production in LDCs just as they do in the U.S.

2. The data for this study was collected primarily from local New England foundries. New England foundries do not employ the most automated methods available, and therefore the data on automated systems was

less than satisfactory. A study of the large scale production foundries in the midwestern U.S. might present quite a different picture of foundry operations, and alternatives available. One advantage though, of the data collected from jobbing and small production shops is that a wider range of methods and skill levels are still used, and information on "out of date" techniques is still available.

3. The model presents only a static picture of the equipment selection problem which does not accurately portray the realistic setting in which existing facilities are expanding and modifying their production capability. The need to adapt new equipment to existing facilities often results in non-optimal selection of individual components like molding equipment. Also time-phasing of equipment selections to respond to anticipated future demands will incorporate judgments about the ability of the alternatives to adjust to these changes, not simply minimize costs for one production level.

3. IRON FOUNDRY OPERATIONS

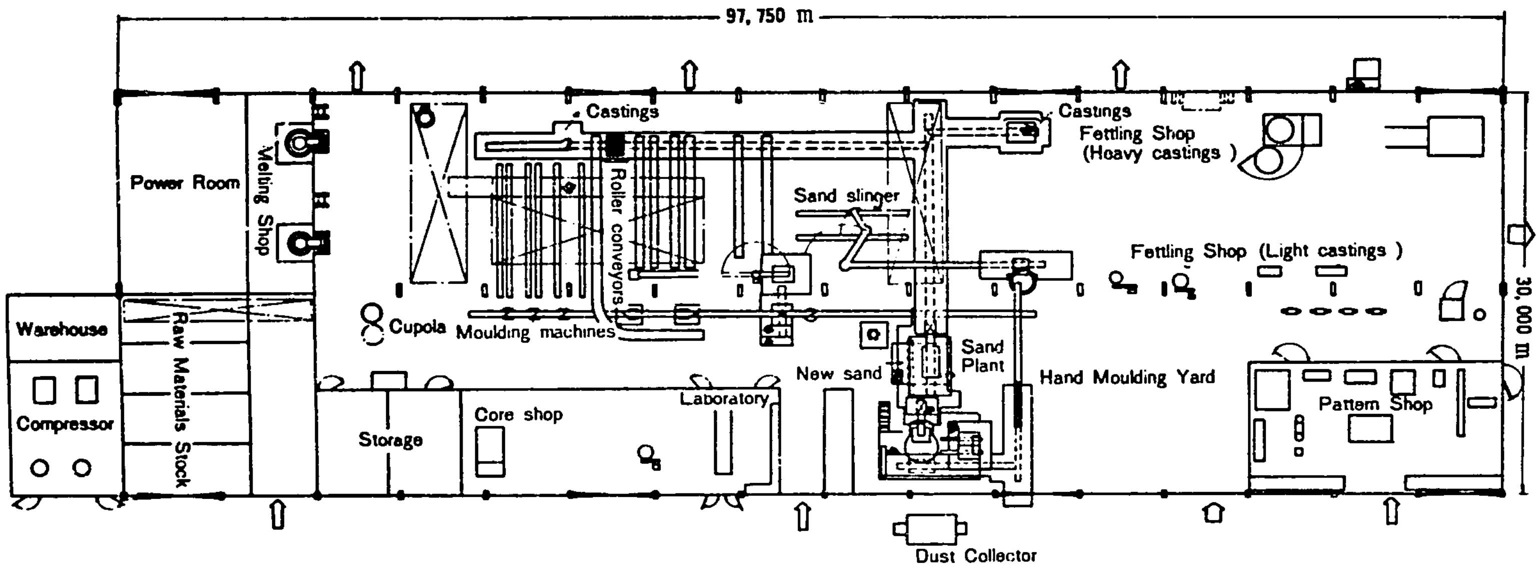
3.1 Overview of Foundry Activities

There is significant diversity in the design and organization of foundry operations depending on the type and quantity of castings produced. The two basic methods of organizing foundry operations are the "jobbing" and production shops. The job shop has the flexibility to produce a wide range of casting sizes and quantities. This flexibility requires higher skilled workers, and more labor intensive molding methods. The production shop handles higher quantities of a more restricted range of casting sizes. Opportunities for mechanization (direct worker and machine interaction), and automation (automatically controlled machines) are much greater. While a job shop in the U.S. may produce 5,000 to 10,000 tons of castings a year, work with several thousand casting designs, and with a majority of orders below 100 pieces, a production foundry might produce 50,000 tons a year with only a few hundred patterns. Layouts and descriptions of representative jobbing and production foundries are presented in Figures 1 and 2.

Despite this large variation in production requirements, the basic sequence of foundry activities remains unchanged. The following discussion of the most important activities focuses on grey iron foundries, but is generally applicable to steel and non-ferrous foundries as well. Figure 3 presents a flow chart of the principal foundry activities.

Depending on the design of the product, patterns (for the external shape) and coreboxes (for the internal shapes if the part is not solid) must be designed and manufactured. From these, the molds and cores can be made and assembled by a wide range of hand and machine based techniques. The finished molds are then transported to the pouring area, where the mold is filled with metal. The poured castings, separated from the mold, require a sequence of activities before shipment. The gates, (through which the metal flows into the mold), risers (to supply metal to the castings as it contracts upon cooling), flashing and residual sand must be removed. The casting is then cleaned, inspected, and heat treated (for malleable and ductile iron). Figures 4 to 5 illustrate these foundry operations.

Any discussion of the operations required to produce cast parts must emphasize the materials handling requirements of foundries. For every ton of castings produced, up to 10 tons of sand can be handled, and up to 100 tons



Ref. Data No. 1 **An Example of Layout of a Jobbing Foundry, having a production capacity of 5,000 tons/year. (FC = 4,000 tons. SC = 1,000 tons)**

Moulding = F. FD. VJ. DBS lines.
Sand = Green. CO_2, Self hardening.
Melting = Induction Furnaces. 5T x 50Hz 2T x 150Hz. & Cupola (3T/hr.)

Figure 1 : Layout of a Jobbing Foundry(1)

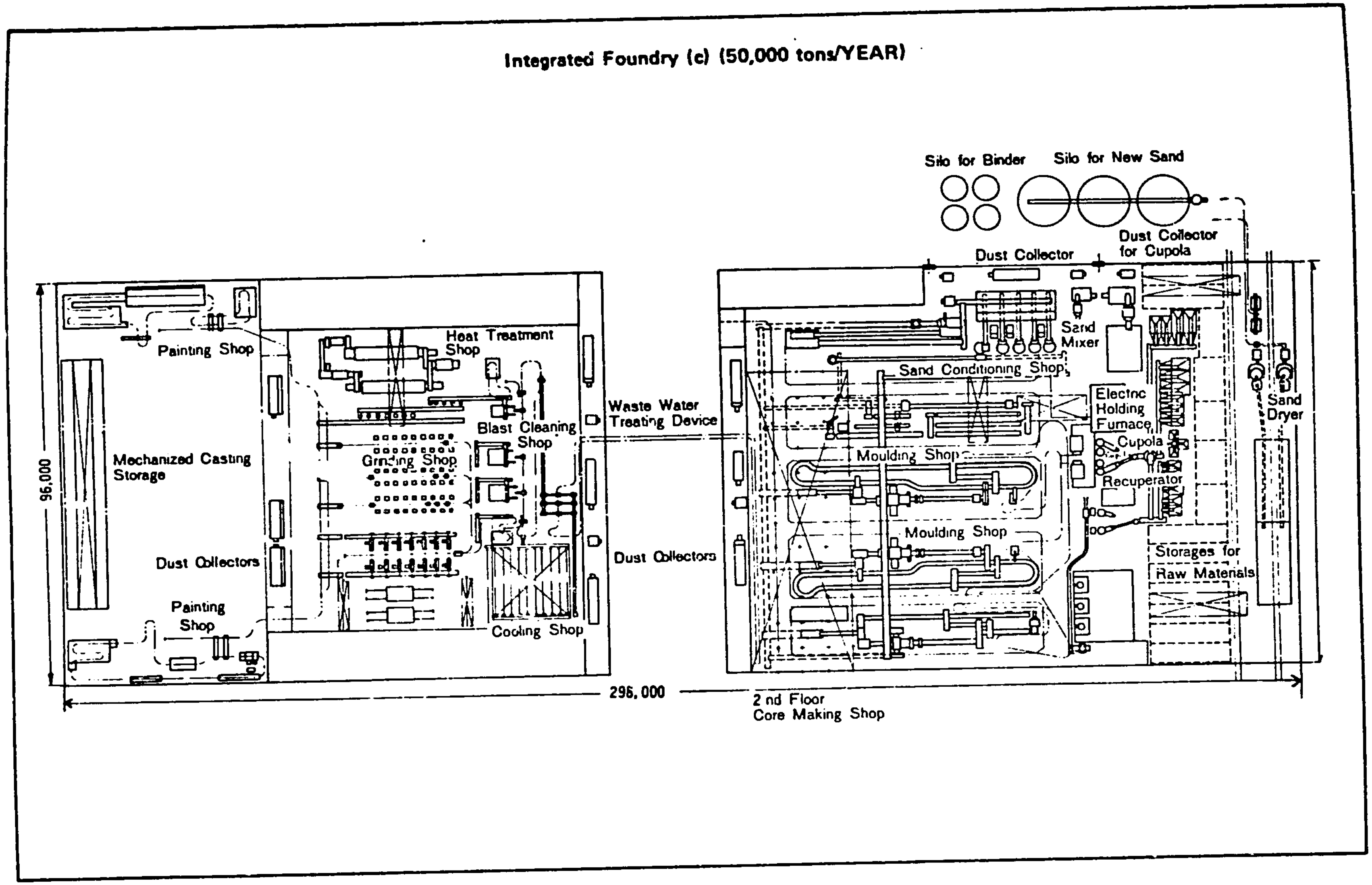


Figure 2: Layout of a Production Foundry(1)

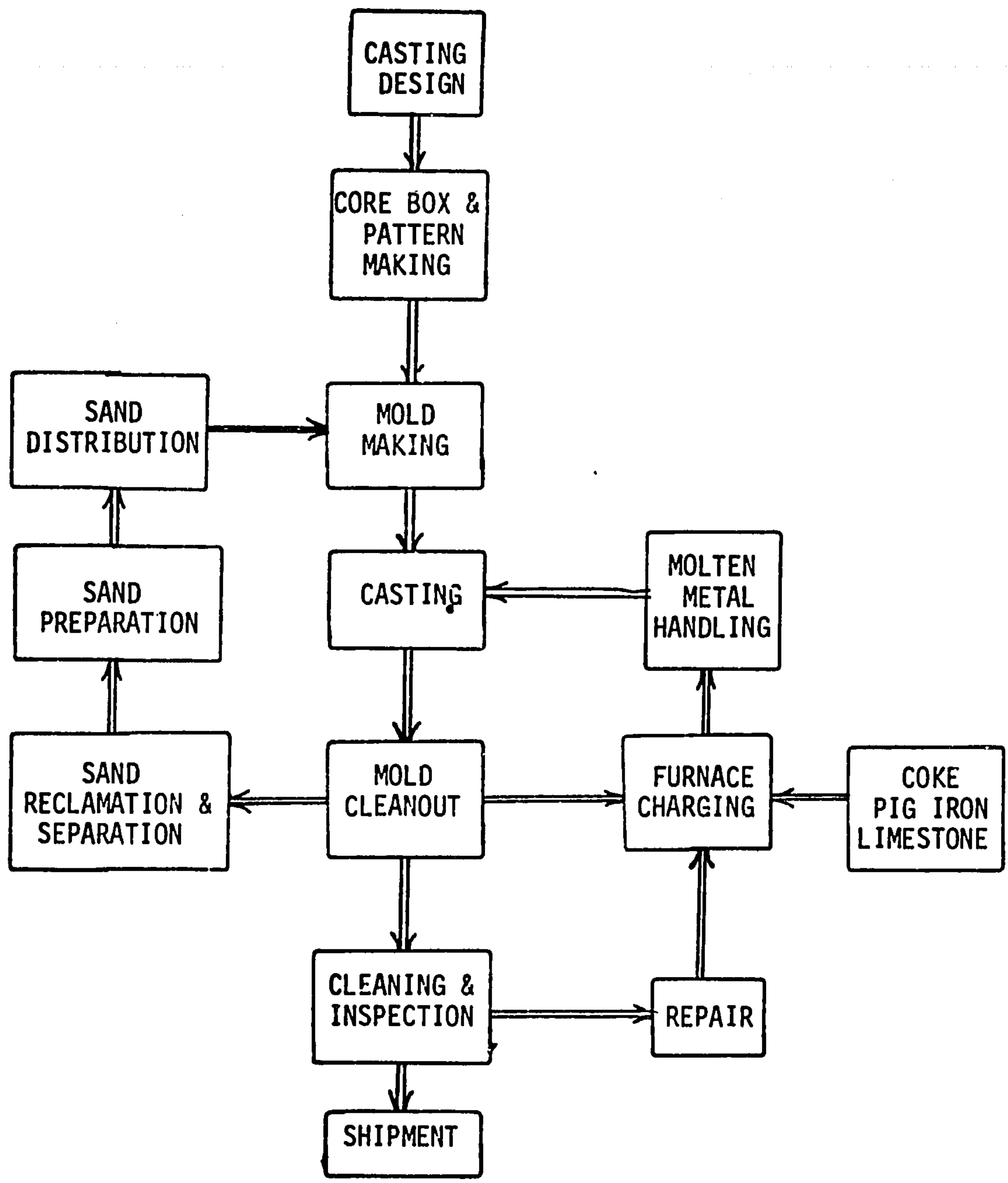


Figure 3 : Grey Iron Foundry Activities

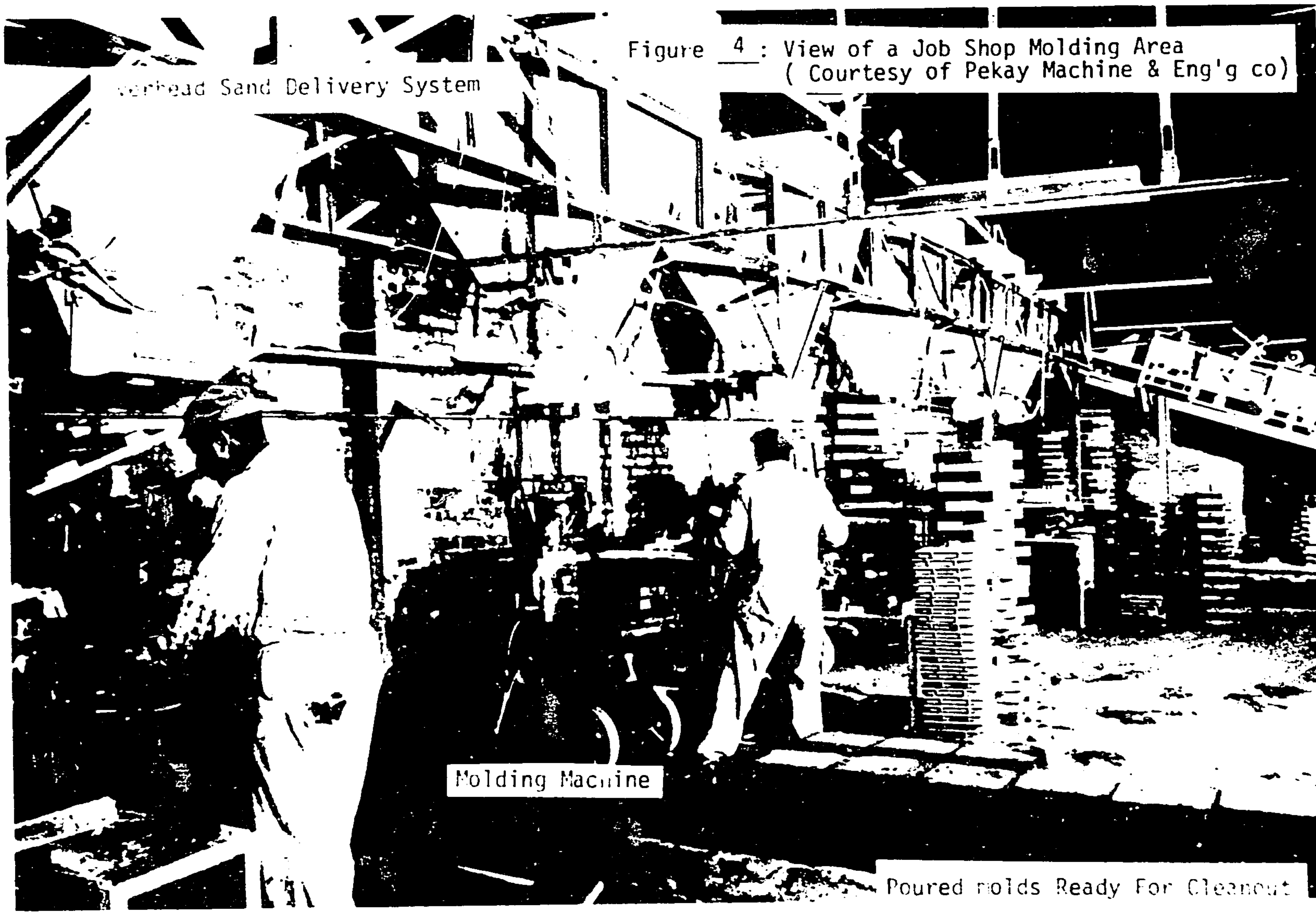
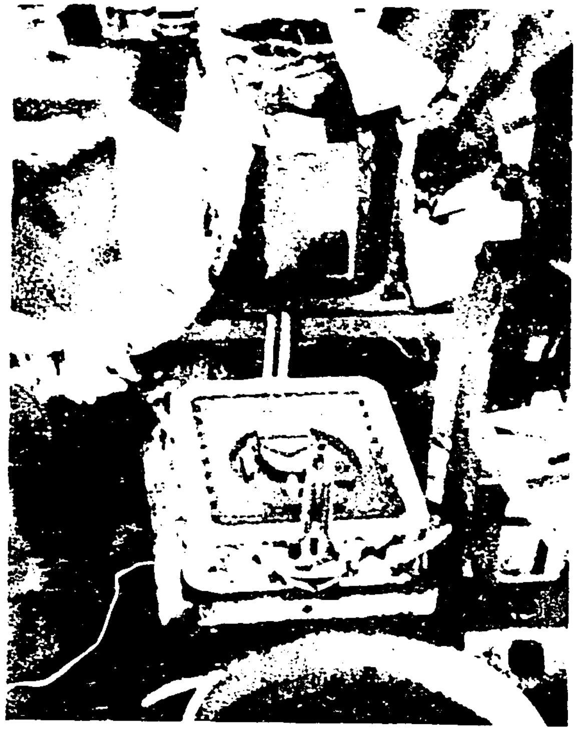


Figure 4 : View of a Job Shop Molding Area
(Courtesy of Pekay Machine & Eng'g co)

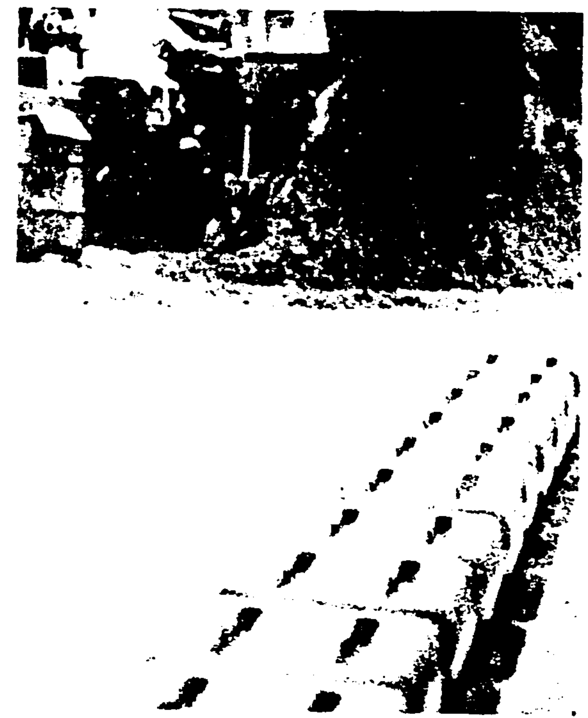
Matchplate pattern and Flask Mounted
on Molding Machine

Pattern Being Drawn From Drag Flask

Figure 5 : Sequence of Operations Required For Green Sand Molding - Marchplate Process
(Courtesy of Draper Div., Rockwell International)

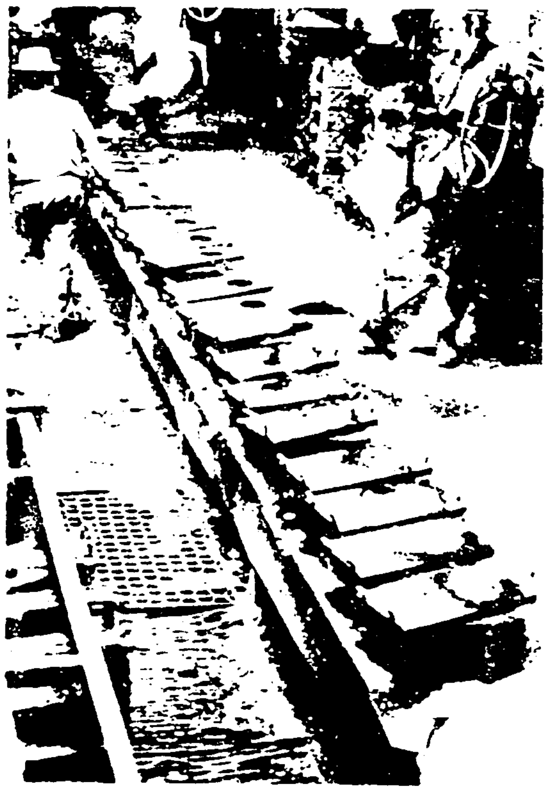


Cope Flask and Mold Being Placed Over Drag Flask and Mold. Note Cores (Light Pieces) in Mold



Completed Molds After Flasks Have Been Removed; Ready For Weights, Jackets, and Pouring

Figure _5_: Continued



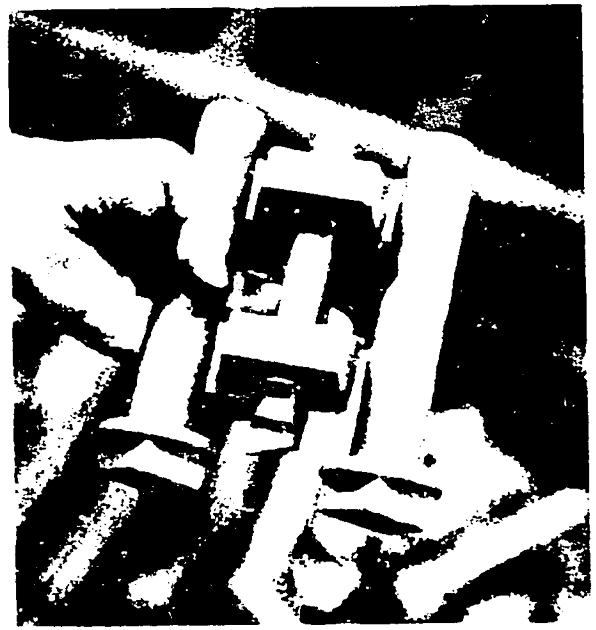
Molds Being Poured on a Mold Conveyor

Shakeout of Mold After Cooling

Figure 5 : Continued

Snagging (removing burrs) from
a Large Casting

Figure 5 : Continued



A Finished Casting

of materials get handled when considering the number of times the metal, molds, castings, and sand are moved. The principal materials involved are the sand and clay used in moldmaking, and the scrap, and pig iron (and limestone and coke for cupola melting). The materials handling systems determine in large part, the type of molding, pouring, and cleanout methods that can be used in a foundry.

Each of the principal foundry activities has a range of alternate methods by which the same operations can be accomplished. These alternatives tend to fall into two classes:

a. Alternative techniques that are required to satisfy specific design requirements (dimensions, surface finish, detail, etc.). These will be called alternate "process" technques.

b. Alternate techniques that can be applied to the same product and are selected as a function of quantity (total or lot size), skill levels and degree of automation. These will be called alternate "production" techniques.

This distinction between process and production alternatives deserves some clarification. Alternate processes or "process techniques" will produce different qualities in the finished product. They are determined primarily by specifications that appear on a blueprint. For example, a specification on surface finish will determine whether a part may be finished by milling or grinding.

"Production techniques" will be used here to describe alternatives which do not substantially influence the qualities of the finished product. They can be chosen independently from blueprint specifications, and are selected primarily to minimize cost for a specified production quantity. Efficient allocation of available equipment and skilled workers will also influence the choice between "production" alternatives. For example, a bench lathe, a turret lathe and an automatic screw machine represent the "production" alternatives for the manufacture of threaded fasteners. The appropriate "production" alternatives can be selected solely on the basis of a comparison of unit cost curves.

It is inherent in technologies, however, that different "production" techniques can more or less easily satisfy particular design requirements, and conversely, "processes" lend themselves to a specific level of production. While this distinction is valuable in appreciating when alternatives can be considered substitutes, and when quality considerations constrain the choice of techniques, it should by no means be considered a precise or exclusive classification system.

3.1.1 Pattern and Core Box Making

Patterns and core boxes are used to represent the shapes of the casting design. During molding, sand is rammed against the patterns and in the core boxes to produce the cavity in which the molten metal will be poured. The type of pattern selected is determined by the quantity of castings, the part complexity, and the type of molding process used. Since all the alternative pattern designs can produce the same casting qualities, only production alternatives exist in patternmaking.

The main production alternative is the choice of materials. This determines the lifetime (in molds) of the patterns. Table 1 lists common pattern materials and estimates of their durability and cost.

Table 1: Pattern Materials

	Metal	Plastic	Wood
Material:	Al & Fe Casting Fe & Steel Machined	Epoxy Resin Polyurethane	Cherry, Cedar, Maple Cypress, Mahogany
Production Lot:	10,000+	500+	1-500
Maximum Durability: (in molds)	50,000+	10,000+	1,000
Cost Comparison:	12-20	3-5	1

Source: References 1 and 2

Within these general classifications, there exist a wide variety of composite designs to satisfy a specific requirement.

The other major influence on pattern design is the molding method used. The molding system specifies the mounting arrangement of the pattern (as well as often limiting the material choice). Hand molding methods can be used equally well with a variety of pattern designs, but Matchplate and cope and drag lines require specific pattern mountings. Matchplate patterns have half the part reproduced on each side of one pattern plate and are usually metal or metal backed. Cope and drag lines use separate patterns for the top (cope) and bottom (drag) portions of mold. This requires some additional effort in making and rigging the patterns to the molding machines. Semi-automatic and automatic molding methods usually require specially designed patterns, or at least special rigging for existing Matchplate or cope and drag patterns. Figures 6 and 7 illustrate these different pattern designs.

3.1.2 Moldmaking

Process Alternatives

There are several competitive molding processes available for making iron castings. The one common feature of these methods is that they use sand to take the shape of the pattern.

a. Green Sand Molding

The traditional, and most widely used, process is green sand molding. Over 85% of iron castings currently produced (U.S., 1972) are made by green sand molding. A mixture of sand, clay, and water (3-10%) is compacted against the pattern surface to form the shape of the casting. The process is relatively simple, flexible and suited to a wide range of production levels.

b. High Pressure Molding

High pressure molding is a variation of green sand molding in which the molding sand is compacted at high pressure (above 80-100 psi) to improve the dimensional accuracy and surface finish. The high pressures involved

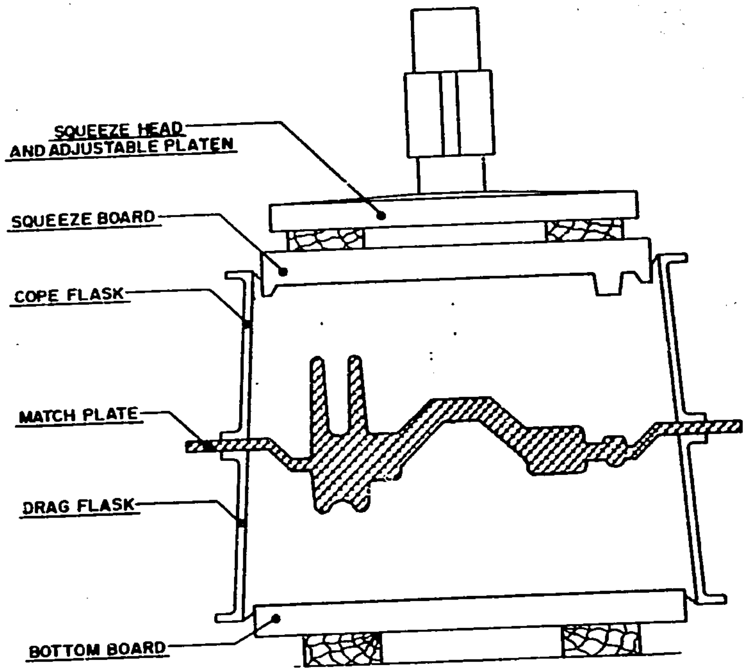


Figure 6 : Arrangement of Matchplate Pattern and Flasks

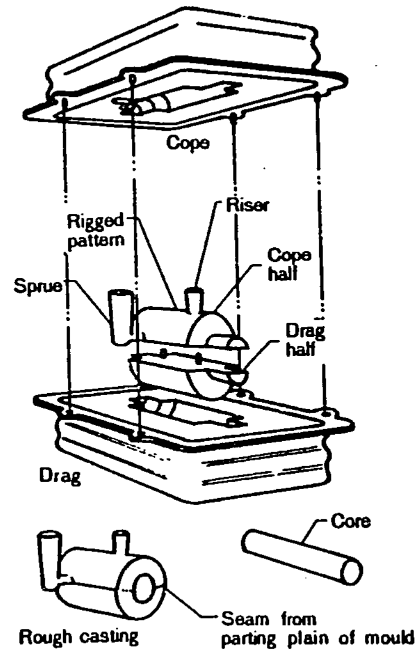


Figure 7 : Arrangement of Cope and Drag Patterns and Flasks(1)

require pneumatic or hydraulically powered compaction and limit the choice of molding equipment.

c. Floor Molding

Floor or pit molding is another variation of green sand molding used for making large castings. The mold is made directly on (or in) the floor of the foundry, and molten metal is brought to the mold for pouring. Dried green sand, chemically bonded sands, or even brick and cement are used to form the mold surfaces. Floor molding is typically performed by hand methods, though sand slingers can be used to deliver and ram the sand (the slinger literally "slings" the sand into the mold and the energy required to compact the sand is provided by the sand itself).

d. Chemically Bonded Sand Molding

A different set of alternatives to green sand molding are the methods based on chemically bonded sands. They differ from the above techniques in that the mold material <u>sets</u>, and does not require compaction. The bonding agents include sodium silicate, portland cement, and solid and liquid resins. The chemically bonded processes permit thinner sections and improve mold stability before and during the pouring operation. Pattern drawing (removed from the mold) is also facilitated and the risk of mold breakage is reduced.

The low skill requirement makes chemically bonded methods attractive for LDCs. However, the materials mixing and recycling equipment tend to be more expensive than green sand molding equipment, and the gases released during setting create an environmental problem. However, furfyl alcohol, the principal ingredient in one chemically bonded process, can be manufactured from bagasse, corn cobs and other agricultural "wastes". It is possible that low materials costs and skill requirements may combine to make chemically bonding molding economically feasible for LDCs. These processes are, however, relatively new and their economic advantage over green sand molding has not been clearly demonstrated.

Finally, it should be noted that chemically bonded techniques do not represent <u>purely</u> process alternatives. For example, at very low production quantities, chemically bonded techniques may be justified for large mold sizes by the reduction in set up costs achieved. The reduced skill requirement, mentioned above, also represents a "production" rather than a "process" variable. The distinction between process and production alternatives is less than perfect in this case.

Production Alternatives

The production alternatives for moldmaking fall into two general classes: tight flask and "flaskless" molding. The flask is a foursided (or occasionally round) metal or wood frame that forms the sides of the sand mold. It is secured to the pattern, and filled with sand which is then compacted by hand or machine. In tight flask operations, the flask remains with the mold during the mold handling, pouring and mold cooling periods. In flaskless molding, specially designed flasks called slip, pop, or snap flasks are removed and the sand mold is transferred to the pouring area on a bottom board.

One variant of flaskless molding--vertically parted flaskless molding developed by Disamatic, Inc.--requires no flasks, jackets or weights. The Disamatic equipment, however, is expensive and suited to long production runs in a restricted class of casting sizes. While the flaskless method reduces the inventory of flasks, jackets are required to support the mold during the pouring operation. Figure 8 illustrates a tight flask molding operation. Figures 9 and 10 illustrate an automated flaskless molding operation. The Disamatic vertically-parted flaskless system is illustrated in Figure 11. A range of hand, simple machine, and automated production techniques are available for both tight flask and flaskless molding methods.

3.1.3 Core Making

Cores fill cavities inside cast parts. They reduce casting weight and therefore cost. The influence of core making techniques on casting qualities is negligible and the alternatives may all be considered production techniques.

Since cores are supported at only one or a few locations in the mold, they require greater strength than the mold itself. The traditional method of making cores consists of ramming a mixture of sand and linseed oil in a core box, and baking the core in an oven for several hours. The core pieces can be then pasted together to form the complete core assembly. Often reinforcing wires are needed to keep the core from breaking during core placement and the

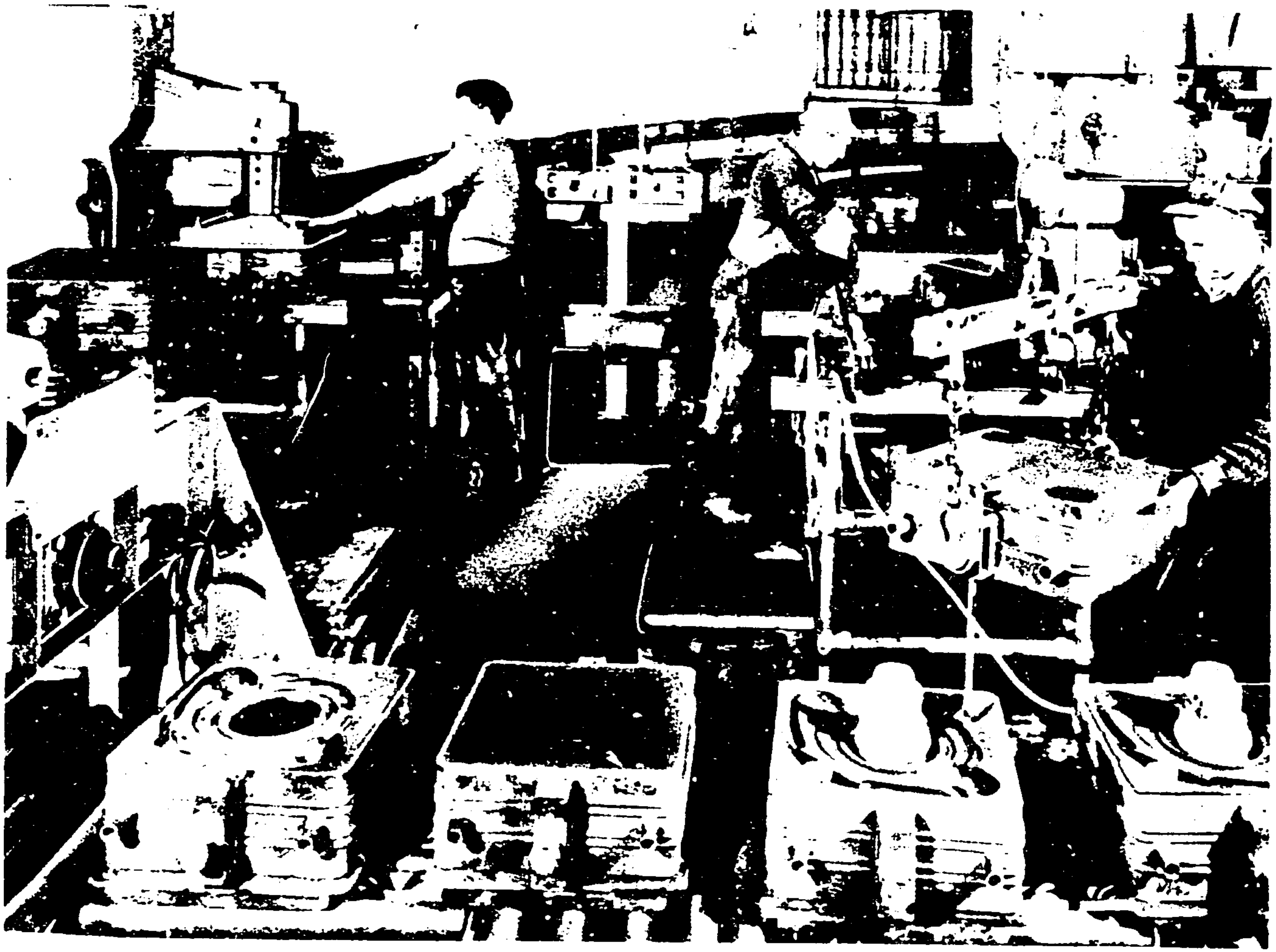


Figure 8: Tight Flask Molding Operation (Courtesy of BMM, Inc.)

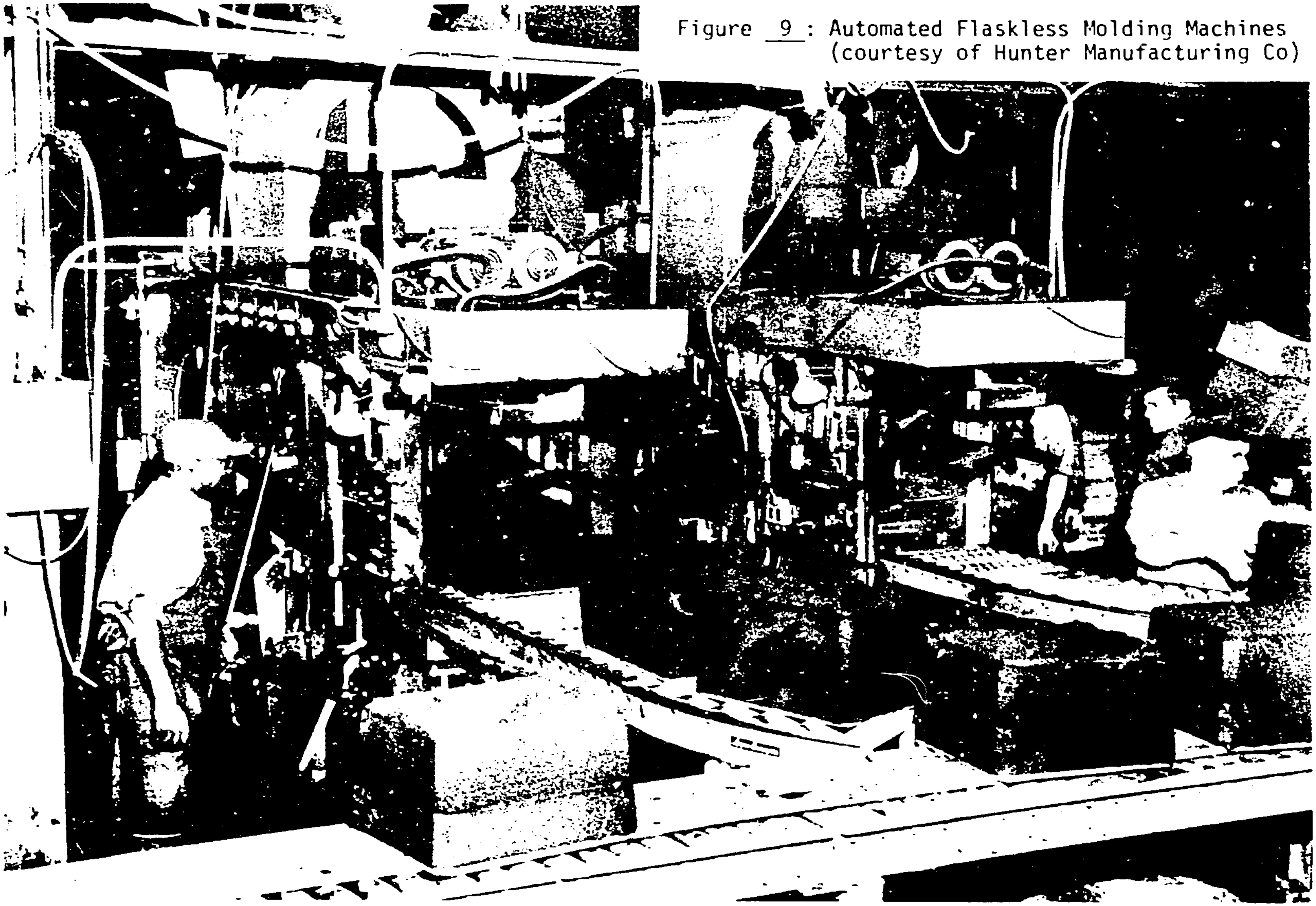


Figure 9 : Automated Flaskless Molding Machines (courtesy of Hunter Manufacturing Co)

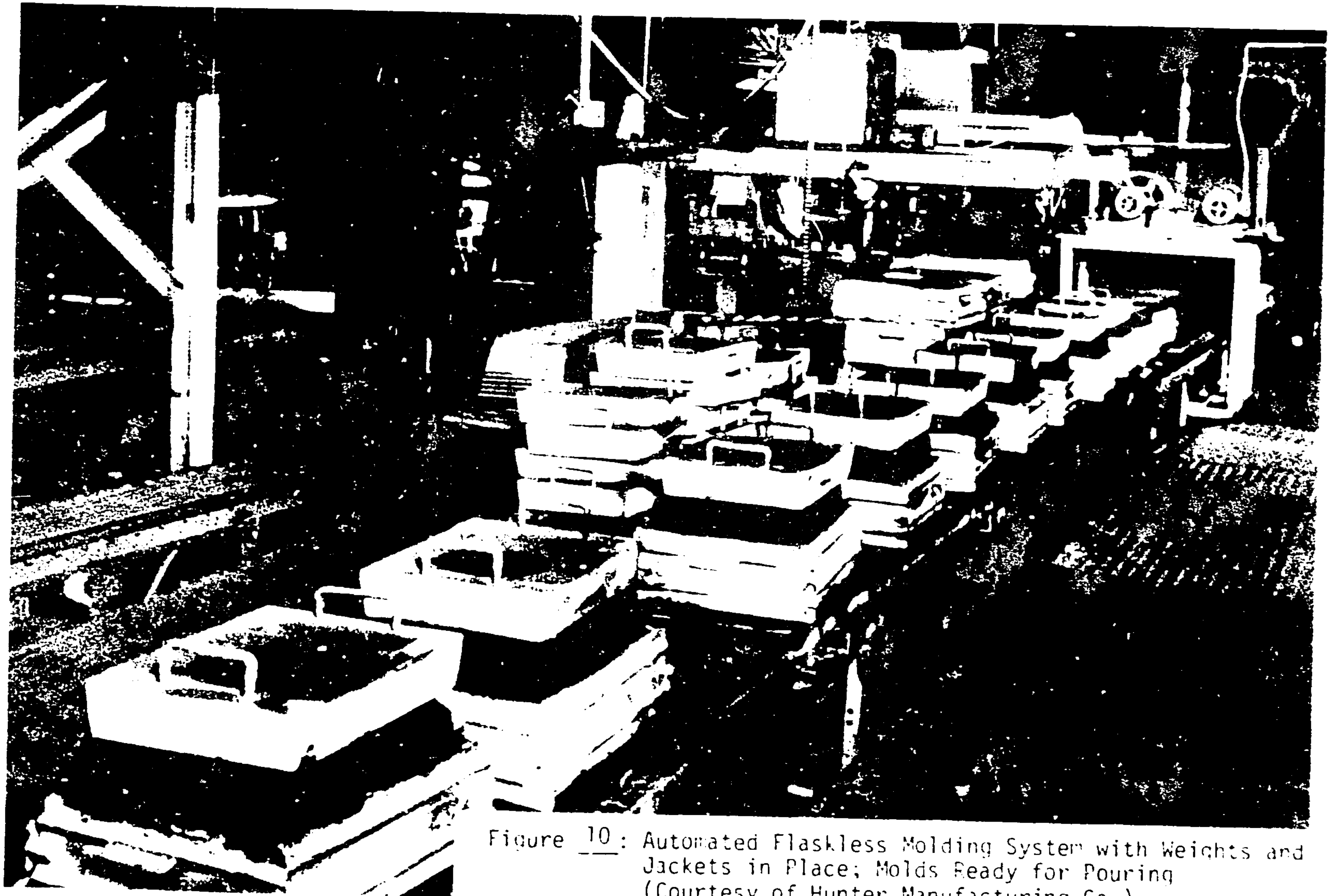


Figure 10: Automated Flaskless Molding System with Weights and Jackets in Place; Molds Ready for Pouring (Courtesy of Hunter Manufacturing Co.)

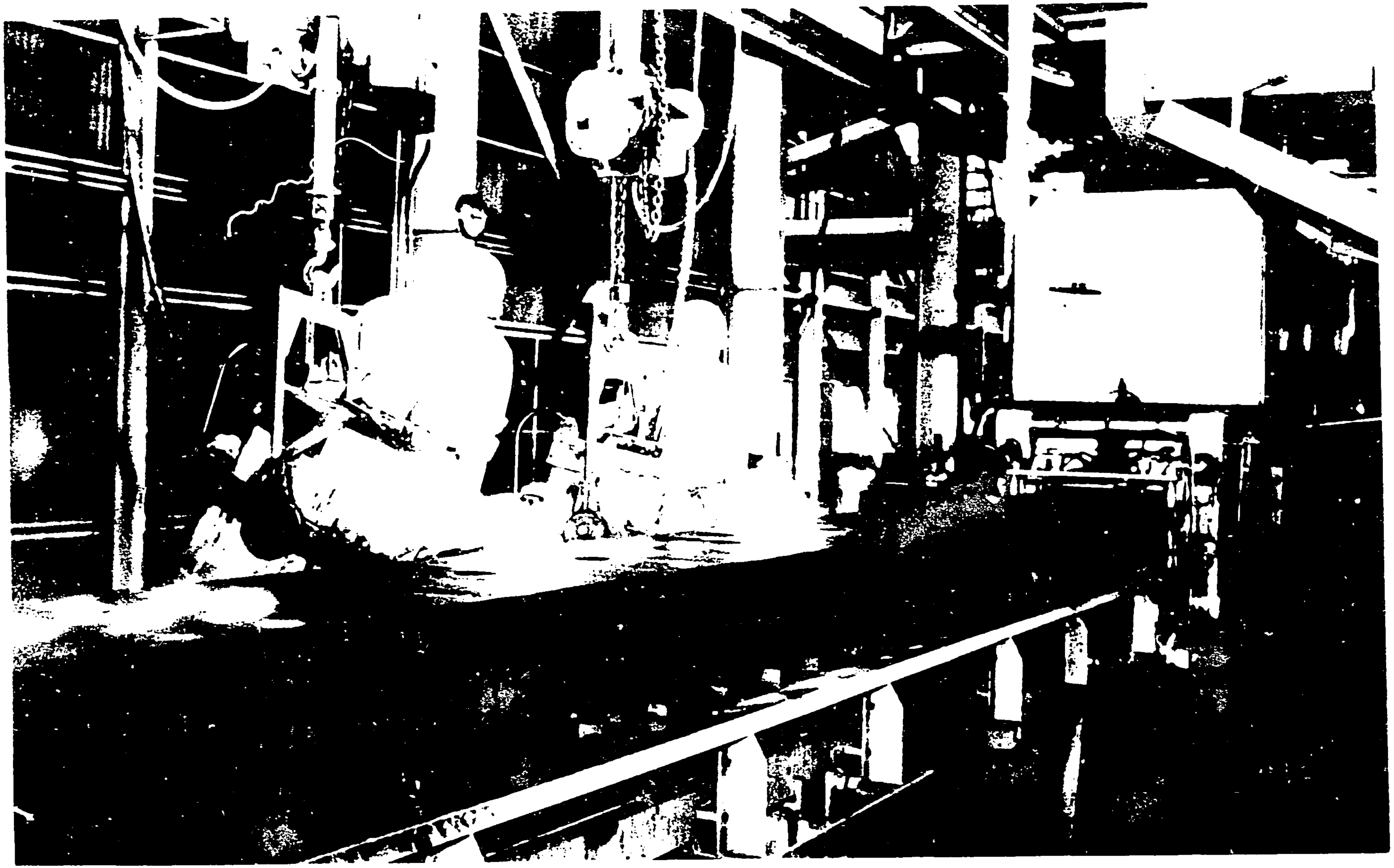


Figure 11: Automated Flaskless Molding System (Courtesy of Disamatic, Inc.)

pouring operations. This method is labor intensive and requires a high degree of skill.

Recently, chemically bonded sand techniques have gained wider acceptance in core making. High labor cost and scarcity of skilled labor have combined with the environmental and energy costs associated with baking linseed oil cores to make chemically bonded sands more attractive. The choice between two principal chemical techniques, the CO_2 process and phenolic resins, is based primarily on specific production requirements, though casting design is also considered. CO_2 processes are inert and do not have a disposal problem like the phenolics. However, CO_2 bonded cores do not store as well and removal from the poured casting is considerably more difficult than with phenolic based methods.

3.1.4 Sand Handling: Reclamation, Preparation, and Distribution

As mentioned above, sand represents the most significant materials flow in a foundry. The types and grain sizes of the molding sands directly influence the quality and surface finish of the cast product. The techniques by which the sand is handled in a foundry directly influence the molding, and mold handling systems and the general plant layout. The types of sand and additives used represent process alternatives. The types of processing and transport equipment selected represent production alternatives.

The two types of sand used in green sand molding are naturally bonded sands and "synthetic" sands in which silica sands and clay (bentonite) are mechanically mixed together in the foundry to produce a formable green sand. Availability limits the usage of naturally bonded sands, and the U.S. foundry industry depends overwhelmingly on synthetic sands. European foundries still use naturally bonded sands, but synthetic sands which permit more precise control of grain size and sand/clay ratios represent a more progressive, scientific approach to the foundry "arts".

To the basic sand, clay, and water mixture, additives are often mixed to produce desirable properties. Seacoal and pitch are commonly used to improve the surface finish of grey iron castings, and silica flour is used to improve the hot strength.

Sand qualities of interest in casting are:

1. Flowability during molding
2. Green strength (as molded)
3. Dry strength (when the molten metal is flowing)
4. Hot strength (as the liquid cools)
5. Permeability (ability to release gases)
6. Thermal stability (dimensional stability when heated)
7. Refractories (resistence to melting, sticking, or softening during pouring.
8. Grain shape: round, angular, subangular (will affect all properties above)

The sand handling cycle begins when the casting is removed from the cooled mold. Before the sand can be used to make another mold, any iron scrap must be removed, and lumps of molding or core sand crushed. The green strength must be restored by mixing water (and additives as needed) with the sand. The prepared sand must then be distributed to the molding stations. Figure 12 illustrates three levels of mechanization in sand processing equipment, and suggests the range of "production" alternatives available.

All the sand handling operations may be performed by hand, batch or continuously operating equipment. The iron scrap is removed by screening or magnetic separating conveyors. Rotary screens can be used to remove any lumps, though often these are not necessary. The key to the sand processing is the mixing or "mulling" of the sand, water, and any additives to restore the green strength to the sand. Figures 13 and 14 illustrate alternative methods of mulling.

3.1.5 Metal Melting

The selection of the furnace is largely dependent on the raw materials and power available, the volume of production, and any environmental requirements. The influence in casting quality of the alternative furnace designs is minimal and the cupola, induction and electric arc furnaces can be considered "production" alternatives.

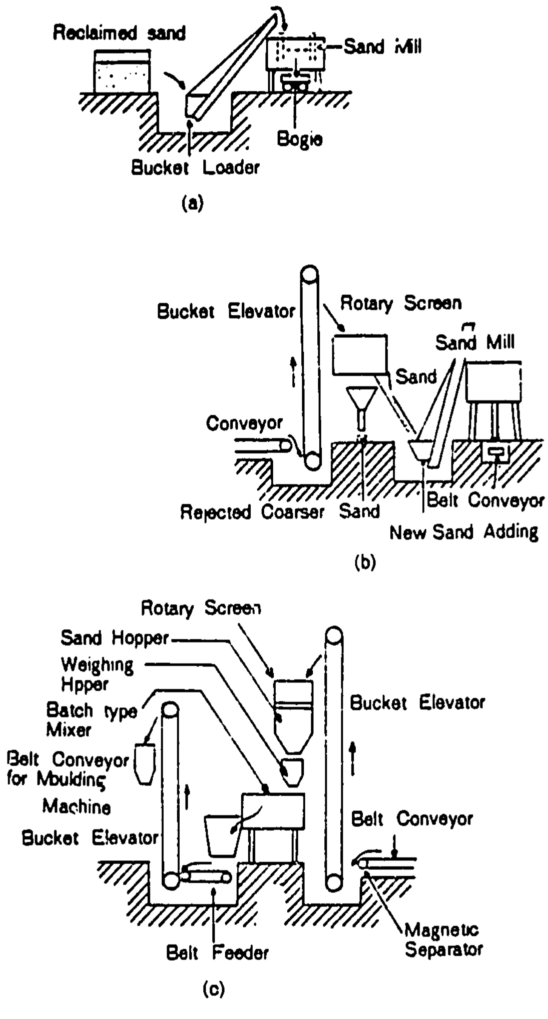
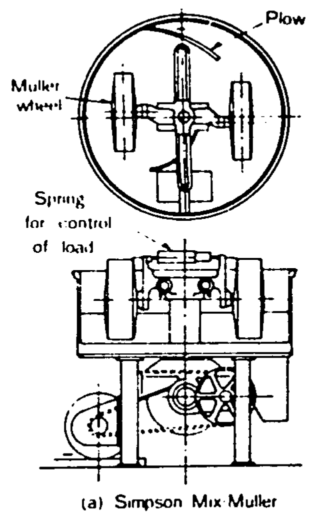
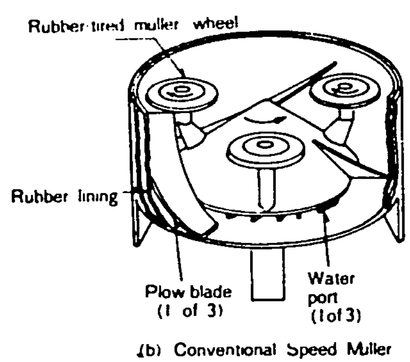


Figure 12 : Three Types of Sand Conditioning Plants(1)



(a) Simpson Mix-Muller



(b) Conventional Speed Muller

Figure 13: Modern Mulling Machines

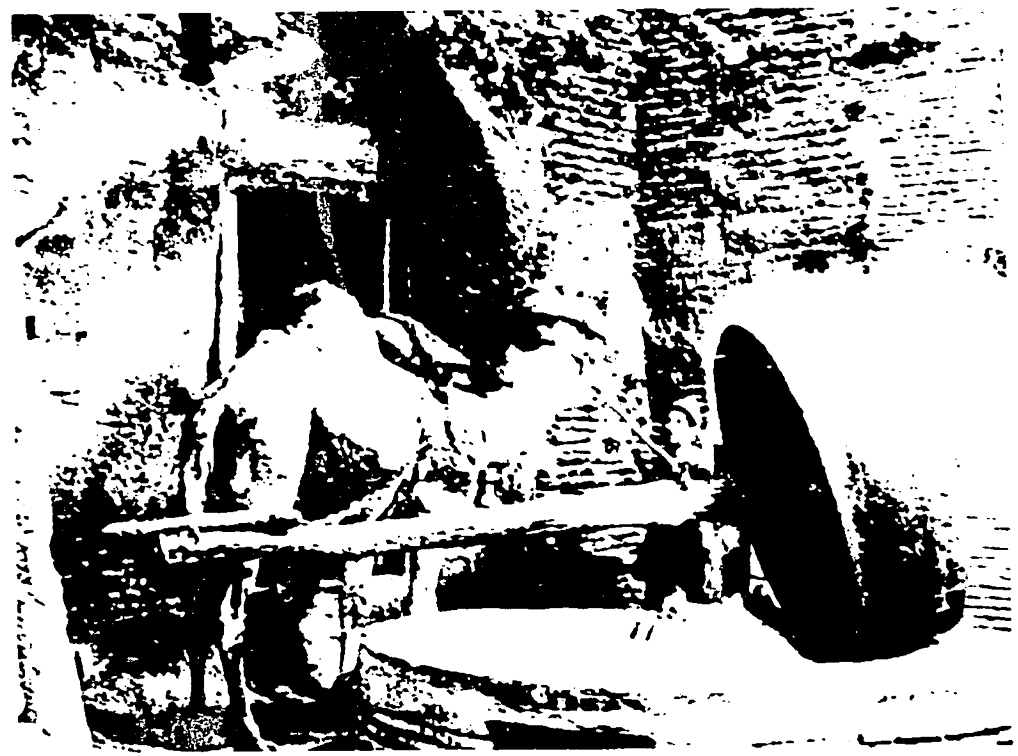


Figure 14 : A Traditional Method of Sand Mulling

The cupola is the traditional furnace design for foundries. It is simple, straightforward, and easy to operate and control. Basically, it is a tall, vertical cylinder lined with refractory materials. It is charged alternately with coke, limestone (to aid slag formation), and pig and scrap iron. A typical charging arrangement and general geometry of the cupola are presented in Figure 15.

The major problem with cupola melting is the large amount of particulate and chemical pollutants released to the atmosphere. To help control these, air pollution equipment, usually more expensive than the cupola itself, is being required in the U.S. and elsewhere. To eliminate the environmental and fuel handling costs, and to improve the quality control of the melt, induction and electric arc furnaces have become popular in foundries. Induction furnaces have lower melting rates than electric arc furnaces, but are virtually pollution free. Depending on the operation and raw materials, electric furnaces may or may not require air pollution equipment. A comparison of the characteristics of cupola and electric melting is presented in Table 2.

3.1.6 Cleanout, Casting Cleaning and Inspection Alternatives

After the mold has cooled, the casting must be separated from the molding sand, excess metal and coring removed from the casting, and the casting cleaned and inspected. The cleanout and casting cleaning do not influence the casting qualities to any great extent and hand, mechanized and automated "production" alternatives are available. The selection of the specific alternatives is largely constrained by the design and production rate of the mold making and handling systems. Inspection techniques are selected in accordance with design specifications and the visual, acoustic, or x-ray techniques represent "process" alternatives.

A typical mechanized casting cleaning system performs the following operations:

1. The casting is removed from the flask at a "punchout" station on the mold handling conveyor.

2. The castings pass over a vibrating grate to remove mold and core sand.

Characteristic	Cupola: Conventional	Cupola: Water-cooled, hot-blast	Coreless induction furnace	Arc furnace
Type of operation	Continuous	Continuous	Cont. or batch	Batch
Shape	Cylinder	Cylinder	Cup	Saucer
Source of energy	Coke	Coke and gas	Electricity	Electricity
Meltdown efficiency	60 to 70%	50 to 60%	70%	80%
Superheat efficiency	5 %	5 %	70 %	20 to 30 %
Refractories	Acid	Carbon or base	Acid	Acid or base
Slag chemistry	Acid	Acid or ase	Acid	Acid or base
Control of composition	Fair	Fair	Excellent	Excellent
Control of temperature	Fair	Good	Excellent	Excellent
Capital cost, installed, $/ton/hr	$10-20,000	$40,000	$60,000	$60,000

Table 2 : Comparison of Melting Equipment For A Grey Iron Foundry(1)

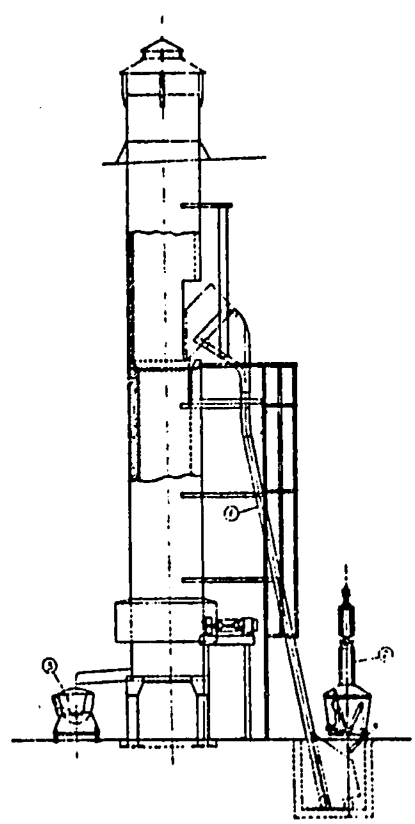


Figure 15: Charging Arrangement For A Cupola - Skip Charger 1, Weigh Lorry 2, Holding Ladle 3.(14)

3. Gates, risers, and flashing are removed by flame cutting, metal saws or grinders.

4. The casting is sand or shot blasted to clean its surface.

5. The part is inspected and prepared for shipment.

Scrap rates vary between 5 and 10% with well controlled, high quality foundries somewhat lower, and less controlled, lower grade iron producing levels somewhat higher. Gates and risers account for roughly 50% of the poured metal, and the yield of finished parts is approximately 40-45% of the metal charged at the furnace. With larger castings the yield may approach 60% of the metal poured.

3.2 Technological Progress in Green Sand Molding

The following comments focus on changes in the U.S. foundry industry. When relevant, the appropriateness of these changes for LDCs is also considered.

The demand for cast products is intimately linked to industrial growth. The ability to produce large intricate, medium strength shapes with good machining and wear properties at costs much lower than forged or machined from stock parts insures the future of iron castings. The major failing of grey iron, its susceptibility to fracture, has been partially overcome by the malleable and nodular grades, and increased quality control in grey iron. In weight sensitive areas, light alloy castings and plastic have provided recent competition, but cast iron is still dominant in the production of machine bases and frames, housings, pipe, fittings, etc.

While the basic operations of green sand molding have remained unchanged during the last several decades, the increased use of molding machinery, materials handling equipment and industrial engineering have significantly altered the organization, investment, and labor skill requirements. In early U.S. iron foundries, simple bench and floor molding methods were used. The molds were poured and broken out on the floor. Sand was prepared on the floor, shoveled and transported back to the molding stations.

The major stimulus for technical change has been from:

1. Increased demand for castings

2. High cost and scarcity of skilled labor

3. Improved casting qualities

4. Increased cost of raw materials

Traditionally, metal was poured once a day. With mechanized mold and sand handling, all reusable materials can be recycled every two hours.

3.2.1 Moldmaking

The most significant innovation in molding in the last thirty years has been the Matchplate molding. Inexpensive pattern design and high production rates for small and medium sized castings have resulted in widespread use of Matchplate mo˙ding in both production and jobbing foundries. Automated Matchplate and other flaskless molding methods have been developed to satisfy the demand for high quantities of small and medium sizes in the automotive, plumbing supply and heavy equipment industries.

Automatic cycle control of cope and drag lines has been applied to the larger flask sizes to provide mechanized molding and handling of heavy molds. Automatic cycling is efficient for even small production levels, but is not widely used in jobbing foundries. Large scale, fully automated tight flask molding lines have been developed for larger flask sizes over the last twenty-five years. With investments of several million dollars, requiring 10 or more tons of metal and 100 or more tons of sand per hour, the actual moldmaking operation becomes a small part of the automated materials processing system.

3.2.2 Mold Handling

Production foundries invariably have some methods for mechanically handling the molds (compare the molding conveyor systems illustrated in Figures 1 and 2). Mold handling systems have evolved over the last several decades from hand placement of the molds on the floor of the shop for pouring, to sections of roller conveyor connecting the molding stations with a pouring area, to most recently powered pallet conveyor loops that bring the molds to the pouring station and return the empty flasks to the molding machines. Jobbing foundries currently operate with any and all of these handling systems.

3.2.4 Sand Handling

To handle the higher volumes of sand needed and to increase control over its properties, "synthetic" sands and mechanical ing have been adopted.

Magnetic separation has been combined with screen separation for better quality control, and front loaders and conveyors have replaced the wheelbarrow for sand delivery in all but the most primitive shops. Overhead sand delivery is now widely used, primarily for the increase in productivity it provides for the moldmaking activity.

Technological changes should not obscure the fact that sand handling represents a foundry activity with straightforward labor substitution possibilities. Any and all of the sand reclamation, preparation and distribution tasks may be performed by hand or simple manpowered equipment, and prevailing labor rates will directly determine what equipment alternatives are selected. Most foundries in Iran, Pakistan and India, for example, use no material handling equipment at all. The alternatives for sand handling will be discussed further in the next section.

3.2.4 Metal Melting

The major change in the melting activity has been the reduction in the movement of the molten metal. The need to bring molten metal to the molds is gradually being eliminated by mechanized mold handling. This improves quality by more accurately controlling the pouring temperature, eliminates auxiliary pouring equipment, and reduces the pouring manpower required. Required air pollution equipment has generated a significant cost increase in operation of a cupola and it is unlikely that new cupolas will be installed in the U.S. A final judgment on the future of metal melting alternatives will depend on permissible particulate and gaseous emission levels and the prices of coal and other energy sources.

3.2.5 Quality Control

Improvements in quality control have resulted from greater demands on the performance of cast parts and are directly linked to the increased automation of foundry operations. Measuring the strength of green sand by feel and the temperature of molten iron by eye are no longer satisfactory. Closer tolerances on the sand properties are necessary for the automated high pressure molding systems. Sand quality, grain size and strength are measured both in the handling equipment and in the quality control laboratory. Spectrographic analysis of the melt is common in production and jobbing foundries alike, and pyrometers are used regularly to measure the metal temperature. Improvements in quality control have reduced scrap and returns, increased equipment productivity and improved the casting quality. It is an essential part of any foundry mechanization program.

Production shops have led the way in automation. Jobbing shops, needing more flexibility with shorter runs and a wider variety of pattern requirements, have been slower to mechanize. Many (in the New England area) have no mechanical mold handling, and sand remains on the floor except when it is shovelled into the molds.

3.3 Identification of Areas Where Technical Choice is Greatest

In designing foundries for LDCs, it is important to identify foundry activities which could be modified from current design practice to better suit the labor, capital, and materials resources of the area. This requires an understanding of the alternate techniques available (or possible) which accomplish the same tasks with a different mix of economic resources. These alternatives are based on:

1. Existing competitive methods.
2. Methods that are competitive at different production levels
3. Methods suitable with acceptable changes in the product specification
4. Historical methods no longer employed
5. Innovative methods specially designed to make use of the local resources most efficiently - "intermediate technologies"

From these alternatives, methods are selected to produce castings at the lowest real cost. For a private enterprise, the real cost might be based on local wages, import tariffs, etc., while a regional or national planning organization would consider "shadow prices" and national development goals in determining costs. As a cautionary note, only ideally do strictly comparable alternatives exist. Real methods invariably alter or bias the production activity, making it more attractive for one set of requirements and less for another. Our objective here is to identify areas in which a quantative analysis of substitution possibilities is feasible.

Substitution possibilities are easier to compare in materials handling activities since they do not influence the nature of the product to nearly the degree that the actual materials processing activities do. Unfortunately, they are also more sensitive to the design and layout of the individual foundry.

In most of the required activities of a foundry, there are limited opportunities for capital-labor substitution. Patterns require a great deal of handwork, the costs are sensitive to part complexity and pattern materials; they require a high level of skill, and there are few alternative methods. The actual techniques used to make patterns are machine shop activities. It is not unusual, and typical of small job shops, to have no pattern making facilities at all.

The melting operation also has limited alternatives since the demand for metal is determined by the mold production and the mold handling systems. The alternate methods of melting are limited to cupola or electric furnaces in foundries of commercial size. With either design, there is little opportunity for labor substitution. The cupola does require charging with pig iron and scrap, coke, and limestone, and this operation can be performed by hand, wheelbarrow, bucket loaders or automatic conveyor. The impact on foundry employment, however, is small.

The molten metal handling system does have some basic alternatives. In the simplest, least mechanized foundry design, the molten metal is transported to the molds by ladles suspended from the cranes or carried by hand. In automated foundries, a mold handling conveyor brings the molds to the melting system. The alternatives again. are largely determined by the molding and mold handling systems.

Casting cleaning and finishing activities can be performed by mechanized systems or labor intensive methods (though cleaning operations are rarely performed solely by hand). Grinding and cutting of gates, risers, and flashing, sand or shot blasting, finish machining, painting, etc. all require investment in equipment. The types of operations and the effort required are determined by the product specification, pattern design, and molding method. While the options are less restricted than with the pattern or melting activities, the problem of identifying and comparing equivalent alternatives is greater as the actual operations to be performed tend to be product specific.

3.3.1 Sand Handling

All the sand handling operations:

1. Mold Cleanout
2. Tramp Metal Separation
3. Mulling and Aeration
4. Distribution of Sand to Molding Stations

can be performed by hand, simple machinery or fully automated systems. There are virtually as many alternate methods as there are foundries. To demonstrate the range of alternatives, Table 3 presents three alternatives for these operations, employing hand, "mechanized", and automated methods.

While a wide range of sand handling methods can be designed, a quantitative model of sand handling would encounter several difficulties. The plant layout, the floor space available and the location and accessibility of the molding equipment will greatly influence the times required to perform these operations. Also the flexibility of the sand handling system is greatly reduced with increasing automation. The requirements of mulling and aeration are dependent on the cycle time of the sand, amount of drying during the mold cooling period, and characteristics of the locally available sands. These limitations do not imply that a quantitative model for materials handling alternatives could not be constructed. On the contrary, there is every reason to expect that a realistic and informative analysis can be made. The problem is that any model of sand handling would be more characteristic of granular materials handling in general than of a specific foundry process that is the present research objective. Finally, the substitution possibilities in sand handling activities are relatively straightforward, and as mentioned above, many foundries in LDCs already fully exploit this opportunity for expanded employment.

3.3.2 Moldmaking

Moldmaking represents an activity in which a wide range of labor substitution possibilities exist. In small job shops, over 50% of the labor force is involved with the molding activity, while in an automated shop, no molders exist, per se. As a material processing activity, it is less related to problems in plant layout. It is somewhat easier to isolate from the other foundry

	HAND	MECHANIZED	AUTOMATED
Sand Cycle Time	once/day	once/day	30 minutes
Tramp Metal Separation	1/4" mesh screen and shovel	magnetic	magnetic
Mulling and Aeration	watered, mixed and riddled on floor	batch muller	continuous or batch muller
Distribution of Green Sand	shovel and wheelbarrow	front loader transports to molding station c/b overhead	overhead sand conveyor and chutes

Table 3: Typical Hand, Mechanized, and Automated Sand Handling Alternatives

activities. As data on equipment costs, manpower requirements and productivities proved to be available at minimal cost, moldmaking was selected as the topic of a quantitative evaluation of the substitution possibilities in foundry activities.

3.3.3 Coremaking

The traditional oil sand method of coremaking has many of the same operations required in moldmaking and the opportunities for K/L substitution should be comparable. However, recently developed methods including shell coring, the CO_2 process, resin binders, etc. are being widely used in U.S. foundries. Increased materials and equipment costs have been offset by reduced skill and handling requirements and the elimination of baking ovens. For large cores, resin binders reduce the danger of breaking the core during handling or core placement in the mold. These advantages are difficult to analyze quantitatively, however, and depend on the availability and cost of the resin/sand mixtures, and the size and complexity of the part. For these reasons, it was decided to exclude the core making activity from the equipment selection model.

4. A QUANTITATIVE MODEL FOR EVALUATING ALTERNATIVE MOLDING METHODS

The objective of the Equipment Selection Model is to determine what types of foundry equipment are most suited to the economic conditions of developing countries. The model is restricted to the moldmaking activity as this represents a major potential source of employment, is relatively independent from the other foundry activities and plant layout, and a wide range of alternatives are available.

The model requires the following:

1. An understanding of the moldmaking operations and development of a set of alternate production methods to perform them.
2. Identification of the major costs associated with moldmaking.
3. Development of a data base for the costs associated with each alternative production method.
4. An analytic method for optimizing the selection of molding equipment under the range of economic conditions existing in LDCs.

Underlying the classification and evaluation of this set of alternatives are a number of assumptions, some fundamental to process and activity analysis, and some unique to foundry operation. A discussion of the most important assumptions is included at each phase of the model construction.

4.1 Selection of the Alternate Production Methods

The following is an outline of the operations required to make a green sand mold.

Moldmaking Operations

1. Pattern and flask placement
2. Cope ramming and pattern draw (removal)
3. Drag ramming and pattern draw
4. Drag rollover
5. Core placement
6. Mold closing
7. Mold removal

These operations can be performed by hand, manually or automatically controlled machines. Simple machines usually replace hand ramming or pattern drawing as these represent physically arduous, and time-consuming work respectively. Manual operations on typical automatic cycle machines are limited to flask placement and mold removal. Automated molding methods require operators only for maintenance, inspection and pattern changes.

Based on past and current practice in foundries and new equipment available, seven different basic alternatives can be identified. The evaluation of the substitution possibilities in the moldmaking activity will be based on this set. They will be presented and discussed briefly here. A more complete description of how these methods perform the moldmaking operations, and the associated costs is presented in Appendix C, Data Development.

Roughly according to increasing capital investment, the alternatives are:

1. Hand Methods (Bench or Floor Molding)
2. Simple Machine Methods (Jolt or Jolt/Squeeze Machines)
3. Operator Controlled (O/C) Cope and Drag Methods
4. Automatic Cycle (A/C) Cope and Drag Methods
5. Sand Slingers
6. Automated Flaskless Methods
7. Automated Tight Flask Methods

The first four methods represent the range of equipment typically found in U.S. jobbing foundries today. The last three are methods currently restricted to the longer runs found in production shops.

For each of these alternatives, a wide range of equipment sizes exist. Since it is not feasible to investigate the entire range of mold sizes (and the specific equipment design optimally suited to produce each of them), mold sizes of 12 x 12 x 4/4 to 36 x 48 x 16/16* have been selected as limits for the model and reflect the overwhelming bulk of the demand for cast products. Where possible a representative set (three or more) of sizes for each of the seven alternatives, but the choice is somewhat restricted by design for the more automated models.

*The dimensions in inches represent:

flask length x flask width x cope depth/drag depth

4.1.1 Hand Methods

These techniques perform the seven moldmaking operations entirely by hand. For smaller sizes, these operations are performed on a work bench; larger sizes are molded on the floor. Three sizes have been selected (Methods #1, 2, 3) representing what one molder could handle on a bench by himself (16 x 16 x 6/6), with a helper (24 x 24 x 8/8), and on the floor with a helper (36 x 48 x 16/16).

A common equipment addition to purely hand methods are a range of hand operated air-powered tools to assist the molder in the energy-intensive operation of ramming the cope and drag flasks. As these tools represent a substantial capital investment, a set of alternatives (Methods #4, 5, 6) have been constructed of hand methods with the cost and productivity increases associated with air-powered hand tools.

4.1.2 Simple Machine Methods

In these methods, air-powered molding machines are used to perform the basic operations of flask ramming and pattern drawing. In "simple jolt" machines, a rapid up-down motion of the molding table compresses the sand against the pattern. "Jolt/Squeeze" machines are used in Matchplate molding and a combined jolting and squeezing operation compresses the molding sand. Figure 6 illustrates the arrangement of Matchplate flasks with the squeezing head of the molding machine. For both the simple jolt, and jolt/squeeze machines, a wide range of sizes are available from which representative sets have been selected (Methods #7-13).

4.1.3 Operator Controlled (O/C) Cope and Drag Methods

Increased efficiency of operation can be achieved when separate molding stations prepare the cope and drag halves of the mold separately. Patterns can be permanently mounted to the molding machines, and increased specialization of the operator tasks can increase productivity. Offsetting these advantages is the higher investment necessary for the molding and accessory equipment. Figure 8 illustrates a typical O/C cope and drag line. Again, a wide range of sizes are available from which a representative set has been selected (Methods #14-17).

4.1.4 Automatic Cycle (A/C) Cope and Drag Methods

These systems perform the molding operations with pre-set cycle controls which optimize the sequencing and time of the operations to suit the specific requirements of the casting to be produced. Higher investment costs are compensated for by slightly higher productivities and reduced labor skill required (Methods #18-20).

4.1.5 Sand Slinger Methods

Sand slingers combine the sand delivery and mold ramming tasks. The energy of compaction is provided by the molding sand which is delivered at high velocity to the flask. The other molding operations can be performed by hand or machine. Two representative systems have been selected (Methods #21 and 22).

4.1.6 Automated Flaskless Methods

A number of foundry equipment manufacturers provide complete, automated systems for flaskless molding. Figures 9-11 illustrate two representative systems. The range of available sizes is restricted, however, and mold sizes of 24 x 30 x 12/12 represent an upper limit on presently available equipment (Methods #23-27).

4.1.7 Automated Tight Flask Methods

For larger flask sizes (greater than 24 x 30), tight flask molding systems are the only automated molding alternatives. These are integrated, highly capital intensive systems that are designed for a narrow range of mold requirements, and typically only one flask size. Two representative systems have been selected (Methods #28-29).

The dimensions and major characteristics of the 29 alternative techniques are presented in Table 4.

In constructing a set of "equivalent" alternatives, a number of assumptions on the influence of moldmaking on the rest of the foundry activities, and on the casting produced are necessary.

The fundamental assumption inherent in this method of analysis is that product qualities are independent of the production technique. In mold making, more automated techniques are capable of producing castings with closer tolerances, improved surface finish, smaller scrap levels, and a reduction in the machining required. Ignoring these product differences is in part justified by the fact that the bulk of castings needed in LDCs do not require these precise tolerances. Ignoring scrap and machining differences introduces a small bias in favor of hand and simple machine methods. This is more than compensated for by the tighter requirements on the quality on the molding sands needed for automated methods. Core requirements have been ignored to avoid another set of variables in the model whose alternatives are much less "equivalent" than molding methods, and use materials whose availability in LDCs is uncertain.

In summary, a set of alternatives for producing green sand molds has been assembled which reflects a wide variety of capital and labor inputs. They can be considered equivalent alternatives with regard to product specification with only slight reservation. To insure their equivalence, costs associated with each method must be collected.

4.2 Major Sources of Costs Associated with Moldmaking

The major influences on the cost of a molding system are the capital cost of the equipment, the direct labor involved, pattern costs, maintenance requirements, and the cost of the energy consumed. A discussion of the major contributors to these costs, the major assumptions made, and the summaries of costs are presented here. A description of the sources and methods for estimating costs is presented in Appendix C, Data Development.

Table 4: Description of Alternative Production Methods

No.	Method Name	Pattern Type	Flask Type	Maximum Mold Size	Sand Fill	Pattern Ram	Pattern Draw	Mold Removal	Pouring Location
1	Hand	C/D	SF	16 x 16 x 6	H	H	H	H	Floor
2	Hand	C/D	SF	24 x 24 x 8	H	H	H	H	Floor
3	Hand	C/D	TF	36 x 48 x 16	H	H	H	Crane	Floor
4	Hand	C/D	SF	16 x 16 x 6	H	Pneu	H	H	Floor
5	Hand	C/D	SF	24 x 24 x 8	H	Pneu	H	H	Floor
6	Hand	C/D	TF	36 x 48 x 16	H	Pneu	H	Crane	Floor
7	Simple Machine	C/D	TF	12 x 12 x 10	H	Pneu	H	H	Conveyor
8	Simple Machine	C/D	TF	24 x 31 x 16	H	Pneu	H	H	Conveyor
9	Simple Machine	C/D	TF	36 x 48 x 20	H	Pneu	H	Crane	Conveyor
10	Simple Machine	M/P	SF	16 x 20 x 8	H	Pneu	H	H	Conveyor
11	Simple Machine	M/P	SF	20 x 25 x 10	H	Pneu	H	H	Conveyor
12	Simple Machine	M/P	SF	24 x 30 x 11	H	Pneu	H	Crane	Conveyor
13	Simple Machine	M/P	SF	30 x 36 x 13	H	Pneu	H	Crane	Conveyor
14	O/C Cope & Drag	C/D	TF	18 x 26 x 9	H	Pneu	R/D	H	Conveyor
15	O/C Cope & Drag	C/D	TF	22 x 32 x 9	H	Pneu	R/D	Crane	Conveyor
16	O/C Cope & Drag	C/D	TF	36 x 48 x 16	H	Pneu	R/D	Crane	Conveyor
17	O/C Cope & Drag	C/D	TF	40 x 30 x 12	H	Pneu	R/D	Crane	Conveyor
18	A/C Cope & Drag	C/D	TF	26 x 16 x 9	Ohead	A	A	Conveyor	Conveyor
19	A/C Cope & Drag	C/D	TF	36 x 18 x 12	Ohead	A	A	Conveyor	Conveyor
20	A/C Cope & Drag	C/D	TF	47 x 27 x 13	Ohead	A	A	Conveyor	Conveyor
21	Slinger	C/D	TF	36 x 54 x 20	Sling	A	H	Crane	Floor
22	Slinger	C/D	TF	36 x 54 x 20	Sling	A	R/D	Crane	Floor
23	A Flaskless	A M/P	NF	14 x 19 x 7	Ohead	A	A	A	Furnace
24	A Flaskless	A M/P	NF	20 x 24 x 8	Ohead	A	A	A	Furnace
25	A Flaskless	A M/P	NF	24 x 30 x 12	Ohead	A	A	A	Furnace
26	A Flaskless	A NF	NF	19 x 24 x 8	Ohead	A	A	A	Furnace
27	A Flaskless	A NF	NF	24 x 30 x 12	Ohead	A	A	A	Furnace
28	A Tight Flask	A TF	TF	24 x 32 x 12	Ohead	A	A	A	Furnace
29	A Tight Flask	A TF	TF	40 x 48 x 16	Ohead	A	A	A	Furnace

Legend:
- H = Hand
- A = Automated
- SF = Snap Flask
- TF = Tight Flask
- NF = Flaskless
- MP = Matchplate
- C/D = Cope and Drag (2 molding machines are used)
- R/D = Rollover/Draw Machine
- Pneu = Hand Pneumatic Rammers
- O/C = Operator Controlled
- A/C = Automatic Cycle

4.2.1 Capital Costs

The capital costs associated with each of the alternative production methods includes the cost of the molding machine, hand or power tools, mold conveyors, cranes, flasks, jackets and weights needed to produce a poured mold. The cost of the molding machine itself is typically 50% of the cost of the complete molding system. Conveyors are included to deliver the molds to the pouring station (the hand methods #1 to #6 assume the molds are poured on the floor and do not include conveyor costs). Flasks, jackets and weights are included since flaskless and tight flask methods are being compared. The cost of sand delivery has not been included for hand and simple machine methods. It is assumed that the molder shovels the molding sand from the floor and the effect of this operation is reflected in the overall productivity of these methods. The costs of the metal delivery equipment have also not been included even though the pouring labor is accounted for in the next paragraph. This omission requires a brief comment. The investment in metal delivery equipment is particularly sensitive to the design of the molding system and plant layout.

Automated molding systems deliver the molds to the furnace for pouring and the relatively small investment in ladles and cranes can be safely ignored for hand and simple machine methods, which require the distribution of metal to a number of molding stations, this investment may be substantial. The cost will remain a small percentage of the investment <u>per</u> molding station, and though it introduces a small bias in favor of labor intensive techniques, it may be reasonably ignored. The pouring labor costs are significant, and can represent up to 25% of the total labor cost for the labor intensive alternatives. For environments in which labor costs are a large percentage of total labor costs, the omission of pouring labor would introduce considerable error.

4.2.2 Direct Labor Costs

The direct labor required for each method includes the molder (or machine operator), any helpers, maintenance and pouring crews. The pouring labor required for each hand and simple machine method is based on standard estimates of the productivity of a pouring crew operating in a job shop where molds are poured on the floor. For automatic molding methods, a full time pouring crew (usually one man) is employed.

4.2.3 Pattern Design and Cost

A significant influence on the selection of equipment is the cost of making and rigging the required patterns. These costs vary greatly with the quantity and complexity of the castings, the type of molding system employed, and the pattern materials.

For short production runs (under 200 to 500), a myriad of pattern designs and riggings are commonly used, and it is impossible to standardize the pattern costs independent of the casting design. For longer running jobs (greater than 500-1000), the choice of designs is more restricted. Epoxy, aluminum, and steel are the three principle choices though wood is still used for larger molds. The pattern costs are less dependent on the casting complexity and more related to the mold size. Based on estimates of the range of pattern costs for each of the alternate pattern designs, Figure 16 presents the standard pattern costs as a function of the mold area for each of the alternate pattern designs. The pattern cost relations are based on data gathered from foundries and the rule of thumb that costs vary as the square root of the mold area.

The large variation in costs between patterns for hand and simple machine techniques, on the one hand, and automated methods on the other, results primarily from the rigging requirements for these methods. The pattern and rigging for the automated methods must be well supported to handle higher molding pressures, and precisely machined to insure accurate alignment within the molding chamber. This increased demand for accuracy and strength produces a substantial increase in cost per pattern. With proper design and projected future demand, the lifetime of the pattern is usually not determined by its materials. It is generally determined by the design life of the casting. While some casting designs remain unchanged for decades, foundry managers interviewed estimated an average pattern life in the range of three to four years.

Four years has been selected as the average lifetime for the cost calculations.

4.2.4 Equipment Repair and Energy Costs

Periodic maintenance and overhaul of the molding equipment requires the replacement of parts. This cost is insignificant for hand and simple machine molding methods, but can become a significant cost for automatic machinery. Energy consumption (compressed air and electricity) data are available for most

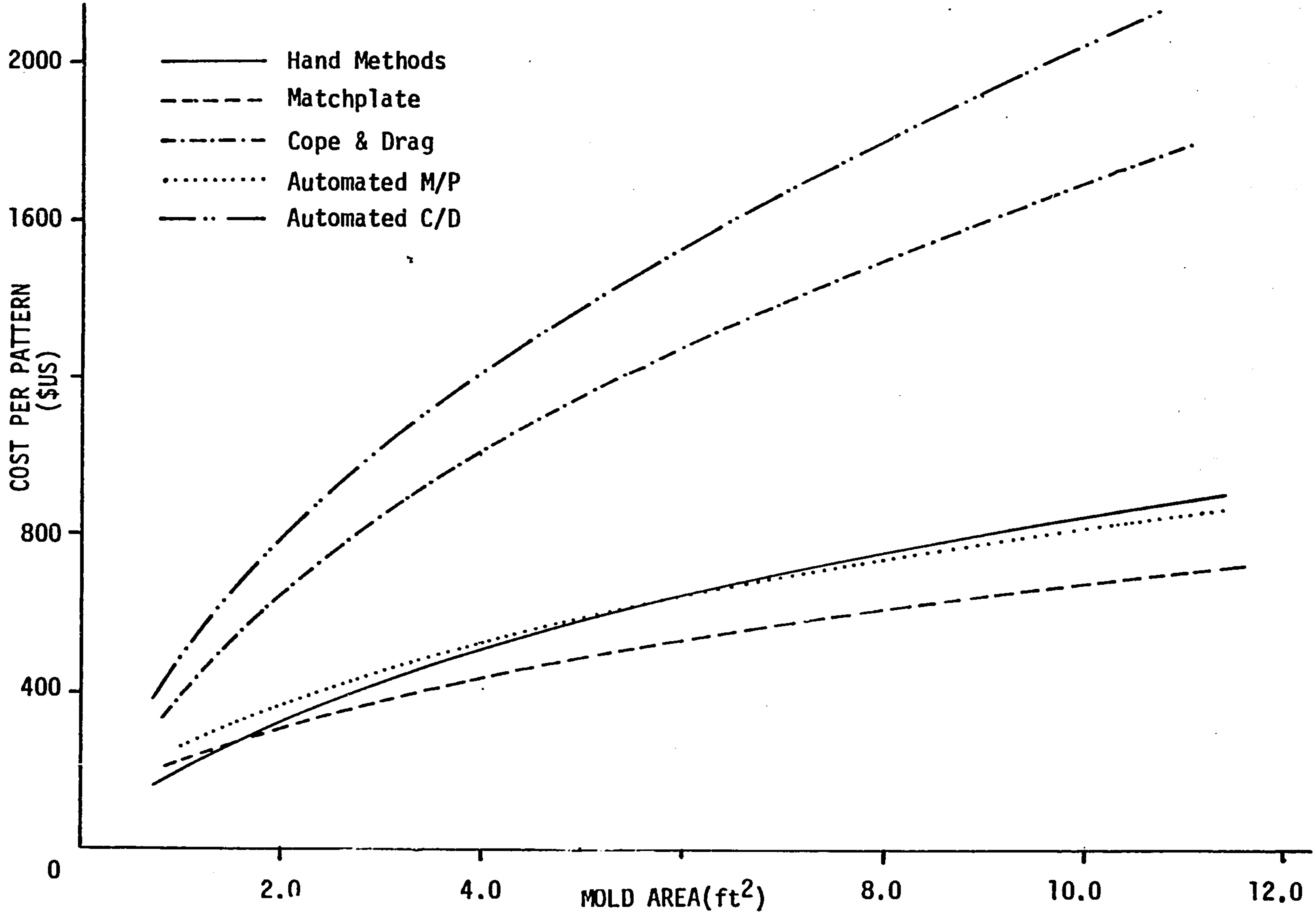


Figure 16: Standard Pattern Costs

of the equipment in the model. Engineering estimates are made for the methods in which this information is not available (see Appendix C).

4.2.5 Additional Assumptions on Equipment Costs

1. Equipment lifetimes which are typically long have been standardized to 25 years. Many automatic systems have not been in operation that long, and this estimate may be optimistic. Discounting equipment costs minimizes the influence on non-uniform lifetimes.
2. Overhead and fixed plant costs are not considered. Automated molding methods better utilize the floor space available in a foundry but also require additional plant improvements and services.
3. Labor wage differentials for the various foundry skill levels are based on U.S. (New England) wage scales. Allowances for scarcity of skilled labor in LDCs can be included in the model, but data is not available.

A summary of the technical and cost characteristics of the alternatives is presented in Table 5.

4.3 Comparison of Unit Costs for One Mold Size

To develop an appreciation of the influence of the numerous technical and economic factors on the costs associated with green sand molding in a realistic setting would require extensive and costly simulations. Without sacrificing much generality, many of these factors can be investigated by considering only one mold size for which a set of alternatives exists. To investigate the major technical and economic variables in our model, the alternatives for an 18 x 18 8 mold size were selected and the unit costs curves constructed. In addition to suggesting the influence of these separate variables, the range in which the existing alternatives influence optimal choice is helpful in limiting the number of large scale simulations required.

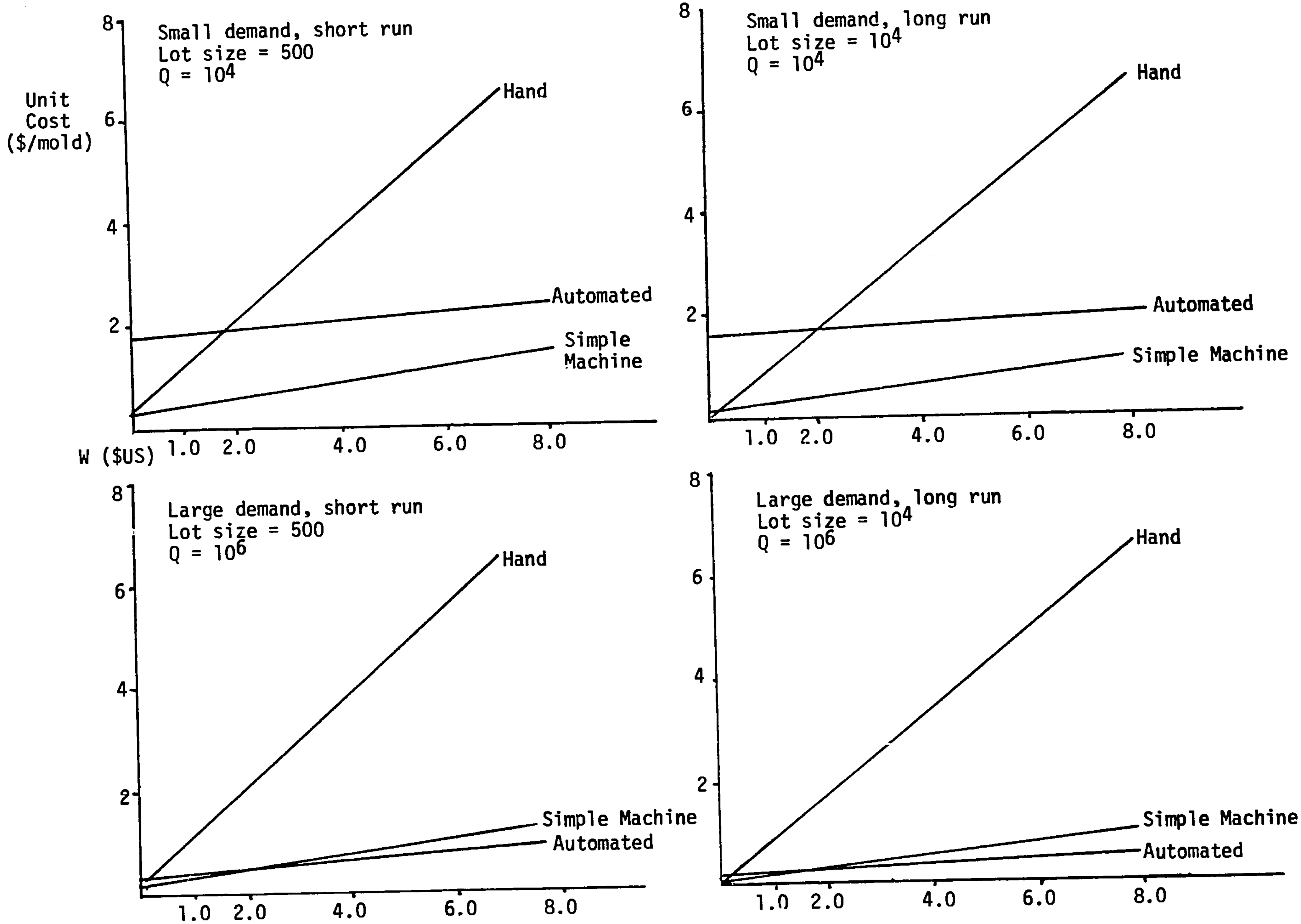
4.3.1 Influence of Wage Rates

The influence of wage rate on unit costs has been investigated for a number of production environments. Four production environments are illustrated in Figure 17, representing the combinations of two lot and total yearly production sizes. The wage against which the unit costs are plotted is the base

Table 5: Summary of Cost and Technical Data for the Alternate Production Methods

No.	Method Name	Capital Cost	Power Consumption: Air (SCF/M)	Power Consumption: Electricity (KW)	Maintenance Cost ($/hr)	Actual Molds/ Hour	Labor (Hour/Production Hour): Un-Skilled	Labor: Semi-Skilled	Labor: Skilled	Labor: Maintenance	Labor: Pouring
1	Hand	766				10			1		.28
2	Hand	945				4		1	1		.16
3	Hand	2,965				1		1	1		.12
4	Hand	1,526	16			11			1		.34
5	Hand	1,656	37			4.5		1	1		.18
6	Hand	3,515	110			1.2		1	1		.14
7	Simple Machine	2,670	13		.0175	13.5		1		.0065	.38
8	Simple Machine	6,274	63		.0325	9	1	1		.022	.50
9	Simple Machine	11,600	146		.06	4		1	1	.049	.62
10	Simple Machine	6,090	7		.0175	24		1		.024	.72
11	Simple Machine	9,060	8		.0325	20		1		.039	.74
12	Simple Machine	15,370	11		.04	15		1		.082	.75
13	Simple Machine	20,550	14		.0525	10		1		.12	.68
14	O/C Cope & Drag	13,600	26		.0325	16		1		.058	.57
15	O/C Cope & Drag	22,790	84		.04	25		2		.10	1.2
16	O/C Cope & Drag	33,900	155		.12	14	1	2		.16	2.2
17	O/C Cope & Drag	21,400	50		.06	10		1		.12	.8
18	A/C Cope & Drag	45,480	24		.20	20	2			.072	.61
19	A/C Cope & Drag	70,000	58		.30	20	2			.072	.7
20	A/C Cope & Drag	137,500	145		.60	15	2			.072	1.3
21	Slinger	56,300		20	.50	2.4			2	.20	.31
22	Slinger	112,700		52	1.01	6		4		.40	.78
23	A Flaskless	58,000	6		2.21	96		1		.50	1.0
24	A Flaskless	79,900	1	15	3.16	80		1		.50	1.0
25	A Flaskless	111,620	1.9	26	4.6	64		1		.50	1.0
26	A Flaskless	394,500	20.7	30	5.0	288		1		.70	1.0
27	A Flaskless	647,000	22	40	7.5	240		1		.70	1.0
28	A Tight Flask	1,412,000		75	12.5	240		1		1.00	1.0
29	A Tight Flask	2,500,000		125	30.0	192		4	1	1.00	1.0

Figure 17: Influence of wage rate on unit costs for 18 x 18 x 8 mold size



(unskilled) wage. Wage costs associated with other skill levels are based on the following proportions for the various wage rates:

Wage Rate Ratios	
Unskilled	1.0
Semi-skilled	1.35
Skilled	1.75
Patternmaker	2.5
Maintenance	1.75
Pouring	1.35

Other wage rate ratios will be investigated below.

The results suggest that little change in the optimal technique will occur for wages greater than $4.00, and that hand techniques are attractive, for the selected mold size, only at wage rates approaching zero.

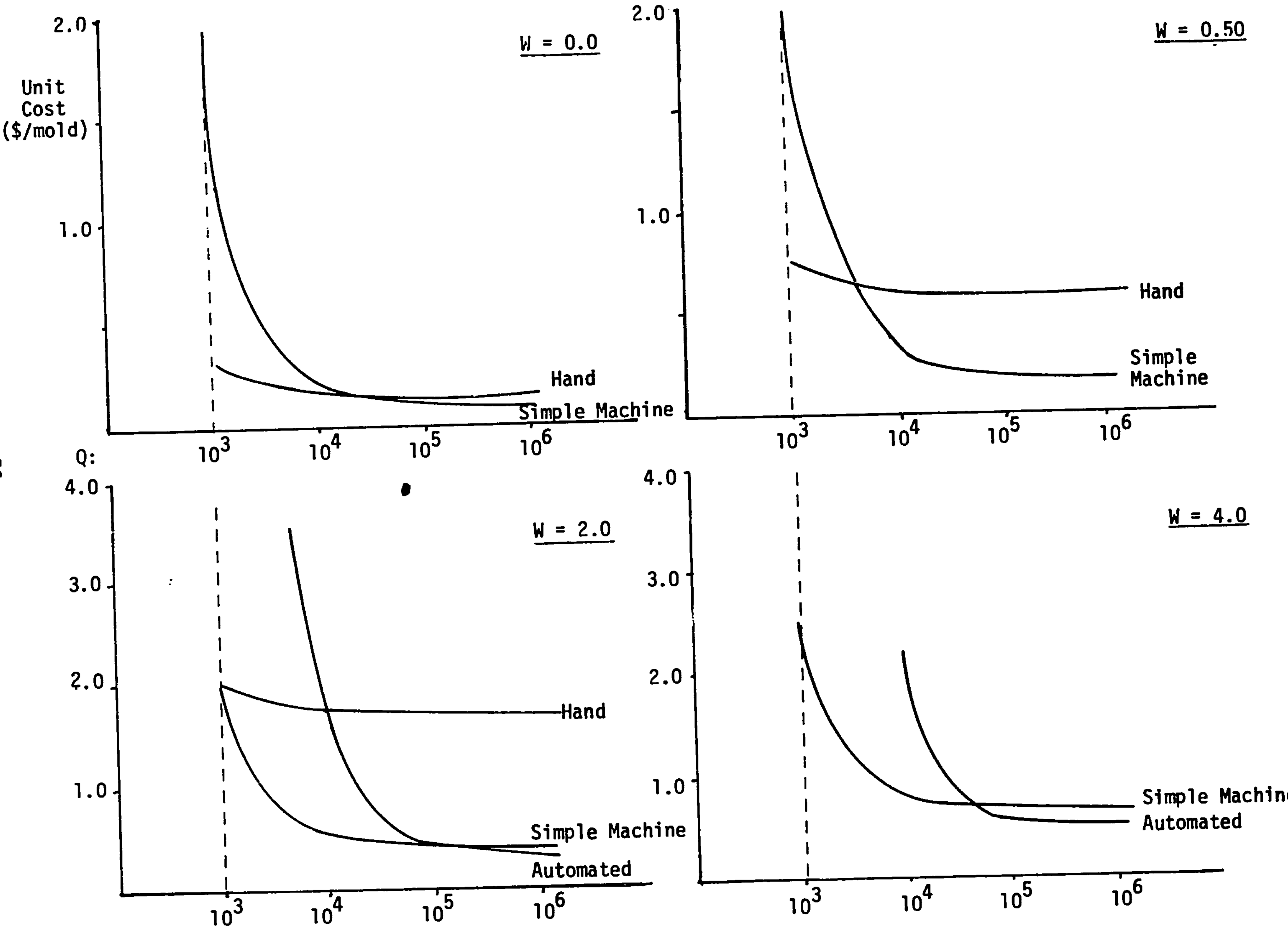
4.3.2 Influence of Yearly Production Quantity

The unit costs for hand, simple machine, and automated techniques are presented as a function of the yearly production quantity in Figure 18. They are presented for four wage rates and suggest that changes in the optimal technique occur predominantly in the range of 1,000 to 100,000 molds per year. Similar curves for different lot sizes (100, 10,000) reinforce this judgment. For lower production levels, the unit costs for simple machine and automated methods rise rapidly, and hand techniques dominate the choice of alternatives. At higher production levels (greater than 100,000), the unit cost curves flatten and choice of technique is influenced primarily by the variable (and particularly wage) costs.

4.3.3 Influence of Lot Size

The lot size establishes the relation between pattern and total molding costs. Since set-up charges for each production lot are rarely significant in foundries, the only cost sensitive to lot size is the cost of the pattern required. In this context, lot size comes to mean the yearly number of molds

Figure 18: Influence of yearly production quantity on unit costs for 18 x 18 x 8 mold size



produced for each specific pattern. Therefore, halving the pattern life (say from four to two years), or doubling the cost of a particular type of pattern, has roughly the same influence as halving the lot size. Figure 19 presents the influence of lot size on unit costs for the pattern cost characteristics assumed for the model, and for a yearly production quantity of 10,000 molds. Results for other production quantities (1,000 and 100,000 molds per year) support the finding that below lot sizes of 500 to 1,000, lot size begins to be the major influence on the unit costs. The influence of errors in estimating pattern costs will be more pronounced, and conclusions from the model about substitution possibilities for small lot sizes must be considered more tentative.

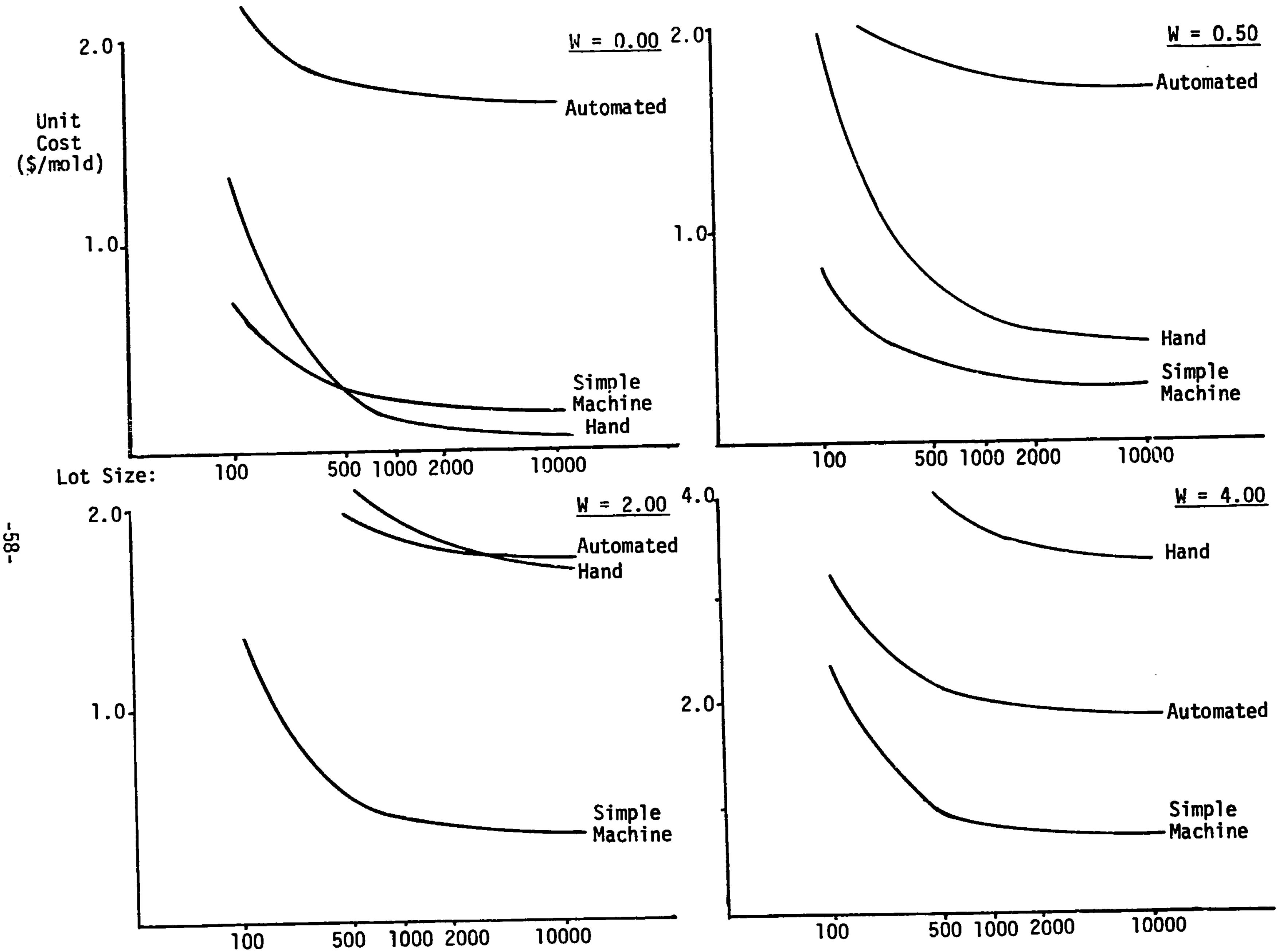
4.4 Mixed Integer Programming Model

If the alternate molding methods produced a single, identifiable product, the equipment selection could be performed by a straightforward analysis, based on a series of unit cost curves like the ones described above. However, since molding equipment suitable for the small markets of LDCs must be flexible enough to produce a variety of mold sizes, a more sophisticated optimization method is necessary. Mathematical programming procedures have the capability to handle multiple variable, constrained optimization problems and are commonly employed in activity analysis (36,37,40) and capital budgeting problems (29). For these reasons, a linear programming model has been selected to perform the equipment selection by minimizing the present discounted value of all costs associated with the purchase and operation of the equipment (a description of the programming system is presented in Appendix C).

Since the quantities of equipment purchased are small, and the cost per unit of equipment is a significant fraction of the total cost, a mixed integer programming model with integer values for the equipment purchased is required. The objective function is the sum of the capital costs and the present discounted value of the production costs associated with each method. The decision (structural) variables are the number of units of each method selected, and the quantity of molds produced by each method.

The constraints on the objective function are based on the yearly demand for a set of specified mold sizes, a time constraint based on one or two shift operation over the year, a non-negative requirement on the molds produced by

Figure 19: Influence of lot size on unit costs for 18 x 18 x 8 mold size   Q = 104



by each method, and the integer constraint on the equipment selected. The effects of varying the wage and interest rate, the yearly demand, and the number of operating shifts are investigated by successive optimizations. Figure 20 presents the mathematical description of the programming model.

Before discussing specific simulation results, the limitations of the model that have been suggested in the paragraphs on cost estimating and unit cost characteristics above, should be stated explicitly. The need for standardizing pattern costs, and limiting the range of lot sizes and production quantities makes the model unsuited for assessing the substitution possibilities in very small jobbing foundries (less than 1,000 tons/year) that are frequently found in LDCs. From what little data is available on them, these small scale, often rural, foundries employ primarily hand molding techniques, and have few resources and little justification to change. The technical and managerial problems of these foundries are quite different from the "organized" foundries, located in or near industrial centers, and have not been dealt with directly in the model. The conclusions drawn from the following simulation will, therefore, be relevant only for the "larger", organized foundries oriented toward the local industrial demand for castings in LDCs.

4.4.1 Equipment Selection for a Small Production Foundry (10,000 tons/year)

Information for individual foundries and national production of cast products has been obtained for several LDCs. The demands vary greatly and depend *primarily* on the local demand for industrial goods. For example, 10,000 tons/year capacity represents 20% of the *total* demand in Colombia (1974) and only 20% of the yearly *increase* in demand (1974) in the Greater Sao Paulo district of Brazil (ABIFA).

The selection of 10,000 tons as a yearly capacity insures a foundry size small enough to be applicable to most LDCs and still be large enough to handle medium and long run jobs effectively. Table 6 presents the job specification for the small production foundry simulation, and Table 7 presents the range of the principal parameters.

The effect of the number of shifts on the selection of equipment was *approximated* by doubling the equipment hours available and halving the equipment lifetimes. All hourly costs were held constant. A more accurate estimate

Figure 20: Mixed Integer Programming Model

OBJECTIVE FUNCTION:

$$\sum_{i,j} [F_i * X_i + \sum_{t}^{L} \frac{1}{(1 + R)^t} (E_i + M_i + H_{i,j} + w\sum_k \alpha_k n_{i,k}) P_{i,j} * Y_{i,j}]$$

CONSTRAINTS:

Demand: $\sum_i Y_{i,j} = Q_j$

Time: $\sum_j P_{i,j} * Y_{i,j} \leq C$

$Y_{i,j} \geq 0$

X_i Integer

List of Symbols:

C = Equipment hours per year available for production of molds - 2,000 hours for single shift operation
E = Hourly energy cost
F = Capital cost for method i
H = Hourly pattern cost
L = Equipment lifetime = 25 years
M = Hourly maintenance cost
Q = Yearly quantity of molds for mold size j
R = Discount rate
X = Decision variable - no. of units of method i
Y = Decision variable - no. of molds of size j produced by method i
i = Index for the alternate production methods
j = Index for the mold sizes required
k = Index for the skill levels
n = No. of worker hours per production hour
p = Productivity (hours/mold)
t = Index for time
w = Base wage rate
α = Ratio of skill level k wage to base wage

Table 6: Small Production Foundry Job Specification

Mold Size (j)	Flask Dimensions (inches)	Yearly Demand (Number of Molds)	Number of Jobs	Lot Size
1	12 x 12 x 4/4	830,000	207	4,000
2	18 x 18 x 8/8	368,000	184	2,000
3	24 x 30 x 12/12	41,400	41	1,000
4	36 x 48 x 16/16	17,300	17	1,000

Table 7: Range of Parameters for the Small Production Foundry Simulations

Base Wage ($/hour): 0.00, 0.25, 0.50, 2.00, 4.00, 7.50

Interest Rate (%): 0.10, 0.20, 0.30

Number of Shifts: 1, 2

would require information on changes in maintenance and energy costs, equipment productivities, and any wage premiums paid.

4.2.2 Simulation Results

Solutions to programming problems provide a wealth of information including the value of the objective function, and the decision variables, any slack variables for the constraints, and a set of shadow prices for the decision variable (coefficients and constraints). As our present interest is developing an appreciation for the influence of parameters like wage and interest rate on equipment selection, and the overall capital-labor substitution possibilities for the molding activity, we will focus only on the results that directly concern this issue.

The most general result of the simulations was the high degree of joint production (the use of one technique to produce two or more mold sizes), and "multiple technique" production (the use of two or more techniques to satisfy the demand for one mold size). Both of these production characteristics occurred in virtually every solution. Joint production of three mold sizes occurred in a third of the cases and "multiple technique" production employing three or more of the alternatives occurred over half the time. This high density of joint activity reflects the flexibility of many of the production alternatives considered in the model, and the need to best utilize available equipment capacities.

The equipment selections have been summarized in terms of the seven principal alternatives in Table 8. The general trends for equipment selection are fairly well represented in this set of selections and the major findings should be highlighted.

Table 8: Small Production Foundry Equipment Selections: Wage Rate Variation*

Base Wage Rate	12 x 12	18 x 18	24 x 30	30 x 48
0.00	Hand	Hand	Hand/Simple Machine	Hand
0.25	Simple Machine	Simple Machine	Simple Machine	Hand/Simple Machine
0.50	Simple Machine	Simple Machine	Simple Machine/ O/C Cope & Drag	O/C Cope & Drag
2.00	Automated Flaskless	Simple Machine/ Automated Flaskless	Automated Flaskless	O/C Cope & Drag
4.00	Automated Flaskless	Automated Flaskless	Automated Flaskless	O/C Cope & Drag
7.50	Automated Flaskless	Automated Flaskless	Automated Flaskless	O/C Cope & Drag

*Interest Rate = 0.10
Single Shift Operation (2,000 hours)

1. At production levels at which automated techniques would be employed in the U.S., foundries in LDCs have a range of hand and simple machine techniques which better suit their economic environments.

2. Variations in the interest rate produced only a slight modification in the equipment selections outlined in Table 8. At higher interest rates, automated equipment is selected at slightly higher wage levels.

3. Two shift operation influenced only the number of units of equipment selected, not the type. As the capital requirement for two-shift production is substantially reduced, in foundries as elsewhere, two shift operation is an attractive strategy for LDCs. As the investigation of two shift operation considered the changes in equipment lifetime and operating hours per year, the relation between number of shifts, and the number and type of equipment should not be considered a strong conclusion. Better information is needed on maintenance, labor and productivity changes for the production alternatives in <u>realistic</u> settings before a general statement on two shift operation can be made.

4. While simple machine methods have a relatively broad range of environments in which they are best suited, the use of hand methods for <u>production</u> runs is suggested only at wage levels approaching zero. As a foundry worker in India receives $.20-.25 per hour, in Colombia $1.00 per hour, and in Spain $2.00 per hour, it is unlikely that environments can be identified which can justify the use of hand techniques. The lower skill levels required relative to hand methods suggest that shadow pricing arguments for various skill levels will also reinforce the selection of simple machine methods.

The solutions of the programming model are presented in detail in Appendix D.

To develop an appreciation for the employment generating potential of the selected alternatives, the capital-labor ratios and the production function isoquant for the Small Production Foundry Simulation are presented in Figures 21 and 22. The labor required is based on the actual production time required for the selected alternatives and does not include labor for slack production time All hours of skilled time are converted into standard hours by multiplying by the ratio of the skill level wage to the base wage.

A rough estimate of the employment potential for moldmaking can be obtained from the production relation in Figure 22. At a base wage of $7.50, 2.5 direct molding workers are required per 1,000 tons of yearly capacity (based on 2,000 man-hours per man-year). Reducing the base wage rate from $7.50 to $0.50 per hour will approximately double the employment potential of the moldmaking activity. This represents approximately three jobs for each 1,000 tons of yearly capacity. An additional 1.5 jobs per 1,000 tons are generated by reduction in the base wage to $0.25. The large employment gains, of course, come as the wage rate approaches zero. Then, approximately 30 molding workers are required per 1,000 tons of yearly capacity, increasing the employment nearly tenfold over the $7.50 per hour base wage rate. Again, however, it should be emphasized that it is unlikely workers with the requisite molding skills can be valued at wage rates approaching zero, and realistic expansion of the employment for the molding activity will not likely reach the tenfold increase suggested by the simulations.

4.5 Sensitivity Analysis of Model Results

The model construction required a number of assumptions regarding the productivities and cost of the alternatives, and the production environment. For a standard linear programming problem, post-optimization routines are available that can efficiently evaluate the influence of a wide range of values for the variables of interest. This capability is unfortunately greatly restricted in mixed integer programming problems, and a set of additional simulations are required for each alternative hypothesis. As a result, these investigations are limited to the variables which appear to have either the greatest variability in their estimation, or the greatest influence on equipment selection. The following are the variables chosen for this sensitivity testing:

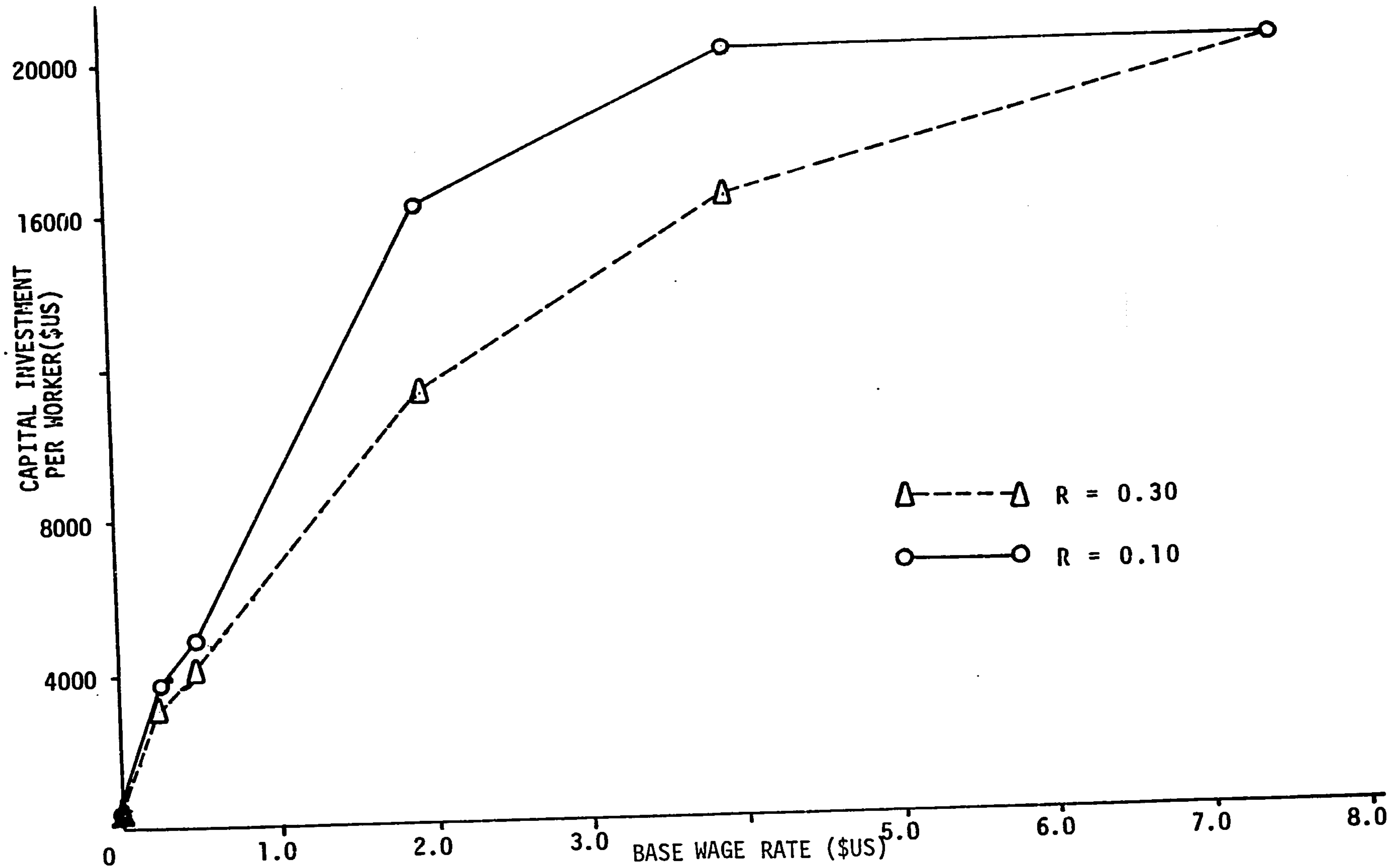


Figure 21: K/L Ratios,Small Production Foundry

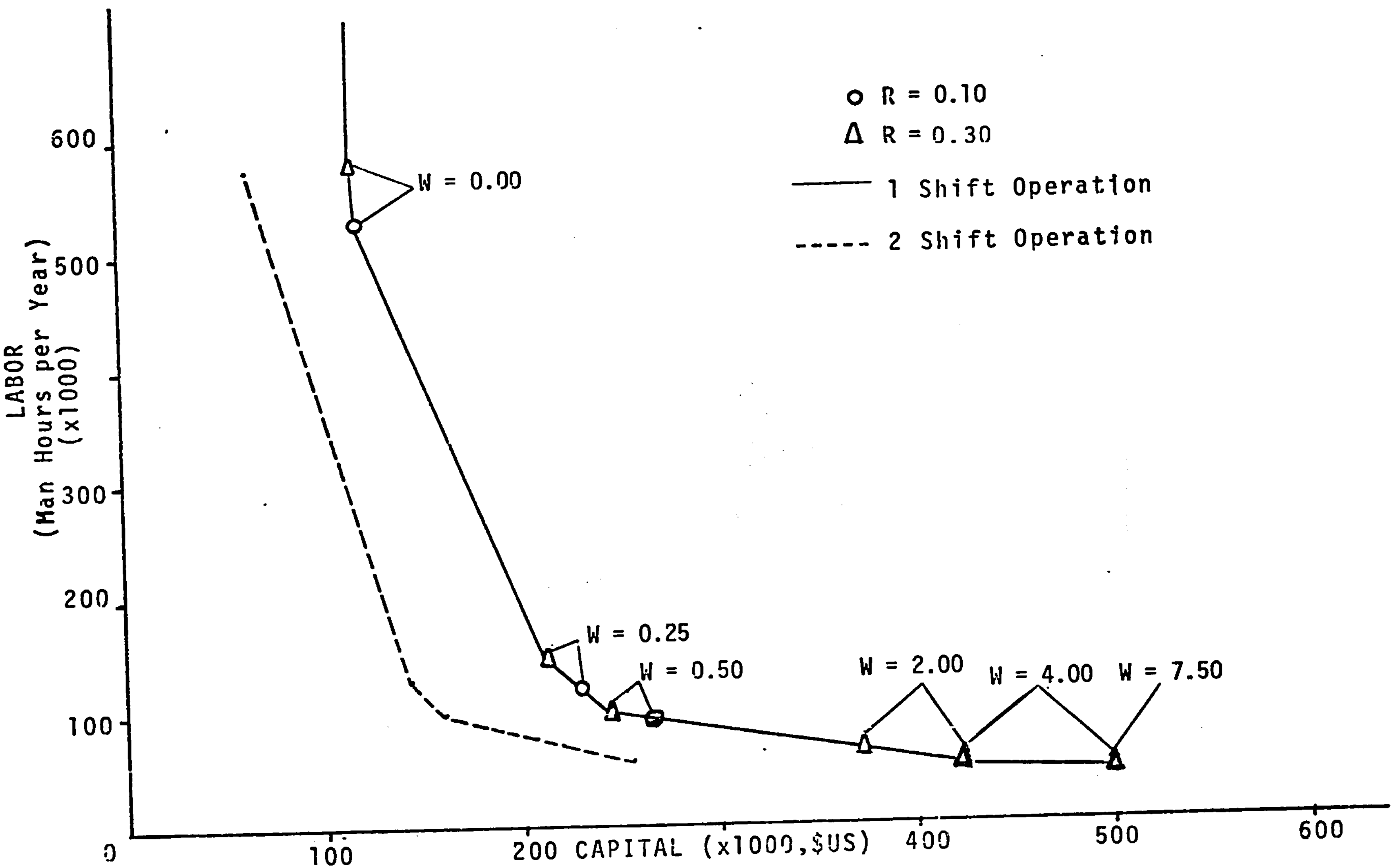


Figure 22 : Production Function for Small Production Foundry

1. Scale of Production
2. Equipment Productivities
3. Equipment Capital Costs
4. Shadow Pricing of Labor

4.5.1 Scale of Production: The Influence of Production Level and Lot Size

To test the influence of scale on equipment selection, a large production foundry (50,000 tons/year) was simulated. In addition to the larger scale of operation, the influence of lot size on equipment selection was tested by breaking down the production into long and short run jobs. Table 9 presents the job specifications for the Large Production Foundry Simulation (the large mold size [36 x 48 x 16/16] has not been included in this set of simulations). The breakdown between long and short run jobs is based on the "80%-20%" rule. This rule of thumb specifies that 80% of the production volume is generated by 20% of the jobs. The long run jobs have lot sizes twice as long as in the original simulation; the short run jobs are one tenth as long.

In general, substitution possibilities correlate well with the original model. The overall capital-labor ratios for a given wage and interest rate are similar to those in the original model, though the large quantity of molds for the long run jobs permits the use of more capital intensive equipment at higher wage levels. Two shift operation again affects the quantity of equipment purchased but not the type. The use of hand and simple machine methods for long production runs at low wage rates suggests that the use of <u>any</u> highly mechanized or automated equipment in industrial centers in LDCs must be carefully scrutinized. The types of equipment selected are presented in Table 10. The capital-labor ratios and production isoquants are illustrated in Figures 23 and 24.

A comparison between short and long run jobs illustrates how pattern costs affect the equipment selection. At wage rates of or near zero, simple machine methods are still preferred for short run jobs for all three mold sizes. The apparent anomaly of short run jobs at zero labor cost being produced by machine methods is resolved when pattern costs are included in the measure of capital investment.

Table 9: Large Production Foundry Job Specification

Short Run Jobs

Mold Size (j)	Flask Dimensions (inches)	Yearly Demand (Number of Molds)	Number of Jobs	Lot Size
1	12 x 12 x 4/4	830,000	1863	440
2	18 x 18 x 8/8	368,000	1656	220
3	24 x 30 x 12/12	41,400	369	112
4	12 x 12 x 4/4	3,312,000	414	8,000
5	18 x 18 x 8/8	1,472,000	368	4,000
6	24 x 30 x 12/12	164,000	82	2,000

Table 10: Large Production Foundry Equipment Selections:

Wage Rate Variation*

	Flask Size					
	12 x 12		18 x 18		24 x 30	
Base Wage Rate	Short Run	Long Run	Short Run	Long Run	Short Run	Long Run
0.00	Simple Machine	Hand	Simple Machine	Hand	Simple Machine	Simple Machine
0.25	Simple Machine	Simple Machine	Simple Machine	Simple Machine	Simple Machine	Simple Machine
0.50	Simple Machine	Simple Machine	Simple Machine	Simple Machine	Simple Machine	Simple Machine
2.00	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless
4.00	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless
7.50	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless	Automated Flaskless

*Interest Rate = 0.10
Single Shift Operation

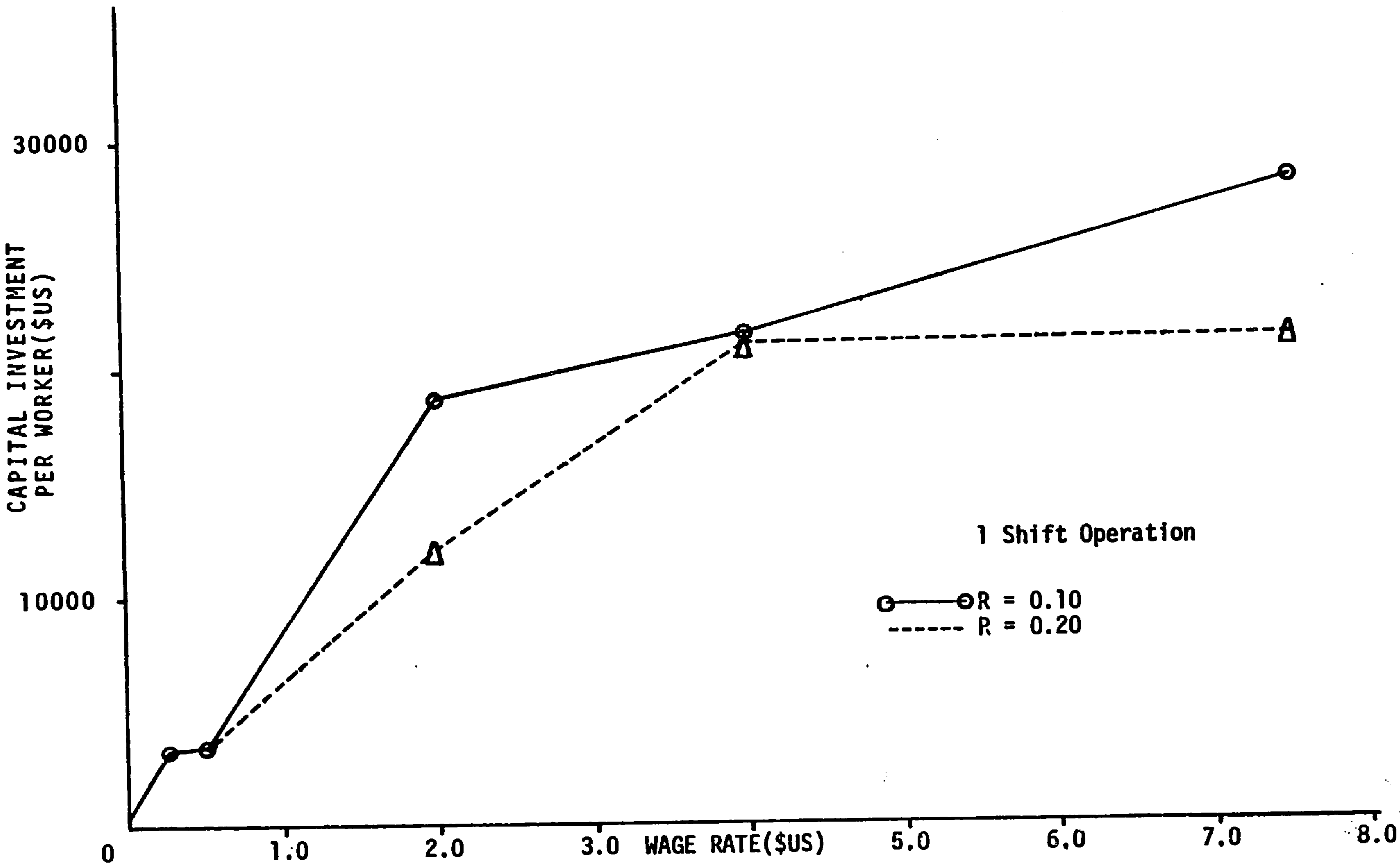


Figure 23: K/L Ratios, Large Production Foundry

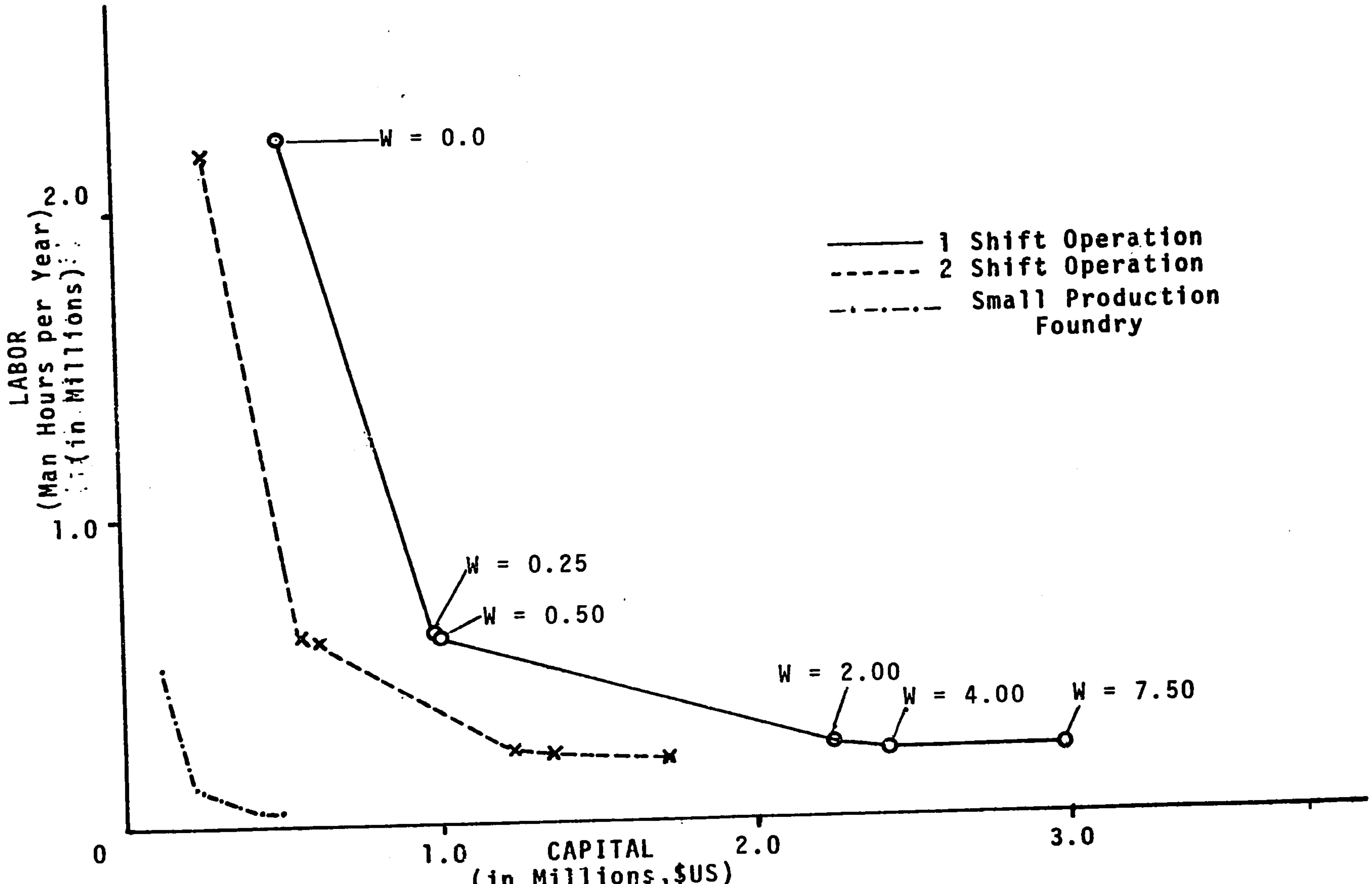


Figure 24: Production Function, Large Production Foundry

A brief calculation, based on the 18 x 18 mold size, will illustrate how a non-labor operating cost, the fixed pattern cost, can swamp the investment cost and make a "hand" molding method technically inefficient at zero wage.

	Method (i)	
	Hand (#2)	Simple Machine (#11)
Number of short run jobs (j = 2):	1,656	
Number of castings per year, $Y_{i,j}$:	368,000	
Productivity, $P_{i,j}$ (hours/mold):	0.25	0.05
Number of units required, X_i:	46	9.2
Equipment cost:	$945	$9,060
Total capital investment:	$43,470	$83,352
Pattern cost @ w = 0.00:	$250	$197
Hourly pattern cost, H_i (approx.):	$1.12	$4.40
Net present value of pattern costs: (based on 25 year life and 0.20 interest rate)	$504,900	$393,600

That a $50 difference in cost per pattern can offset $100,000 capital investment when lot sizes are small attests to the sensitivity of equipment selection to pattern cost assumptions and reinforces the judgment made above (Section 4.3) that the model is not adequate to describe lot sizes below 500 to 1,000 units.

4.5.2 Equipment Productivities

Estimates of productivities for the alternative production methods were obtained from foundry engineers and equipment manufacturers. The estimates varied significantly, reflecting different operating environments, and implicit assumptions about casting complexity, coring requirements, etc. The variation was greatest for hand techniques, up to a factor of five for some methods. Despite attempts to select average estimates, this variation will limit the precision of the model.

Two characteristics of the productivity estimates have been selected for a more detailed investigation:

a. The technique for calculating equipment productivities

b. The influence of alternate productivity estimates for the hand methods

a. Technique of Calculating Productivities

The productivities have been calculated on the geometric requirements of the production methods and the required mold sizes. Large molding machines can handle more than one small mold. The integer number of molds that can be made in one flask are calculated as the largest number of molds that can fit inside the specified flask geometry without overlapping.

An alternate method of calculating the productivities is based on the assumption that each specified mold size represents realistically a range of different sized products. The productivity would be based on the ratio of the maximum flask area of each method to the required mold area, and be a non-integer number of molds per flask. While this assumption is more representative of actual foundry demands, the risk of biasing the results with a few methods which have slightly high productivity estimates is increased. A large machine with a high estimate might be selected for all production. A small error in the data would be magnified greatly. By requiring an integer value for the molds per flask, one machine will not be optimally efficient for all mold sizes Since the alternate production methods include several machines of the same basic type for each of the seven basic alternatives, we may still expect the correct general alternative to be selected.

These different productivity assumptions have been investigated in a series of simulations. The capital-labor ratios as a function of wage rate are presented in Figure 25. The higher, "continuous" productivity estimates, better utilizing the equipment, yield smaller capital-labor ratios.

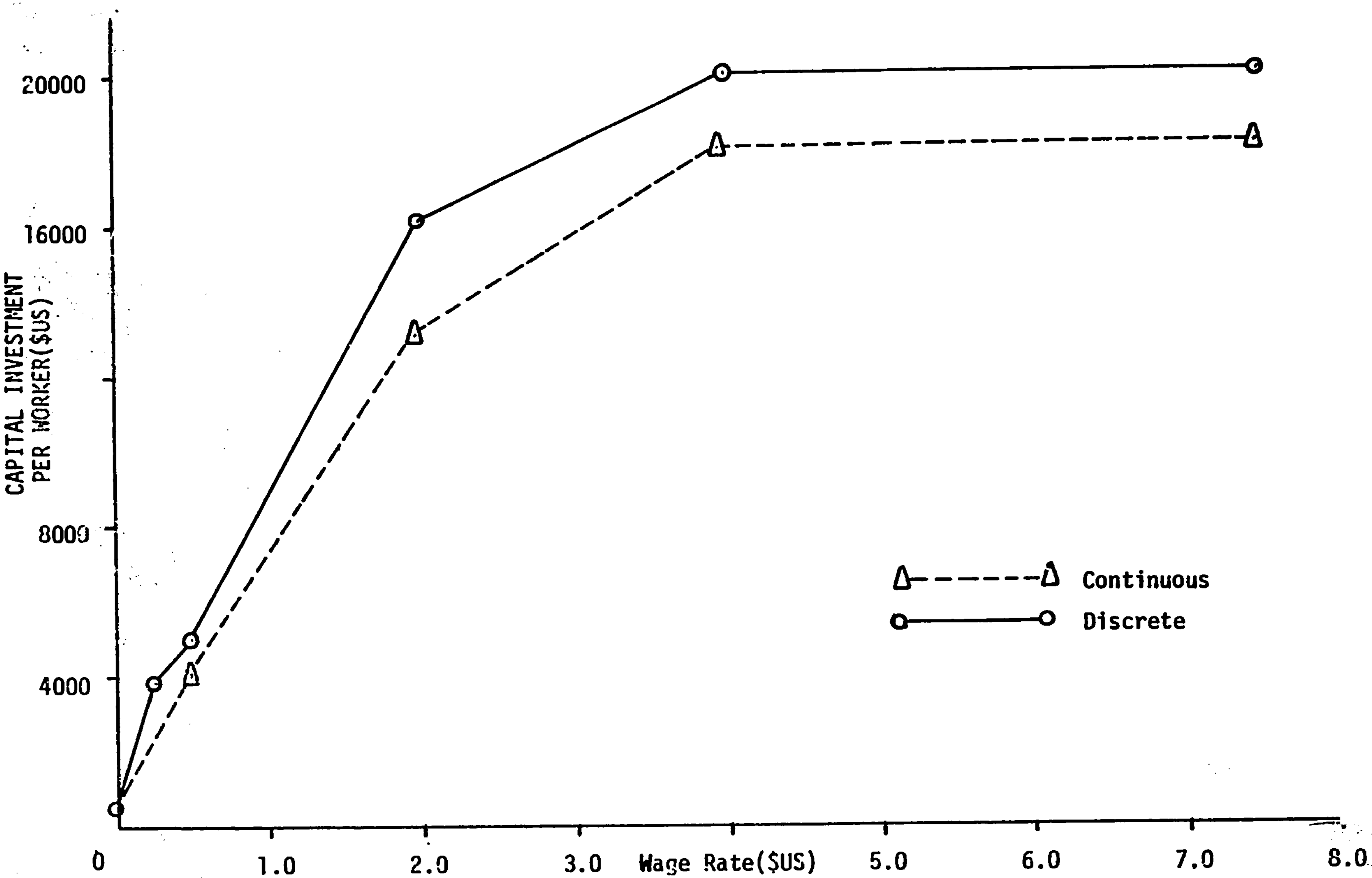


Figure 25: K/L Ratios, Alternate Productivity Assumptions
Small Production Foundry

b. Alternate Productivity Estimates for Hand Methods

Owing to the high degree of variability in the estimates for hand techniques (methods #1-6), a set of simulations were performed in which the overall productivities were increased by 50%.

A natural consequence of this improvement in efficiency is to reduce the total capital and labor required whenever hand techniques are selected. However, with only one exception (12 x 12 mold size @ w = 0.25), the type of equipment selected remained unchanged. Even with these high estimates for productivities of hand techniques, simple machine techniques are lower cost alternatives at low wage rates.

4.5.3 Equipment Capital Costs

Capital cost estimates are based on U.S. f.o.b. prices. This clearly understates the cost of this equipment in a LDC, where shipping charges and foreign exchange shortages may possibly double equipment costs. While no complete evaluation of the sensitivity to price fluctuations has been attempted, some appreciation of the impact of higher equipment costs can be hoped for. To this end, a set of simulations was performed in which the capital costs of all machine methods were increased by 50%. One interest rate (0.20) and one shift operation were chosen. Wage rates were varied from $0.00 to $7.50 per hour.

Again virtually no changes in the types and quantities of the equipment selected, and no substitution of hand for simple machine methods occurred.

4.5.4 Shadow Pricing of Labor

Two simulations were performed to investigate the impact of scarcity of skilled labor on equipment selection. In effect, they represent two hypothetical sets of shadow prices that may more accurately reflect labor value in LDCs. Table 11 presents the wages for the original model and the two sets of shadow wages.

Table 11: Wage Values for Shadow Price of Labor Simulations
(x base wage rate)

	Original Model	Shadow Pricing Sets #1	Shadow Pricing Sets #2
Unskilled	1.0	1.0	0.0
Semi-skilled	1.35	2.0	2.0
Skilled	1.75	10.0	10.0
Maintenance	1.75	10.0	10.0
Pouring	1.35	2.0	2.0
Pattern	2.50	15.0	15.0

The simulations were performed for a base wage of $0.50 per hour, interest rate of 0.20 and for one shift operation.

The simulations for the two sets of shadow prices produced identical results and differ only slightly from the results of the original simulations for the set of economic parameters. Simple machine techniques (and a operator controlled cope and drag method for the 36 x 48 mold size) remained optimal reflecting overall lower skill requirements than either hand or more automated alternatives.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Simulation Model

A simulation model can provide valuable assistance in evaluating technologies for developing countries or more general investigations of technical choice. The major advantage of a simulation model lies in its ability to extrapolate from economic conditions and opportunities in the developed environment to the wide variety of conditions found in LDCs. The influence of a particular set of assumptions or alternative hypotheses can be quickly evaluated.

Added capabilities of the linear programming approach include the investigation of time varying demands, productivities, and maintenance costs. Plant expansion decisions can be determined from the present machine mix, output, and projected demands.

The study of foundry equipment has been limited by the data collected and the need to standardize some of the significant contributors to cost. Two opportunities exist for obtaining an improved picture of technical choice in foundries.

Foundry design and consulting organizations have files available on the production rates, costs, and manpower requirements. Larger organizations have information available that dates back several decades and might provide valuable insight into technological change. This information is available at reasonable cost and should be investigated in any further work.

A second alternative is a foundry product analysis. Much of the uncertainty about productivities and pattern costs can be eliminated by selecting a number of representative casting designs and constructing cost analyses of the alternate methods to make them. The chief advantage of a product analysis lies in the better format it provides to collect data from foundry operators. Giving "typical" numbers is not something they like to do! The increased precision of such a study inevitably limits the generality of the work unless a truly representative class of products is selected. That may require a considerable expansion in the scope of the project.

5.2 Implications for Foundry Design in LDCs

It was pointed out repeatedly during the data gathering that equipment replacement and trends in mechanization are not motivated by technological efficiency alone. Labor scarcity, and particularly the skills required in jobbing foundries are often cited as the primary motives in new equipment selection. It is hot, heavy, noisy, dirty work and conditions in LDCs are no better. Competition for the semi-skilled labor which is required for the bulk of foundry activities from other industries in LDCs is high. Quite conceivably the attracting of a suitable work force is even more difficult in LDCs than in developed countries.

Among the alternatives available to LDCs, the Matchplate molding process is most attractive to their needs, and appeared frequently in the equipment selections at low wage levels. Simple machinery, moderate skill levels, and high quality molds are the principal advantages. Pattern cost is relatively low, and the new epoxy pattern technology is well suited to the process. Epoxy patterns can be manufactured with simple techniques, require moderate skills and little machining. It represents one new technology that can provide substantial benefit to foundries in LDCs.

Melting facilities must rely on locally available power. Cupola melting will only be feasible if local pollution requirements are less stringent than current U.S. standards. From a technological point of view, it is the logical starting point for a LDC; it is simple to operate and control, and does not require the large capital investment needed for electricity distribution, transformers, and the electric furnaces themselves.

The materials handling requirements have several possibilities for labor substitution that have not been investigated here. The movement of sand and discrete parts represent a general class of manufacturing activities in which labor substitution possibilities are great. It is conceivable that the substitution possibilities in several industries could be determined from one study. Studies of materials handling in civil engineering projects (28) can provide valuable information for such a study. Combined with an industrial engineering analysis of the specific materials handling problems in a manufacturing environment, a valuable contribution to the study of technical choice and to the development of "appropriate" technologies can be made.

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APPENDIX A: FOUNDRY DATA SOURCES

A.1 Foundry Interviews

The following foundries were visited during the research program. Foundry managers and engineers were interviewed on general problems of foundry design and for specific data for the Equipment Selection Model.

U.S.M. Foundry
Beverly, Massachusetts
Mr. Frank Hoffman

Wollaston Alloys
Braintree, Massachusetts
Mr. Frank Tibbets

LeBaron Foundry
Brockton, Massachusetts
Mr. F. E. Lebaron
Mr. Thomas Gasse

Bridgewater Foundry
E. Bridgewater, Massachusetts
Mr. George Machado

Meade Foundry
Bedford, Massachusetts
Mr. David Meade

Draper Division, Rockwell International
Hopedale, Massachusetts
Mr. Charles Talbot
Mr. Leonard Boyd

Whitman Foundry
Whitman, Massachusetts
Mr. Armor

Belcher Malleable Iron Foundry
Easton, Massachusetts
Mr. Burgess

Standard Foundry
Worcester, Massachusetts
Mr. Al Indge
(Telephone Interview)

A.2 Foundry Consulting Firms

The following foundry consulting firms were contacted during the course of the investigation.

Lester B. Knight & Associates
Chicago, Illinois

Giffels Associates
Detroit, Michigan

Swindell-Dressler Co.
Pittsburgh, Pennsylvania

Westover Corporation
Milwaukee, Wisconsin

The Austin Co.
Metals and Mining Division
Cleveland, Ohio

Meehanite Worldwide
Division of Meehanite Metal Corp.
White Plains, New York

Klein-Farris, Inc.
Boston, Massachusetts

Ralph Benci
Roslindale, Massachusetts

Herbert Cragin, Jr.
Greeneville, Tennessee

A.3 Foundry Equipment Manufacturers

The following manufacturers provided information on their products.

Baker Perkins, Inc.
Chemical Machinery Division
Saginaw, Michigan

Clearfield Machine Co.
Clearfield, Pennsylvania

Harry W. Dietert Co.
Detroit, Michigan

Molder' Friend, Inc.
Dallas City, Illinois

National Engineering Co.
Chicago, Illinois

Pangborn Division
Carborundum Co.
Hagerstown, Maryland

Pekay Machine and Engineering Co.
Chicago, Illinois

BMM Inc.
Subsidiary, British Molding Machine Co.
Cleveland, Ohio

Beardsley & Piper
Division of Pettibone Corp.
Chicago, Illinois

Herman Corp.
Zelienople, Pennsylvania

International Molding Machine Co.
La Grange Park, Illinois

C-E Cast Equipment
Cleveland, Ohio

Hunter Automated Machinery Corp.
Schaumburg, Illinois

A.3 Foundry Equipment Manufacturers (continued)

Disamatic, Inc.
Countryside, Illinois

Harrison Machine Co.
Wesleyville, Pennsylvania

Osborne Manufacturing Co.
Cleveland, Ohio

Davenport Machine & Foundry Co.
Davenport, Iowa

Tabor Manufacturing Co.
Lansdale, Pennsylvania
Shalco Systems
Cleveland, Ohio

A.4 National and International Foundry Organizations

American Foundrymen's Society
Des Plaines, Illinois

Grey and Ductile Iron Founders' Society
Cleveland, Ohio

British Cast Iron Research Association
Birmingham, United Kingdom

U.N.I.D.O.
Metallurgical Industries Section
Vienna, Austria

South East Asia Iron and Steel Institute (SEAISI)
Singapore 6, Singapore

Instituto Latinoamericano del Fiero y en Acero
Santiago, Chile

Instituto Centroamericano de Investigacion y Tecnologica Industrial (ICAITI)
Guatemala, Guatemala

Federacion Metalurgica Colombiana (FEDEMETAL)
Bogota, Colombia

Asociacion de Industriales Metalurgicos
Santiago de Chile, Chile

Asociacao Brasileira das Industrias de Fundicao de Ferro e Aco
Rio de Janeiro, Brasil

Centro Nacional de Investigationes Metallurgicas (CENIM)
Madrid, Spain

Israel Foundrymens' Society
Tel Aviv, Israel

Sinto Kogio
Nagoya, Japan

Indian Foundry Association
Calcutta, India

APPENDIX B: NATIONAL FOUNDRY STATISTICS FROM COLOMBIA, CHILE AND BRAZIL

B.1 Colombian Foundry Statistics:

Source: FEDEMETAL

Annual Production (1974):	25,000 metric tons
Total No. of Foundries:	10,000 (estimated)
No. of Organized Foundries:	50
Labor Force:	8,000 employees (organized foundries only)
Salary Level:	\$50./week (US)
Raw Materials:	
Locally Available -	Coke Sands Acid refractories
Import Required -	Bentonite Basic refractory materials
Major Problems:	Technological training in small foundries Transportation in mountainous terrain

B.2 Brazilian Foundry Statistics

Source: ABIFA

Iron Foundry Size Distribution:	19 large $\geq$ 1% of total production 25 medium $\geq$ 0.4% of total production 172 small < 0.4% of total production
Total Production:	1,126,000 metric tons
Value of Product:	5.5 million cruzeiros (\$650,000)
Foundry Workers:	50,000

No Salary Data

Little Automated Equipment

B.2 Brazilian Foundry Statistics (continued)

Raw Materials

Locally Available -	Pig Iron Scrap Sands
Import Required -	Coke (local grades have high ash content)

Table B-1 presents estimates of the supply and demand projections for cast iron for 1975-1980.

Table B-1: Supply and Demand Projections for Cast Iron in Brazil (in Metric Tons)

	1975		1980	
Region	Demand	Supply	Demand	Supply
Sao Paulo	958,423	735,979	1,703,559	1,409,040
Guanabara/ Rio de Janeiro	191,684	279,541	330,387	469,495
Minas Gerais/ Espirito Santi	196,008	223,277	387,172	336,919
South	44,678	168,890	59,366	300,385
North/ North East	50,445	2,563	100,665	5,527
TOTAL	1,441,238	1,410,250	2,581,149	2,521,366

Source: ABIFA

B.3 Chilean Foundry Statistics

Source: Compania Industrias Chilenas CIC S.A.

Foundry Production (1971):	Steel	16,000 metric tons
	Grey Iron	31,000
	Non-ferrous	6,000
		53,000 metric tons

Size Distribution:

Total Foundries - 186

20% of the plants produce 80% of the production

In grey iron, 6% of the plants provide 41% of the production

Employment:	Professional & Technical	214
	Unspecialized Operators	1,268
	Specialized Operators:	2,228
	Helpers:	884

No significant problems with raw materials, combustibles, or transportation. In establishing new installations, the major problems lie in achieving production level and maintaining quality control.

APPENDIX C: DATA DEVELOPMENT

Sources

Foundry equipment manufacturers, their representatives, foundry consulting companies, and local Massachusetts foundries were contacted for information related to the costs of alternate green sand molding methods. A summary of the organizations which contributed information is presented in Appendix A.

The data collected on twenty nine alternative molding systems includes the following:

1. Equipment Costs

All equipment necessary to produce the molds is included. This includes benches, hand tools, ramming equipment, and molding machines. Tight flask costs are based on production requirement of one hour. For "flaskless" molding, one snap flask is required and jackets and weights are calculated for one half hour cooling requirement. Cranes are included when the molding weight exceeds 75 pounds per molder. Conveyors are required for methods in which pouring is done at a pouring station remote from the molding area. Conveyors are sized from the flask geometry and one hour's production. The collected capital cost becomes the coefficient of the integer decision variable in the MIP model.

2. Energy and Maintenance

Energy and maintenance (non-labor) costs are evaluated on an hourly rate, based on consumption estimates, and cost and frequency of repairs respectively.

Air consumption estimates for jolt machines are based on 20 3 inch strokes per cycle @ 100 psi. The compressed air used per mold is:

$$SCF/mold = 0.372*D^2 \qquad \text{where D is the jolt cylinder dia.(inches)}$$

Hand rammers are rated at 15 CFM @ 90 psi. Assuming a usage of 5 seconds per square foot of mold area:

$$SCF/mold = 9.028*(\text{mold area, square ft.})$$

Based on estimates of electric compressor conversion efficiencies (Joy Manufacturing Company), the following conversion factor was used:

Electric Power (KW) = 0.153*Air Consumption Rate (CFM @ 100 psi)

Maintenance costs reflect the parts and lubricants required to keep the molding equipment operational. The estimates of the frequency and types of repairs were obtained from equipment manufacturers, and local foundries.

3. Labor Costs

The direct labor required for each alternate method is collected. Six categories of labor are included:

- Unskilled
- Semi-skilled
- Skilled
- Pouring
- Maintenance
- Pattern

Unskilled, semi-skilled and skilled labor are based on engineering estimates of the requirements of each system. Pouring labor is included since automated mold handling systems produce a significant saving in the labor required for pouring. For automated systems one full time pourer is assumed. For all other systems, the amount of pouring labor is scaled to the mold size and hourly production of the method. Estimates of the time and manpower required to pour off molds distributed throughout the shop are converted into pouring man-hours per production hour. Figure C-1 illustrates the pouring labor required as a function of the mold area.

Maintenance labor estimates are based on the time and frequency of repair and inspections.

Pattern labor is discussed below.

The labor input in standard man-hours is calculated by multiplying the hours of each skill level by the ratio of the appropriate wage rate to the base (unskilled) wage.

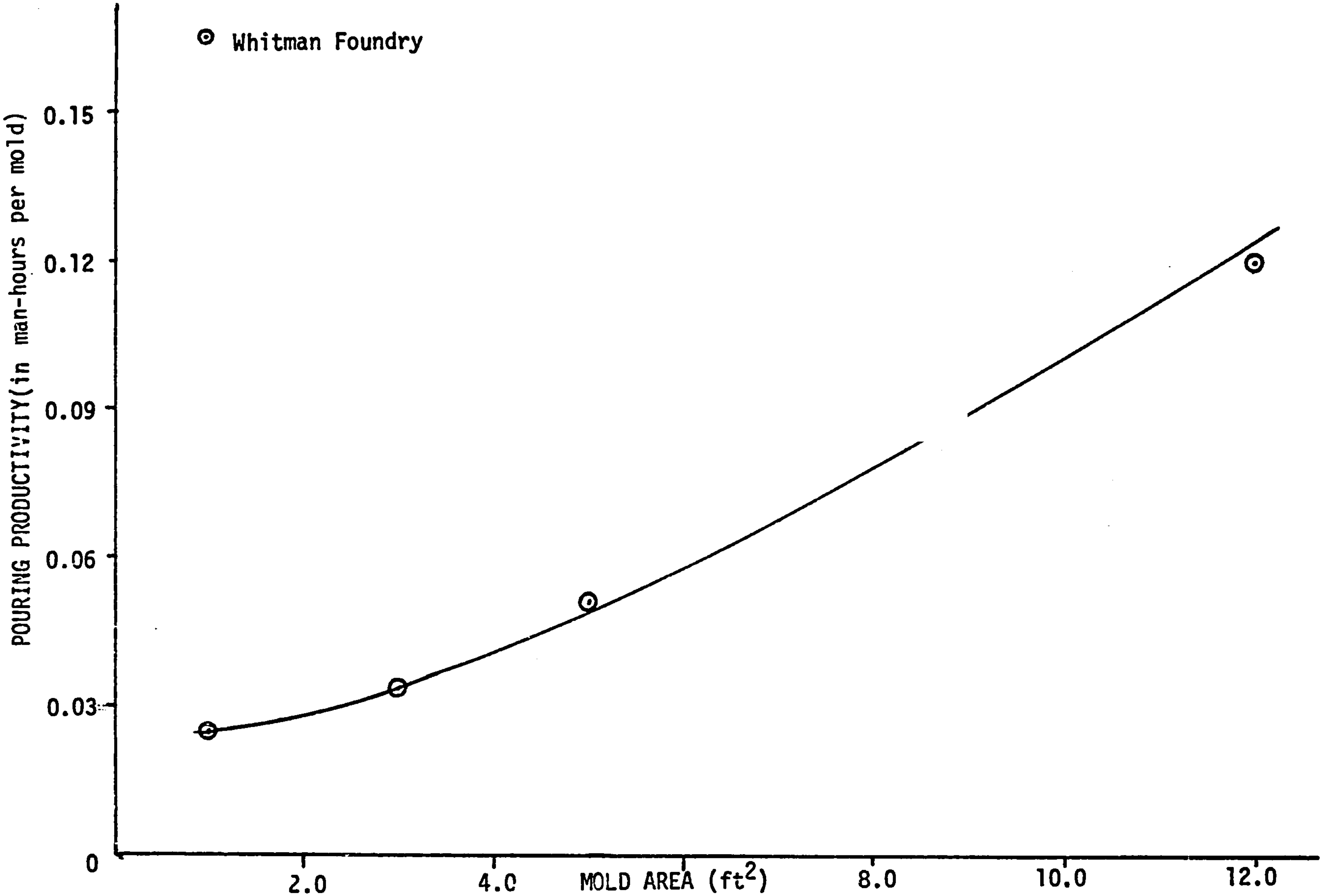

Figure C-1: Standardized Pouring Productivities; Production Methods #1 - #2

4. Pattern Cost

The principal objective in estimating pattern costs is to properly weight the alternative designs of Matchplate, cope and drag, and specially rigged patterns. Granted that actual pattern costs are highly variable, estimates for "average" designs were obtained from foundry engineers and equipment manufacturers. Pattern materials were restricted to epoxy and metal. No attempt was made to investigate pattern designs for short runs (under 500) as the variability in cost, influence of productivities, and number of alternative designs possible increase rapidly. The calculation of pattern costs is based on the following:

4.1 Estimates of Standard Pattern Costs

Estimates for the range of pattern costs for each alternative were obtained. Pattern cost was assumed to vary as the square root of mold area. Functional relationships were obtained for each method based on U.S. data:

	Costs per Pattern
Hand Methods:	$25*(MA)^{1/2} - 100$
Matchplate	$18*(MA)^{1/2}$, where MA = mold area in square in.
Cope and Drag:	$50*(MA)^{1/2} - 200$
Automated Matchplate:	$21.6*(MA)^{1/2}$
Automated Flaskless Molding:	Disamatic 2013 = $1,500 Disamatic 2032 = $1,750
Automated Tight Flask Molding:	$60*(MA)^{1/2} - 240$

Hand methods assume cope and drag designs but each molding station will use only one (cope or drag) pattern. Effectively two molding stations are used to make each mold.

The pattern cost for each method is converted into hourly pattern cost by:

$$\text{Number of new patterns/year} = \frac{\text{Number of patterns required}}{\text{Pattern life in years}}$$

$$\text{Pattern cost/hour} = \frac{\text{Cost/pattern * number of patterns/year * castings/hour}}{\text{Number of castings/year}}$$

In order to permit the pattern cost to fluctuate with the wage level, the hourly pattern cost is separated into capital and labor components. Since direct labor typically accounts for one third of the fully absorbed pattern cost, one half of the hourly pattern cost is allocated to labor costs. The other 50% represents a fixed hourly cost of operation. The number of pattern workers hours per production hour is calculated from the hourly pattern costs based on a wage rate of $7.50 per hour.

5. Productivities

Estimates of the hourly production rates were obtained for each of the alternate production methods. For automatic cycle and automated methods, rated production is specified by the equipment manufacturers. Actual production rates, including downtime for maintenance, repair and pattern changes is based on 80% of the rated production.

Estimates of productivities for hand and simple machines were obtained from foundry engineers and manufacturers representatives in New England. The estimates were highly variable, quite sensitive to the specific combination of sand and mold handling, and the type of pattern specified. For hand techniques, the variation between loose pattern-shovel sand-floor pouring and mounted pattern-overhead sand-conveyor pouring were quite high (up to a factor of five). For standard estimates, the following assumptions were made:

Mounted Cope and Drag Patterns
Flaskless Molding
Shovel Sand
Floor Pouring

These estimates represent actual productivities and no efficiency factor was applied.

6. Summary of Cost Calculations

To briefly summarize, the costs for each method are collected and categorized as capital costs, wage dependent hourly operating costs, and wage independent hourly operating costs. The hourly costs are converted to costs per mold by multiplying by the productivity of each method for each casting size. The present discounted value of these costs represents the coefficient of the continuous production variables in the MIP model. The costs, productivities and manpower requirements for the 29 alternative production methods are broken down in the following paragraphs.

Hand Methods: Methods #1-6

These techniques perform the seven moldmaking operations discussed in Section 4.1 entirely by hand. A flask is placed on a bench by the moldmaker and a pattern representing one half of the part shape is mounted securely to it. The flask is filled with "green" sand and compressed (rammed) tightly against the pattern. The ramming can be done by hand, or air powered tools. The flask is then turned over and the pattern unclamped from the flask. In an operation requiring considerable skill and time, the pattern is removed (drawn) from the flask leaving the impression of the part in the densely packed molding sand. The mold half is then set aside and the process repeated for the other half of the part shape. In a simple two part mold, the top half of the mold, the cope, is made first; then the bottom half, the drag, is made. When both mold halves have been rammed and the patterns removed, the cores (if any) are located in the molds, and the cope placed on top of the drag to close the mold. The mold is now ready for removal to the pouring area.

For some, and particularly large parts the "tight" flasks remain with the completed sand mold when it is removed to the pouring area. Recently, removable "pop" or "snap" flasks have replaced tight flasks for small and medium sized molds. The snap flasks are released from the mold before it is removed to the pouring area, and reused on successive molds. Snap flasks eliminate the requirement of costly, precisely fitted tight flasks and are practical when the molds are small enough to be handled by one or two men. To provide the mold with lateral support, "jackets" must be slipped over the mold before it is poured. Fewer jackets are needed, however, and they do not require the accurate alignment mechanism that tight flasks do.

Methods #1-3:

These methods differ primarily in the size of the mold produced.

Maximum Flask Size

Method #1: 16 x 16 x 6/6
#2: 24 x 24 x 8/8
#3: 36 x 48 x 16/16

Methods #1 and #2 use snap flasks and molds are made on a bench. Method #3 uses tight flasks and the molds are made directly on the floor.

Equipment Costs

Method:	#1	#2	#3
Bench	$100	$200	
Hand Rammer	15	30	30
Shovel	15	15	15
Hand Tools	50	60	60
Bottom Boards, Weights and Jackets*	285	214	120
Flasks	231	340	800
Spares @ 10%	70	86	270
Crane and Hoist	____	____	1,550
Total Equipment Cost	$776	$945	$2,965

*based on one half hour's production requirement

Productivity and Labor Requirement

Productivities varied greatly and reflect the wide range in complexity of casting shapes. An engieering estimate of the actual productivity has been made reflecting a "typical" mold.

		Labor Required per Production Hour		
	Molds/Hour (range)	Skilled	Semi-Skilled	Pouring*
Method #1:	10 (4-30)	1		0.28
#2:	4 (1-10)	1	1	0.16
#3:	1 (0.5-2)	1	1	0.12

*Taken from Figure C-1.

Methods #4-6:

These methods are identical to #1-3 except that pneumatic hand-held rammers replace the simple hand rammers. Offsetting the increase in capital investment is an increase in productivity of approximately 10%-20%.

Maximum Flask Size

Method #4:	16 x 16 x 6/6
#5:	24 x 24 x 8/8
#6:	36 x 48 x 16/16

Equipment costs are increased by the pneumatic rammers (@ $650) and a 10-20% increase in bottom boards, weights and jackets. Operating costs must also consider the air consumption of the equipment.

	Equipment Costs	Air Consumption (SCF/mold)
Method #4:	$1,526	16.0
#5:	$1,656	37.0
#6:	$3,515	110.0

Productivity and Labor Requirement

	Molds/Hour (range)	Labor Required per Production Hour		
		Skilled	Semi-Skilled	Pouring
Method #4:	11 (4-36)	1		0.336
#5:	4.5 (1-12)	1	1	0.18
#6:	1.2 (0.5-2.5)	1	1	0.144

Simple Machine Molding: Methods #7-13

In simple machine molding techniques, pneumatically powered equipment is used to perform the basic operation of moldmaking: flask ramming, and pattern drawing. In simple jolt machines, the surface on which the mold is made is supported by a pneumatic cylinder. The molding sand is rammed against the pattern by a rapid up-down motion of the jolt cylinder. Typically, this jolting is aided by hand operated pneumatic rammers. All other operations can be performed by hand. Often to increase the productive efficiency of the machine, automatic pattern drawing equipment, or roller conveyors to remove the molds will be added.

An important variation on the simple jolting method is the jolt/squeeze machine on which the Matchplate process is based. The sequence of molding operations in Figure 5 is based on the Matchplate molding process, and Figure 6 illustrates the arrangement of the Matchplate pattern and flasks. The cope and drag flasks are clamped to the Matchplate, the drag flask filled with sand and jolted. The flask set is rolled over (by hand for small molds or assisted by trunnion arms for larger ones), and the cope flask filled with sand. The mold halves are then "squeezed" by raising the jolt table while the top of the mold is supported by a squeeze head mounted on the machine. Compaction of the sand by this combined jolt and squeeze increased sand density, and strength, improves the quality of the finished castings, and achieves a substantial increase in productivity. To maximize the efficiency of the jolt/squeeze equipment, pattern drawing is usually aided by lifting devices on the machine or vibrators attached to the pattern.

Simple Jolt Methods: Methods #7-9

These methods all employ simple jolt machines and differ primarily in the size of the mold produced.

	Maximum Flask Size
Method #7:	12 x 12 x 10/10
#8:	24 x 31 x 16/16
#9:	36 x 48 x 20/20

All use tight flasks to support the mold and roller conveyors to hasten mold removal.

Equipment Costs

Method:	#7	#8	#9
Jolt Machine	$831	$2,771	$5,645
Roller Conveyor	150	375	400
Flasks, Weights	795	1,908	2,300
Pneumatic Rammer	650	650	650
2 T. Crane and Hoist			1,550
Spares @ 10%	242	570	1,055
Total Equipment Cost	$2,670	$6,274	$11,600

Energy Consumption and Non-Labor Operating Costs

	Air Consumption (SCF/mold)	Hourly Consumption of Spare Parts
Method #7:	13	$.0175
#8:	63	.0325
#9:	146	.06

Productivity and Labor Requirements

While these machine methods complete the molding cycle more rapidly than the hand methods, there remains considerable variability in the estimates of rated and actual output for these techniques. Also, since the equipment is more sophisticated, estimates of the maintenance labor must be included.

	Molds/Hour (range)	Labor Required per Production Hour			
		Semi-Skilled	Unskilled	Maintenance	Pouring
Method #7:	13.5 (9-18)	1		.0065	0.375
#8:	9 (6-12)	1	1	.022	0.5
#9:	4 (2-6)	1	1	.049	0.625

Jolt/Squeeze Methods: Methods #10-13:

These methods are based on jolt/squeeze machines and employ snap flasks.

Maximum Flask Size

Method #10:	16 x 20 x 8/8
#11:	20 x 25 x 10/10
#12:	24 x 30 x 11/11
#13:	30 x 36 x 13/13

Equipment Costs

Method:	#10	#11	#12	#13
Jolt/Squeeze Machine	$4,037	$4,995	$10,274	$14,690
Roller Conveyor	400	624	600	525
Flasks	257	426	512	613
Bottom Boards, Weights, and Jackets	840	1,090	1,035	1,030
Crane and Hoist		1,100	1,550	1,550
Spares @ 10%	553	823	1,400	1,870
Total Equipment Cost	$6,090	$9,060	$15,370	$20,550

Energy Consumption and Non-Labor Operating Costs

	Air Consumption (SCF/mold)	Hourly Consumption of Spare Parts
Method #10:	7	.0175
#11:	8	.0325
#12:	11	.04
#13:	14	.0525

Productivity and Labor Requirements

	Molds/Hour (range)	Labor Required per Production Hour		
		Semi-Skilled	Maintenance	Pouring
Method #10:	24 (16-32)	1	.0243	0.72
#11:	20 (15-25)	1	.039	0.74
#12	15 (10-20)	1	.082	0.75
#13	10 (8-12)	1	.12	0.68

Cope and Drag Lines: Methods #14-20

The principal difference between Matchplate molding and cope and drag lines is the pattern equipment. The Matchplate pattern has the shapes of the two halves of the casting represented on one metal plate and is mounted to the flask each time a mold is made. Cope and drag lines have two patterns and typically use two molding machines, each of which produces one half of the mold exclusively. The patterns are fixtured to the machine for the entire production run. Tight flasks are generally preferred in cope and drag molding because the mold halves are produced at two different locations and the tight flasks protect the molds during the various mold handling activities.

For smaller sizes and shorter runs, one machine may be used which alternately produces all the cope (or drag) halves, then the others. Cope and drag lines are preferred over Matchplate molding for larger mold sizes and unusual molding requirements like very deep draws.

A number of the operations performed by the molder in hand and simple machine methods are performed by machine in cope and drag molding. In addition to jolt or jolt/squeeze ramming of the molding sand, pattern drawing, drag rollover (if required), and mold closing may be machine operations. In operator controlled cope and drag lines, the timing of each molding step for each molding cycle is manually controlled. In automatic cycle cope and drag lines, the timing of the machine operations is adjusted during setup and thereafter the operator is required only to initiate the molding sequence and remove the completed molds. Figure 8 illustrates a cope and drag line in which most of the molding operations are performed by the operator. In the foreground, cores have been set in two of the completed drag molds and a worker is preparing to lower a cope mold onto one of them. The machine operator in the right background is preparing to mount a flask on the pattern. The other operator has just completed the compaction of the molding sand and is about to begin drawing the pattern from the mold. The mold will be lifted from the pattern on two sets of rollers and the operator will push the mold from the machine station.

Operator-Controlled Cope and Drag Lines: Methods #14-17

These methods are all similar to the molding system illustrated in Figure 8.

Maximum Flask Size

Method #14:	18 x 26 x 9/9
#15:	22 x 32 x 9/9
#16:	36 x 48 x 16/16
#17:	40 x 30 x 12/12

Equipment Costs

Method:	#14	#15	#16	#17
Molding Machine	$7,245	$12,865	$19,500	$15,780
Roller Conveyors	432	1,000	2,182	437
Flasks and Weights	3,584	4,000	6,300	2,550
Hand Rammers		1,300	1,300	
Crane and Hoist	1,100	1,550	1,550	1,550
Spares @ 10%	1,236	2,072	3,080	1,950
Total Equipment Cost	$13,600	$22,790	$33,900	$21,400

Energy Consumption and Non-Labor Operating Costs

	Air Consumption (SCF/mold)	Hourly Consumption of Spare Parts
Method #14:	260	.0325
#15:	84	.04
#16:	155	.12
#17:	50	.06

Productivity and Labor Requirements

	Molds/Hour	Labor Required per Production Hour: Semi-Skilled	Unskilled	Maintenance	Pouring
Method #14:	16	1		.058	0.57
#15:	25	2		.10	1.2
#16:	14	2	1	.156	2.16
#17:	10		1	.12	0.68

Automatic Cycle Cope and Drag Lines: Methods #18-20

Each of these methods is based on two matched molding machines which produce the cope and drag molds with preset cycle controls. Operator interactions are restricted to flask placement, and mold removal and closing. To facilitate the machine "pacing" of the molding activity, the molding sand is supplied by an overhead sand delivery system.

Maximum Flask Size

Method #18:	26 x 16 x 9/9
#19:	36 x 18 x 12/12
#20:	47 x 27 x 13/13

Equipment Costs

Method:	#18	#19	#20
Molding Machine and Sand Delivery Equipment	$37,600	$57,780	$117,400
Roller Conveyor	562	750	875
Flasks and Weights	2,370	3,550	4,860
Crane and Hoist	1,100	1,550	1,900
Spares @ 10%	4,135	6,370	12,500
Total Equipment Cost	$45,480	$70,000	$137,500

Energy Consumption and Non-Labor Operating Costs

	Air Consumption (SCF/mold)	Hourly Consumption of Spare Parts
Method #18:	24	.20
#19:	58	.30
#20:	145	.60

Productivity and Labor Requirements

	Molds/Hour	Labor Required per Production Hour		
		Unskilled	Maintenance	Pouring
Method #18:	20	2	.072	0.61
#19:	20	2	.072	0.70
#20:	15	2	.072	1.26

Slinger Operations: Methods #21-22

For large mold sizes (36 x 48 and above), sand slinger systems represent a technical alternative to cope and drag molding. The essential difference is in the method of compacting the molding sand. Sand slingers deliver the molding sand to the flask at high velocities, and the kinetic energy of the sand being delivered provides the energy needed to compact the sand against the pattern and flask surfaces. The other moldmaking operations from pattern drawing to mold closing can be performed by manual or machine techniques. One of the alternatives (Method #21) assumes these operations will be performed by a crew of men using simple equipment. The other (#22) uses a higher capacity slinger, and a rollover/draw machine to improve the productivity and reduce the skill level of the operators. Each method has a maximum flask size of 54 x 36 with effectively no restri on on the maximum draw permitted.

Equipment Costs

Method:	#21	#22
Sand Slinger	$50,000	$76,000
Rollover/Draw Machine		25,000
Roller Conveyor		540
Flasks and Weights	1,750	3,405
Crane and Hoist	2,550	2,550
Spares	2,000	5,000
Total Equipment Cost	$56,300	$112,700

Energy Consumption and Non-Labor Operating Costs

	Electric Power (KW)	Hourly Consumption of Spare Parts
Method #21:	20	$0.50
#22:	52	$1.01

Productivity and Labor Requirement

		Labor Required per Production Hour			
	Molds/Hour	Skilled	Semi-Skilled	Maintenance	Pouring
Method #21:	2.4	2		0.2	0.31
#22:	6.0		4	0.4	0.78

Automated Flaskless Molding: Methods #23-27

The automated flaskless molding methods included in the foundry model are automated Matchplate methods (#23-25) and the Disamatic molding method (#26-27). In both designs, the basic molding operations are all performed by machine. Semi-skilled equipment operators and maintenance workers provide support for the machine-based systems. These alternatives are illustrated in Figures 9, 10, and 11.

Data is provided by Disamatic, Inc. and the Hunter Automated Machinery Corporation.

Maximum Flask Size

Method	
#23: HMP 10	14 x 19 x 7
#24: HMP 20	20 x 24 x 8
#25: HMP 30	24 x 30 x 12
#26: DISA 2013	19 x 24 x 8
#27: DISA 2032	24 x 30 x 12

Equipment Costs

Method:	#23	#24	#25	#26	#27
Machinery	$44,200	$63,200	$92,000	$301,000	$518,250
Conveyor	4,500	5,880	5,760	73,447	98,960
Jackets/Flasks	3,042	3,560	3,712		
Spares	5,274	7,265	10,150	20,000	30,000
Total Equipment Cost	$58,000	$79,900	$111,620	$394,500	$647,000

Energy Consumption and Non-Labor Operating Costs

	Air Consumption (SCF/mold)	Electric (KW)	Hourly Cost of Spare Parts
Method #23:	0.6	9	$2.21
#24:	1.0	15	3.16
#25:	1.9	26	4.60
#26:	20.7	30	5.00
#27:	22.0	40	7.50

Productivity and Labor Requirement

		Labor Required per Production Hour		
	Molds/Hour	Semi-Skilled	Maintenance	Pouring
Method #23:	96	1	.5	1
#24:	80	1	.5	1
#25:	64	1	.5	1
#26:	288	1	.7	1
#27:	240	1	.7	1

Automated Tight Flask Molding: Methods #28-29:

Specially designed tight flask molding lines are used in the largest production foundries where a limited and well-controlled set of mold sizes is required. Particularly in the automotive, and plumbing supply markets, these systems appear to be competitive with the more recently innovated flaskless methods. Some equipment cost and productivity estimates were obtained during the survey, but they should be regarded as only typical of the range of costs and production rates these systems are capable of. Production and cost variables will vary with a specific application, and more precise estimates from equipment manufacturers was not available. Though the molding equipment usually perform all necessary tasks, these tight flask molding lines invariably require a sizable operating crew. Maximum flask sizes are 24 x 32 x 12 (for Method #28), and 40 x 48 x 16 (for Method #29).

Equipment Costs

Method:	#28	#29
Basic Molding Line	900,000	2,500,000
Conveying and Flask Handling Equipment	312,000	353,000
Flask, Sand Handling, Spares	200,000	1,035,000
Total Equipment Cost	$1,412,000	$3,888,000

Energy Consumption and Non-Labor Operating Costs

	Electric Power (KW)	Maintenance Cost ($/hour)
Method #28:	75	$12.50
#29:	125	30.00

Productivity and Labor Requirements

		Labor Required per Production Hour			
	Molds/Hour	Skilled	Semi-Skilled	Maintenance	Pouring
Method #28:	240		1	1	1
#29:	192	1	4	1	1

7. Programming Requirements

The investment and operating costs were assembled into the objective function and constraint coefficients by a FORTRAN program. The input data consisted of the problem specification, and the costs, production rates, and manpower requirements. The output data consist of the objective function and constraint coefficients.

The mixed integer programming problem was solved by the MPSX programming system. MPSX is an IBM designed program package to perform optimization operations of mathematical programming problems. It can solve linear, separable, mixed integer, and generalized upper bound programming problems. The relevant IBM source documents are presented in the list of references (42, 43, 44).

The values of the X_i's and $Y_{i,j}$'s are used to calculate the capital and labor input required for each simulation run. A FORTRAN program was used to perform these manipulations.

APPENDIX D: MIXED INTEGER PROGRAMMING MODEL SOLUTIONS: SMALL PRODUCTION FOUNDRY(10,000 T/YEAR)

I = ALTERNATE PRODUCTION METHOD NUMBER
X = DECISION VARIABLE - NO. OF UNITS OF METHOD I
Y = DECISION VARIABLE - NO. OF MOLDS J PRODUCED BY METHOD I PER YEAR

ECONOMIC PARAMETERS					VALUES OF Y FOR MOLD SIZE(J)			
WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.0	0.10	2000.	1	42	830000.	0.	0.	0.
			2	46	0.	368000.	0.	0.
			3	9	0.	0.	1400.	17300.
			6	1	0.	0.	4000.	0.
			8	2	0.	0.	36000.	0.
00.25	0.10	2000.	6	1	0.	0.	0.	1300.
			8	3	0.	0.	41400.	0.
			9	2	0.	0.	0.	16000.
			11	10	64000.	368000.	0.	0.
			12	6	719986.	0.	0.	0.
00.50	0.10	2000.	11	9	0.	360000.	0.	0.
			12	7	830000.	2495.	0.	0.
			13	2	0.	5504.	37248.	0.
			16	1	0.	0.	4152.	17300.
02.00	0.10	2000.	11	1	0.	40000.	0.	0.
			16	1	0.	887.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	2	830000.	7113.	41400.	0.

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
04.00	0.10	2000.	16	1	0.	0.	0.	17300.
			24	3	0.	368000.	0.	0.
			25	2	830000.	0.	41400.	0.
07.50	0.10	2000.	16	1	0.	0.	0.	17300.
			24	3	0.	368000.	0.	0.
			25	2	830000.	0.	41400.	0.
00.25	0.20	2000.	6	1	0.	0.	0.	1300.
			8	3	46000.	0.	41400.	0.
			9	2	0.	0.	0.	16000.
			11	19	784000.	368000.	0.	0.
00.50	0.20	2000.	8	2	0.	0.	36000.	0.
			11	9	0.	360000.	0.	0.
			12	7	830000.	2496.	0.	0.
			16	1	0.	5504.	5400.	17300.
02.00	0.20	2000.	11	1	0.	40000.	0.	0.
			16	1	0.	887.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	2	830000.	7113.	41400.	0.
04.00	0.20	2000.	11	1	0.	40000.	0.	0.
			16	1	0.	886.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	2	830000.	7113.	41400.	0.
07.50	0.20	2000.	16	1	0.	0.	0.	17300.
			24	3	0.	368000.	0.	0.
			25	2	830000.	0.	41400.	0.

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.0	0.30	2000.	1	40	800000.	0.	0.	0.
			2	47	30000.	368000.	0.	0.
			3	4	0.	0.	5400.	5300.
			6	5	0.	0.	0.	12000.
			8	2	0.	0.	36000.	0.
00.25	0.30	2000.	3	1	0.	0.	0.	1300.
			8	3	46000.	0.	41400.	0.
			9	2	0.	0.	0.	16000.
			11	19	784000.	368000.	0.	0.
00.50	0.30	2000.	8	2	0.	0.	36000.	0.
			11	9	0.	360000.	0.	0.
			12	7	830000.	2496.	0.	0.
			16	1	0.	5504.	5400.	17300.
02.00	0.30	2000.	11	1	0.	40000.	0.	0.
			12	4	479990.	0.	0.	0.
			16	1	3587.	8000.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	1	346422.	0.	41400.	0.
04.00	0.30	2000.	11	1	0.	40000.	0.	0.
			16	1	0.	887.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	2	830000.	7113.	41400.	0.
07.50	0.30	2000.	16	1	0.	0.	0.	17300.
			24	3	0.	368000.	0.	0.
			25	2	830000.	0.	41400.	0.

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.0	0.20	4000.	1	21	830000.	0.	0.	0.
			2	23	0.	368000.	0.	0.
			3	4	0.	0.	0.	16000.
			6	1	0.	0.	5400.	1300.
			8	1	0.	0.	36000.	0.
00.25	0.20	4000.	6	1	0.	0.	0.	1300.
			8	2	46014.	0.	41400.	0.
			9	1	0.	0.	0.	16000.
			11	5	64000.	368000.	0.	0.
			12	3	719986.	0.	0.	0.
00.50	0.20	4000.	11	5	64000.	368000.	0.	0.
			12	3	72000.	0.	0.	0.
			13	1	46000.	0.	32330.	0.
			16	1	0.	0.	9070.	17300.
02.00	0.20	4000.	11	1	0.	40887.	0.	0.
			16	1	0.	0.	0.	17300.
			24	1	0.	320000.	0.	0.
			25	1	830000.	0.	41400.	0.
04.00	0.20	4000.	11	1	0.	40887.	0.	0.
			16	1	0.	0.	0.	17300.
			24	1	0.	320000.	0.	0.
			25	1	830000.	7113.	41400.	0.

LARGE PRODUCTION FOUNDRY(50,000 T/YEAR)

ECONOMIC PARAMETERS					VALUES OF Y FOR MOLD SIZE(J)					
					SHORT RUN JOBS			LONG RUN JOBS		
WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	12X12	18X18	24X30
00.0	0.10	2000.	1	165	0.	0.	0.	3300000.	0.	0.
			2	185	0.	8000.	0.	4999.	1470750.	0.
			7	31	830000.	0.	0.	7001.	0.	0.
			8	12	0.	0.	41400.	0.	1250.	164000.
			11	9	0.	360000.	0.	0.	0.	0.
00.25	0.10	2000.	7	31	830000.	0.	0.	0.	0.	0.
			8	12	0.	0.	41400.	0.	0.	164000.
			11	47	0.	368000.	0.	72065.	1472000.	0.
			12	27	0.	0.	0.	3239935.	0.	0.
00.50	0.10	2000.	7	31	830000.	0.	0.	0.	0.	0.
			8	11	0.	0.	41400.	0.	0.	156011.
			11	46	0.	368000.	0.	0.	1472000.	0.
			12	27	0.	0.	0.	3239935.	0.	0.
			13	1	0.	0.	0.	72065.	0.	7989.
02.00	0.10	2000.	11	3	0.	97634.	0.	0.	0.	0.
			23	4	767975.	0.	0.	0.	0.	0.
			24	4	62025.	270366.	0.	37390.	319926.	0.
			25	8	0.	0.	41400.	3274609.	0.	164000.
			26	2	0.	0.	0.	0.	1152074.	0.
04.00	0.10	2000.	23	4	767975.	0.	0.	0.	0.	0.
			24	3	62024.	368000.	0.	37202.	0.	0.
			25	7	0.	0.	41400.	2762577.	0.	164000.
			26	3	0.	0.	0.	512221.	1472000.	0.
07.50	0.10	2000.	24	5	830000.	368000.	0.	0.	0.	0.
			25	1	0.	0.	41400.	0.	0.	0.
			26	3	0.	0.	0.	129071.	1472000.	0.
			27	2	0.	0.	0.	3182929.	0.	164000.

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	SHORT RUN JOBS 12X12	SHORT RUN JOBS 18X18	SHORT RUN JOBS 24X30	LONG RUN JOBS 12X12	LONG RUN JOBS 18X18	LONG RUN JOBS 24X30
00.0	0.20	2000.	1	165	0.	0.	0.	3300000.	0.	0.
			2	185	0.	8000.	0.	4999.	1462750.	0.
			7	31	830000.	0.	0.	7001.	0.	0.
			8	12	0.	0.	41400.	0.	9250.	164000.
			11	9	0.	360000.	0.	0.	0.	0.
00.25	0.20	2000.	7	31	830000.	0.	0.	0.	0.	0.
			8	12	0.	0.	41400.	32062.	0.	164000.
			11	48	0.	368000.	0.	160000.	1472000.	0.
			12	26	0.	0.	0.	3119938.	0.	0.
00.50	0.20	2000.	7	31	830000.	0.	0.	0.	0.	0.
			8	12	0.	0.	41400.	0.	0.	164000.
			11	47	0.	368000.	0.	72065.	1472000.	0.
			12	27	0.	0.	0.	3239935.	0.	0.
02.00	0.20	2000.	11	17	560000.	368000.	0.	0.	32000.	0.
			12	1	78006.	0.	0.	37390.	0.	0.
			23	1	191994.	0.	0.	0.	0.	0.
			24	9	0.	0.	0.	0.	1440000.	0.
			25	8	0.	0.	41400.	3274610.	0.	164000.
04.00	0.20	2000.	12	1	30018.	0.	0.	37202.	0.	0.
			23	3	575982.	0.	0.	0.	0.	0.
			24	3	224000.	368000.	0.	0.	0.	0.
			25	7	0.	0.	41400.	2762577.	0.	164000.
			26	3	0.	0.	0.	512221.	1472000.	0.
07.50	0.20	2000.	7	1	3202.	0.	0.	0.	0.	0.
			24	5	826798.	368000.	0.	37202.	0.	0.
			25	7	0.	0.	41400.	2762577.	0.	164000.
			26	3	0.	0.	0.	512221.	1472000.	0.

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	SHORT RUN JOBS 12X12	18X18	24X30	LONG RUN JOBS 12X12	18X18	24X30
00.0	0.20	4000.	1	82	0.	0.	0.	3280000.	0.	0.
			2	90	0.	0.	0.	0.	1440000.	0.
			7	16	830000.	0.	0.	32000.	0.	0.
			8	6	0.	0.	41400.	0.	0.	164000.
			11	5	0.	368000.	0.	0.	32000.	0.
00.25	0.20	4000.	7	16	830000.	0.	0.	0.	0.	0.
			8	6	0.	0.	41400.	32062.	0.	164000.
			11	24	0.	368000.	0.	160000.	1472000.	0.
			12	13	0.	0.	0.	3119938.	0.	0.
00.50	0.20	4000.	7	16	830000.	0.	0.	0.	0.	0.
			8	6	0.	0.	41400.	0.	0.	164000.
			11	23	0.	368000.	0.	0.	1472000.	0.
			12	14	0.	0.	0.	3312000.	0.	0.
02.00	0.20	4000.	11	2	0.	97634.	0.	0.	0.	0.
			23	2	767975.	0.	0.	0.	0.	0.
			24	2	62024.	270366.	0.	37390.	319926.	0.
			25	4	0.	0.	41400.	3274610.	0.	164000.
			26	1	0.	0.	0.	0.	1152074.	0.
04.00	0.20	4000.	23	1	383988.	0.	0.	0.	0.	0.
			24	3	446012.	368000.	0.	37390.	319926.	0.
			25	4	0.	0.	41400.	3274610.	0.	164000.
			26	1	0.	0.	0.	0.	1152074.	0.
07.50	0.20	4000.	24	3	830000.	368000.	0.	0.	177000.	0.
			25	1	0.	0.	41400.	700639.	0.	0.
			26	1	0.	0.	0.	0.	1152074.	0.
			27	1	0.	0.	0.	2611361.	142926.	164000.

SMALL PRODUCTION FOUNDRY(10,000 T/YEAR)

CONTINUOUS PRODUCTIVITIES

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.0	0.10	2000.	1	24	830000.	0.	0.	0.
			2	26	0.	368000.	0.	0.
			3	6	0.	0.	0.	12000.
			6	3	0.	0.	4200.	5300.
			8	2	0.	0.	37200.	0.
00.50	0.10	2000.	8	1	0.	0.	11400.	0.
			11	12	830000.	368000.	0.	0.
			13	1	0.	0.	30000.	0.
			16	1	0.	0.	0.	17300.
02.00	0.10	2000.	13	2	0.	25798.	41400.	0.
			16	1	0.	0.	0.	17300.
			24	3	830000.	342201.	0.	0.
04.00	0.10	2000.	16	1	0.	0.	0.	17300.
			24	3	830000.	342201.	0.	0.
			25	1	0.	25798.	41400.	0.
07.50	0.10	2000.	16	1	0.	0.	0.	17300.
			25	3	830000.	368000.	41400.	0.

SMALL PRODUCTION FOUNDRY(10,000 T/YEAR)

PRODUCTIVITY OF HAND METHODS INCREASED BY 50%

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.0	0.20	2000.	1	27	809996.	0.	0.	0.
			2	31	20004.	366998.	0.	0.
			3	7	0.	1002.	5400.	17300.
			8	2	0.	0.	36000.	0.
00.25	0.20	2000.	1	24	715600.	0.	0.	0.
			3	1	0.	0.	0.	1300.
			8	3	50400.	0.	41400.	0.
			9	2	0.	0.	0.	16000.
			11	10	64000.	368000.	0.	0.
00.50	0.20	2000.	8	2	0.	0.	36000.	0.
			11	9	0.	360000.	0.	0.
			12	7	830000.	2496.	0.	0.
			16	1	0.	5504.	5400.	17300.
02.00	0.20	2000.	11	1	0.	40000.	0.	0.
			16	1	0.	887.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	2	830000.	7113.	41400.	0.
04.00	0.20	2000.	11	1	0.	40000.	0.	0.
			16	1	0.	887.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	2	830000.	7113.	41400.	0.
07.50	0.20	2000.	16	1	0.	0.	0.	17300.
			24	3	0.	368000.	0.	0.
			25	2	830000.	0.	41400.	0.

SMALL PRODUCTION FOUNDRY(10,000 T/YEAR)

COST OF ALL MACHINE METHODS INCREASED BY 50%

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.0	0.20	2000.	1	42	830000.	0.	0.	0.
			2	46	0.	368000.	0.	0.
			3	4	0.	0.	0.	8000.
			6	5	0.	0.	5400.	9300.
			8	2	0.	0.	36000.	0.
00.25	0.20	2000.	6	1	0.	0.	0.	1600.
			8	4	122399.	0.	41400.	0.
			9	2	3601.	0.	0.	15700.
			11	18	704000.	368000.	0.	0.
00.50	0.20	2000.	8	2	0.	0.	36000.	0.
			11	9	0.	360000.	0.	0.
			12	7	830000.	2496.	0.	0.
			16	1	0.	5504.	5400.	17300.
02.00	0.20	2000.	11	1	0.	40000.	0.	0.
			12	4	479990.	0.	0.	0.
			16	1	3587.	8000.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	1	346422.	0.	41400.	0.
04.00	0.20	2000.	11	1	0.	40000.	0.	0.
			16	1	0.	887.	0.	17300.
			24	2	0.	320000.	0.	0.
			25	2	830000.	7113.	41400.	0.
07.50	0.20	2000.	16	1	0.	0.	0.	17300.
			24	3	0.	368000.	0.	0.
			25	2	830000.	0.	41400.	0.

SMALL PRODUCTION FOUNDRY(10,000 T/YEAR)

WAGE RATE RATIOS(ALPH) REFLECT SCARCE SKILLED LABOR

ALPH1=1, ALPH2=2, ALPH3=10,ALPH4=10,ALPH5=15

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.50	0.20	2000.	8	3	46014.	0.	41400.	0.
			11	10	64000.	368000.	0.	0.
			12	6	719986.	0.	0.	0.
			16	1	0.	0.	0.	17300.

ALPH1=0, ALPH2=2, ALPH3=10,ALPH4=10,ALPH5=15

WAGE ($US)	DISCOUNT RATE	OPERATING HOURS/YR	I	X	12X12	18X18	24X30	36X48
00.50	0.20	2000.	8	3	46014.	0.	41400.	0.
			11	10	64000.	368000.	0.	0.
			12	6	719986.	0.	0.	0.
			16	1	0.	0.	0.	17300.