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Process Planning for Aluminum Tubes: An Engineering-Operations Perspective

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Abstract

Metal forming operations such as rolling, extrusion, and drawing offer many opportunities for operations improvement through better process understanding and improved planning practices. This paper addresses medium term planning issues in aluminum tube manufacturing operations. First, we identify certain distinctive characteristics–the inherent process flexibility, close interdependence between successive stages, and economies of scale–of metal forming operations, and identify the planning and performance tradeoffs. To exploit the strategic potential of process planning, it must be closely coupled with process engineering efforts, and must simultaneously consider the facility's entire product mix. In contrast, current process engineering efforts are mainly reactive, focusing on fixing problems at individual operations, ignoring the interactions between successive stages. Similarly, planning activities are incremental, considering only individual products or orders one at a time rather than the entire range of product sizes to be manufactured. By working together, planners and engineers can develop effective process plans that exploit process capability, and adopt proactive process improvement strategies that focus on critical constraints. We describe a medium-term planning model to select standard extrusion sizes, illustrate the close linkages between planning and engineering activities, and identify research opportunities spanning management science, materials science, and mechanical engineering.

Keywords: Manufacturing, process planning, process improvement, metal forming operations, process modeling.

1. Introduction

The metal forming industry is an important link in the manufacturing chain, supplying plates and sheets, extrusions, and tubes to many major manufacturing enterprises including the automobile, aircraft, housing, and food service and beverage industries. In 1987, shipments of aluminum to United States' markets alone exceeded 15 billion pounds, valued at over $12 billion. (Aluminum Statistical Review, 1987 and Minerals Year Book, 1988). The containers and packaging market segment accounted for approximately 30% of the total usage, while building, construction and transportation consumed 20% each. Over 50% of the shipments were sheet, plate and foil products, with extrusions and tube constituting another 17%.

This paper illustrates planning and process improvement issues in metal forming operations using an example from aluminum tube manufacturing. The metal forming industry is characterized by large investments in plant and equipment, considerable economies of scale, a wide range of product offerings, strategic importance of process technology, and universal standards for specifying, measuring, and testing product quality. Maintaining high levels of utilization for prime equipment, and improving process yield are important strategic objectives. The industry also faces increasing pressures to reduce lot sizes and lead times, and meet more stringent product specifications. These trends make the planning and process engineering functions critical for competitive survival.

Despite the metal forming industry's distinctive characteristics and considerable importance, the management science literature dealing with tactical planning and process improvement models tailored to this industry is limited (e.g., Vasko, Wolf, Stott and Scheirer [1987], Newhart, Stott and Vasko [1993]). Likewise, the materials science and mechanical engineering literature focuses on studying material properties and understanding individual processing steps from a process development rather than a manufacturability or planning perspective. The paper highlights some issues at the interface bewteen engineering and management science, emphasizing the following themes and contrasting them with current practice based upon our experience with aluminum tube manufacturing:

- Just as good product design is critical for the manufacturability of discrete parts (e.g., Nevins and Whitney [1990]), process planning has strategic importance for metal forming operations. This importance stems from the wide flexibility but close coupling and tradeoffs between successive metal processing operations.

- Exploiting the strategic potential of process planning requires a systems view that simultaneously considers the impact on all stages and the processing needs of all products.
- Engineering models to characterize the process constraints must be better integrated with planning models to choose effective processing paths. The planning model uses the process constraints as input; so better process understanding can lead to more effective plans. Conversely, sensistivity analysis of the planning model with respect to process constraints must be used to prioritize engineering process improvement efforts.

Section 2 provides the necessary background on tube manufacturing, covering the overall process flow, the engineering principles and process limitations of tube drawing and extrusion, and typical current practices in planning and process engineering. Section 3 characterizes process flexibility in tube manufacturing, identifies the factors affecting extrusion and drawing workload, and describes a medium-term planning model to decide standard extrusion sizes. We then illustrate how to link engineering and planning activities, and in Section 4 we identify research opportunities in operations and deformation process modeling. Although this paper focuses on medium-term issues in tube manufacturing, the same principles also apply to other metal forming operations such as sheet manufacturing, and to strategic and operational decisions as well.

2. Tube Manufacturing: Process Flow and Engineering Principles

2.1 Characteristics of metal forming operations

Tubular products are identified by their alloy, temper and other mechanical or microstructural specifications, the physical dimensions of each piece and their variance, and geometric tolerances (e.g., eccentricity). For (hollow) tubular products, the physical dimensions are outer diameter, wall thickness, and tube length. We consider a facility that produces tubes to order in several thousand different specifications.

The tube manufacturing process consists of four main stages as shown in Figure 1: ingot casting, extrusion, tube drawing possibly with intermediate annealing operations, and finishing. Each stage can have parallel workcenters, and might be decoupled from other stages by intermediate inventories. We focus on the interactions between the two intermediate deformation processes–extrusion and drawing–although the concepts that we discuss also extend to the other stages. Extrusion, a *hot forming* operation performed by a press, converts heated cylindrical ingots into intermediate sized hollow tubes called *blooms*. Tube drawing, a *cold forming* process performed at a draw bench, further reduces the workpiece's cross-sectional dimensions (outer diameter and wall thickness) while elongating it. Since hot forming deforms the metal at an elevated temperature, it permits greater amount of deformation per unit input of energy, but cannot be tightly controlled. Cold working at or near room temperature is often necessary to achieve tight dimensional tolerances, produce small sizes (e.g., thin wall tubes), and introduce desirable material properties such as strength and uniformity. The process flow shown in Figure 1 also applies to other metal forming operations. In sheet manufacturing, for instance, rectangular ingots first undergo hot rolling and are then processed at cold rolling mills. For an introduction to extrusion, tube drawing, rolling and other metal forming processes see, for instance, Avitzur [1983], or DeGarmo, Black and Kohser [1988].

The process plan for a product is the "recipe" specifying its entire processing path including: (i) the alloy and size of the ingot to be used, (ii) the type of equipment required and the processing parameters (machine setups, processing speeds, special operating instructions) at each step, and (iii) the intermediate and final workpiece dimensions and metallurgical specifications. Equipment limitations, workpiece characteristics and the underlying physics of the deformation process together impose upper limits on the amount of deformation that can be achieved in each hot or cold forming step. In general, the number of processing steps increases as the differential between the geometries (cross-sectional areas) of the initial workpiece and final product increases.

Before discussing the engineering principles and process limitations of tube drawing and extrusion, we note three important features that are common to many metal forming operations.

- Metal forming permits a wide range of *flexibility*, i.e., the processing steps and intermediate dimensions to transform an ingot to finished dimensions can vary widely.
- The successive stages are highly *interdependent*, i.e., the choice of processing path can significantly affect the relative allocation of workload between the upstream and downstream stages.
- Hot forming operations favor *large lot sizes* because the equipment is expensive and setup times are significant. Changing production to a different size can be time consuming because it requires changing dies and other tooling, preheating ingots, and processing test runs. Another contributor to the scale economies is the fixed scrap in each batch (independent of batch size), necessary to meet specifications.

These three characteristics create opportunities to improve manufacturing effectiveness through principled process planning. We can exploit the process flexibility to achieve economies of scale in the upstream operations by introducing a greater degree of commonality in the process plans for different products. In this context, *commonality* across products refers to a shared set of processing steps from ingot casting to some intermediate hot or cold forming step. We can achieve commonality, for instance, by producing only a few standard sizes of blooms even though the number of finished product sizes is very large. Limiting the number of standard sizes has the added advantage of reducing bloom safety stocks. However, selecting a very high degree of commonality might potentially increase the downstream effort significantly since many different finished sizes must be produced from a common bloom.

2.2 Tube drawing

Blooms entering the tube mill are first crimped at one end, and then undergo one or more drawing passes. Figure 2 shows the schematic of a draw-bench for drawing with a mandrel (for illustrations of other types of tube drawing processes see, for instance, Altan, Oh and Gegel [1983] or Rowe [1983]). Each drawing pass starts by threading the tube over the mandrel, lubricating the inner and outer surfaces of the tube, and passing the crimped end of the tube through the opening of the tapered die. A set of jaws on the other side of the die grabs the crimped end of the tube, and pulls the tube through the annulus formed by the mandrel and the die. The mandrel is held in place by a rod that extends past the opposite end of the tube. The diameter of the die and mandrel respectively determine the outside and inside diameters of the drawn tube. As it is drawn, the tube decreases in outer diameter (OD) and wall thickness (WT) and increases in length. Repeated drawing steps permits the manufacture of very small tubes from initially large bloom sizes. In the following discussions, we will focus on changes in the tube's cross-sectional dimensions (OD and WT).

The *Tube Reduction Diagram*, a two-dimensional chart with OD and WT as its x and y axes, provides a convenient way to visualize a tube's process plan, the drawing constraints, and the inherent process flexibility. A more comprehensive representation of the tube drawing process would include other dimensions to represent the tube's length and eccentricity, as well as mechanical properties (e.g., hardness). Tubes (and blooms) of varying sizes correspond to distinct points on the tube reduction diagram. As shown in Figure 3, the process plan for a product is a piecewise-linear, downward-sloping path from the bloom to the finished tube, consisting of line segments, one corresponding to each drawing pass, connecting the successive intermediate drawn tube sizes. The length and orientation of line segments is governed by the following process constraints.

Tube drawing constraints

To optimize the process plan, we must first understand the process limits. For tube drawing these limits are determined by the following considerations:

- *workpiece characteristics*: e.g., the tube must not break during the drawing process;
- *process yield and quality*: the drawn tube must have acceptable surface quality, must meet dimensional tolerances, and have the required metallurgical and mechanical properties;
- *equipment capabilities*: the equipment must sustain the load necessary to draw the tube, and tool wear must be controlled; and,
- *physical and operational considerations:* for example, the setup operations of threading the tube over the mandrel and through the die must be relatively easy.

These considerations lead to five primary process constraints. For each constraint, we first discuss the underlying physics and then express the restriction mathematically (using approximations, if necessary) in terms of permissible changes in the OD and WT during each draw. In the following discussions, the subscripts *in* and *out* refer to the dimensions of the input and output tube for each draw, and CSA = π WT (OD–WT) denotes the cross-sectional area of a tube.

Maximum reduction per draw

The force required to pull the tube through the die depends on a number of factors including the required reduction, the deformation resistance of the material, friction, as well as processing conditions such as ambient temperature, lubrication, and tooling (for instance, die geometry). For a given set of processing conditions, the pulling force increases (more than proportionately) as the amount of required reduction increases. Beyond a certain limit, increasing the force might break the tube, degrade the surface quality, or cause excessive die wear. The maximum pulling force is also limited by the machine's power. Thus, workpiece failure and equipment limit the pulling force and hence the maximum amount of OD and WT reduction that can be achieved in a single drawing pass. We will refer to this restriction as the *max reduction/draw* constraint. We use the *reduction* in tube CSA as a measure for the amount of deformation; the upper limit on CSA reduction is expressed as a proportion of the CSA of the input tube at each draw. Thus, the max reduction/draw constraint becomes:

$$(CSA_{in} - CSA_{out}) / CSA_{in} \quad \leq \quad \delta CSA_{max} , \qquad (2.1)$$

where the upper limit δCSA_{max} is a prespecified value between 0 and 1. Permitting greater reduction per draw corresponds to increasing the length of each segment on the tube reduction diagram, thus decreasing the number of drawing passes needed to transform a bloom to the finished size. Reducing the number of drawing passes not only reduces total drawing effort (e.g., drawbench hours) but also has the significant added benefits of decreasing lead times and inventories, eliminating handling steps, and improving yield.

Work hardening

As the tube is drawn, the deformation within the die work-hardens the metal (and increases the tube's resistance to deformation) by increasing the average dislocation density. The drawing process exploits this hardening while simultaneously limiting its cumulative effect. Work-hardening increases the strength of the metal, preventing the smaller output tube from immediately breaking as it pulls on the remainder of the tube during the drawing process. However, in a multi-draw process plan, where the output from one draw becomes the input to the next draw, the tube work-hardens less with each draw, increasing the likelihood of breaking as it exits the die. To prevent tube breakage, we impose an upper limit on the total amount of deformation that a tube can experience before it must be *annealed.* Annealing consists of holding the tube at an elevated temperature to resoften the metal, permitting additional work-hardening and hence additional draws to further reduce the cross-sectional dimensions. We refer to the restriction limiting the cumulative work-hardening before the tube must be annealed as the *max work-hardening* constraint.

The amount of inelastic deformation, which dictates the amount of work-hardening, correlates approximately with the CSA reduction. Therefore, we can limit the amount work-hardening by specifying an upper limit on the total CSA reduction before an intermediate annealing operation is required. This approximation gives the following max work-hardening constraint:

$$(CSA_s - CSA_e) / CSA_s \quad \leq \quad \Delta CSA_{max} \, , \tag{2.2}$$

where CSA_s and CSA_e denote the tube's starting and ending cross-sectional areas between annealing steps. The parameter ΔCSA_{max} has value between 0 and 1, and exceeds δCSA_{max}.

The actual values of the limits δCSA_{max} and ΔCSA_{max} in constraints (2.1) and (2.2) can be determined through process understanding, experience and experimentation. They vary with alloy and other metallurgical parameters (e.g., Dürrschnabel [1983]), and also depend on equipment capabilities, processing conditions, as well as the dimensions of the tube (e.g., "thin wall" tubes cannot withstand high CSA reduction/draw) and its processing history.

Minimum cold work

The third class of constraints stems from a product's temper specification. Some alloys require a certain minimum amount of work-hardening after the last annealing operation to assure adequate dislocation density so that the product achieves the desired microstructures during final heat treatment. This requirement imposes a *min final cold work* constraint that we express in terms of CSA reduction as follows:

$$(CSA_l - CSA_f) / CSA_l \quad \geq \quad \tau_{min} . \tag{2.3}$$

where the subscript l denotes the tube immediately after the last annealing step, and f represents the finished tube. The parameter τ_{min} depends on the alloy and temper specification.

Sinking, ironing, and mandrel clearance

The orientation of each line segment in the drawing plan determines the relative ratio of reduction in OD to reduction in WT. This *OD-to-WT reduction ratio* impacts the process yield since it affects the surface quality and dimensional tolerances of the drawn tube. The *sinking* operation represents one extreme, with a large OD-to-WT reduction ratio due to large reduction in OD with little or no increase in WT. Sinking can lower process yield considerably. At the other extreme, the *ironing* operation has a relatively small OD-to-WT reduction ratio since it leaves the inner diameter unchanged while reducing the wall thickness. To conveniently thread the tube, we require a minimum clearance between the bulb and the inner diameter of the input tube. A very small clearance, as in ironing, impairs the production rate. We account for all these restrictions by imposing lower and upper bounds on the *drawing angle*, i.e, the slope of the line segment connecting the output tube to the input tube (for each drawing pass) in the tube reduction diagram. The *upper* and *lower* drawing angle constraints have the following form:

$$\tan \theta_{min} \quad \leq \quad (WT_{in} - WT_{out}) / (OD_{in} - OD_{out}) \quad \leq \quad \tan \theta_{max} . \tag{2.4}$$

The constraints described above, with other limitations due to material, equipment, or operating conditions, are expressed as a set of rules or *standard practices* that process planners must follow while deciding the processing steps for each product.

Calibrating the constraints

For a particular alloy and tube dimensions, the standard practice specifies the values of the various maximum and minimum CSA reduction and drawing angle parameters. In the facility that we studied, the rules for tube drawing are primarily experience-based. To accurately calibrate the constraints, we must use a combination of modeling, experimentation, and experience. Process modeling techniques such as finite element methods provide a way to visualize the complicated deformations, die interactions, lubricant effects, and deformation heating effects associated with tube drawing (see, for instance, Boer et al. [1986] or Rigaut et al. [1988] for typical modeling studies). Nonlinear finite element programs such as ABAQUS (Hibbett, Karlsson and Sorenson, Inc. [1991]) and DEFORM (Batelle Research Laboratories [1991]) are sufficiently powerful to model bulk deformation processes including the effects of large deformations, nonlinear constitutive behavior, and coupled thermomechanical deformations, although particular difficulties still exist with the modeling of three dimensional contact. Process models might not necessarily capture or accurately represents all of the relevant factors affecting the process, while designed experiments might not cover the range of conditions that modeling can simulate. So, process understanding requires combining insights from modeling, designed experiments, and manufacturing experience.

2.3 Extrusion

Extrusion involves forcing a hot metal workpiece through a die with a cutout of the required cross section. It can efficiently produce very complicated, and intricate geometries from large, simple starting workpieces. For the production of tubes, the starting extrusion workpieces are simple solid or hollow cylindrical ingots. Extrusion engineers have developed standard practice rules analogous to the tube drawing guidelines to determine if a particular bloom size can be extruded from a specified ingot on a given extrusion press (we refer to extruded tubes as blooms). These guidelines reflect the following process constraints.

First, as the differential between the cross-sectional areas of the ingot and the bloom increases, the required force to push the ingot through the die also increases. The press' capabilities therefore limit the maximum possible cross-sectional reduction. Extrusion engineers might specify this constraint as an upper limit on the *Extrusion Ratio* which is defined as the ratio of cross-sectional areas of the ingot and the bloom. This constraint is analogous to the max reduction per draw constraint for tube drawing. The capacity of the extrusion press and its cylinder size also restricts the length and diameter of the starting ingot.

The extrusion process is also constrained by thermal considerations. The ingot must be preheated above a certain minimum temperature to achieve the required deformation with the available ram force. However, the heat dissipated during deformation increases the temperature of the metal. Above a certain alloy-dependent maximum temperature the metal becomes too soft and produces weak extrusions with poor surface quality. Furthermore, certain alloys can withstand only a limited amount of deformation before they develop internal defects that either weaken the extruded tube or develop later as surface defects. These factors again limit the amount of cross-sectional reduction.

2.4 Current practice in process engineering and planning

Process planning

Process planning has two components: a short-term or *operational planning* activity of preparing the processing instructions or lot tickets for each individual order, and a longer term tactical planning function of deciding standard intermediate sizes and updating standard practice rules. These decisions are constrained by strategic choices regarding facility location, equipment capacities, process technology, and product grouping. Introducing new bloom sizes requires acquiring appropriate tooling and process experimentation. So, in the short-term, the available bloom sizes are fixed. In our experience with tube and sheet manufacturing facilities in the aluminum industry, operational planning activities are well-structured, but the medium-term decisions are often made in an incremental manner whenever the facility faces a large demand for a specific product. The bulk of the literature on process planning (see, for instance, Chang and Wysk [1985], Alting and Zhang [1989], Chang [1990]), influenced by its roots in discrete parts manufacturing, also focuses on deciding the processing steps for individual (typically machined) parts.

In a typical operational planning scenario, when a customer places an order, the planner responsible for tube drawing operations receives the product specifications and must prepare the order's routing sheet within the tube mill. For a new product, the planner: (i) selects an appropriate bloom size from the current set of standard sizes offered by the extrusion plant, (ii) determines the sequence (and intermediate dimensions) of tube drawing and annealing operations to convert the bloom to the finished size, (iii) specifies the necessary finishing operations, and (iv) orders the required number of blooms from the extrusion plant.

The process planning literature classifies planning methods into two categories: *generative* methods that construct process plans from first principles based on part geometry, tolerances, and material, and *variant* methods that identify similar parts produced previously and modify the previous process plan to accomodate any differences in the new part. Generative planning can be complex for machined parts, but is easy to implement for metal forming operations. When applied to tube drawing, we will refer to the method as *draw planning*. This procedure is easy to visualize on the tube reduction diagram (Figure 3). Given the OD and WT of a candidate bloom and the finished tube, the planner first verifies if the bloom is feasible, i.e., if its relative dimensions can satisfy the drawing angle and min cold work constraints. If feasible, the minimum number of draws required to produce the finished tube is:

$$d_{min} = \left\lceil \frac{(CSA_{fin}/CSA_{bloom})}{|\log(1-\delta CSA_{max})|} \right\rceil, \qquad (2.5)$$

where CSA_{fin} and CSA_{bloom} are the cross-sectional areas of the finished tube and bloom, and $\lceil a \rceil$ denotes the smallest integer greater than or equal to a. The process plan consists of dividing the line connecting the two points representing the bloom and the finished product into at least d_{min} segments, each corresponding to a drawing pass. Each segment must satisfy the length and orientation constraints implied by the max reduction per draw and drawing angle restrictions. Appropriate intermediate annealing steps must be introduced to meet the max work-hardening constraints. Within the prescribed limits, the planner might choose a trajectory that ensures good process yield or optimizes drawing effort.

Planners are generally more concerned with selecting a proven process plan, rather than one that explicitly considers drawing or extrusion effort. Therefore, instead of selecting the "closest" feasible bloom size for each order, they might prefer to use a larger bloom that was previously used for a product with similar dimensions. As one example, an analysis of actual process plans over a 3-month period in a tube manufacturing plant revealed that if we replaced the planner's actual bloom choices with the closest available bloom for each order, the total tube drawing effort (drawbench hours) would decrease by approximately 20%. In part, the process planners' emphasis on process feasibility rather than manufacturing effort reflects the disadvantage of using standard practice rules that on based on experience rather than deep process understanding. Furthermore, the standard practice rules do not provide any guidance on how the product quality varies with the process plan's characteristics (e.g., as drawing angle or CSA reduction per draw varies).

Process engineering

Process engineers typically specialize in individual processes, focussing on improving the efficiency or yield of that process. Thus, extrusion engineers are concerned with optimizing the extrusion speed and controlling the defect rate for a specified bloom. Similarly, for a given process plan, tube drawing engineers seek optimum die setups, lubricants, and drawing practices. Setting priorities is a challenge for process engineering since the engineer must address immediate problems with a particular process or batch while still pursuing longer term improvements. Due to the pressure to find quick solutions to disruptions in daily production, the process engineer becomes preoccupied with "fighting fires", and lacks the guidance necessary to formulate a consistent plan of attack for long-term process improvement.

Furthermore, the engineer seeks ways to incrementally modify the current practice without "reengineering" fundamental changes in the process.

Even when the opportunity exists for broader process improvement, it may be difficult to select the most critical part of the process to address. What may appear to be the most difficult problem on a local process scale may not be economically the most important constraint on the process. To increase manufacturing flexibility without sacrificing either manufacturing efficiency or quality, the engineer needs to know both which process constraints, if relaxed, would offer the most benefit and which constraints are most amenable to relaxation. In many cases the rationale for one set of constraint parameter values has been lost due to changes in technology and product mix, and the standard practices specified for a given process may be the result of habit rather than engineering knowledge.

3. Tactical Process Planning for Tube Manufacturing

This section characterizes the flexibility in tube manufacturing, describes the conflicting objectives of extrusion and tube drawing, explains how we can exploit the process flexibility to resolve the extrusion-drawing tradeoff by judiciously selecting standard bloom sizes, and discusses the linkage between the planning model and engineering activities.

3.1 Characterizing the flexibility of tube drawing and extrusion

Standard practice rules are designed for feasibility verification, i.e., planners use these rules to verify if they can produce a particular product from a specified bloom. The mathematical representation of the process constraints discussed in Section 2.2 is powerful because it enables us to assess the flexibility of tube drawing by addressing the converse question, namely, "given a desired target point, i.e., finished tube, what are the possible bloom sizes that can produce this tube?" This "bottom-up" view, shown in Figure 4, illustrates the substantial latitude in selecting appropriate bloom sizes. We partition the *feasible* bloom sizes that can produce a given finished tube size according to the number of drawing passes and intermediate annealing operations they require. Consider, first, the subset of blooms that can produce the finished tube in a single draw. This subset consists of all sizes that satisfy the lower and upper drawing angle constraints (2.4), the minimum cold work constraint (2.3), and the maximum reduction per draw constraint (2.1). We refer to the area contained within the Iso-CSA lines representing the minumum cold work limit τ_{min} and the maximum reduction per draw limit δCSA_{max}, and the lines defining the upper and lower drawing angles as the *1-draw region*. As shown in Figure 4, we can recursively construct the regions for multiple draws, introducing intermediate annealing steps as necessary. The *feasible area* within the constraints provides a concrete, visual characterization of the inherent *range* flexibility (Upton [1991]) of tube drawing. Process engineers can increase flexibility in different directions by exploring the limiting values for each of the constraint parameters δCSA_{max}, ΔCSA_{max}, θ_{max}, and θ_{min}. We can similarly use the extrusion constraints to define the region of ingot sizes that can produce a desired bloom size.

The tube drawing feasible area is analogous to the concept of processing maps that have been popularized in materials manufacturing. Frost and Ashby [1982] and Ashby [1985] have developed deformation maps and hot-isostatic pressing maps that assist the process engineer to operate with a desired range of material behavior. Forming limit diagrams have been applied to the shaping of sheet materials through stamping and sheet drawing (Wagoner et al. [1989]). Woodyatt, Stott, Wolf, and Vasko [1992] use a graphical representation to show the range of mechanical properties and chemistries corresponding to different grades of steel.

We should note that the process flexibility demonstrated by the feasible areas represents a double-edged sword. On the one hand, this flexibility permits us to exploit upstream economies of scale by introducing commonality in the processing paths for different products. However, the flexibility also permits the planner, during lot ticket preparation, to choose dramatically different processing paths for similar tubes. Without a consistent set of practices, process engineers cannot rely upon historical data or implement system-wide improvements.

3.2 Determinants of extrusion and tube drawing effort

The planner faces wide spectrum of bloom size and draw planning choices. How do these choices affect extrusion and tube drawing effort?

Extrusion effort

To understand *extrusion workload*, we will focus on how the *effective extrusion speed* varies with bloom dimensions and lot size. Effective speed is the number of "good" pounds extruded per hour of press usage; it depends on both the total processing time for a batch and the process yield. The total time to extrude a batch of blooms with specified length and CSA includes the press setup time to preheat the ingot and change the tooling, and the actual extrusion time which equals the batch size (including scrap) times the extrusion rate. The extrusion rate (i.e., ram speed) decreases as the cross-sectional area (especially, wall thickness (Akeret [1981]) of the bloom decreases. Extrusion yield also decreases with increasing batch size and bloom dimensions. Planned scrap, consisting of fixed lengths from the leading and trailing ends of each batch and each bloom, decreases as a % of total extruded weight when the batch size increases, and inherent process defects (surface defects and dimensional variations) tend to increase as the bloom's CSA decreases. Because effective extrusion speed increases with batch and bloom size, extrusion managers strongly prefer to produce fewer and preferably large and thicker bloom sizes in large batches .

Tube drawing effort

Tube drawing workload increases with the number of drawing passes. The drawing time for each batch varies with the batch size and tube dimensions. We can broadly decompose the total time required *for each drawing pass* into two components: (i) *batch setup time*: consisting of the time to load and unload racks of tubes, to change the die set, and to draw one or more trial tubes to debug the drawing pass; and (iii) the *processing time for each tube*: consisting of the time to set up the tube on the draw bench, and the actual drawing time which equals the length of the output tube divided by the drawing speed (which does not vary much within standard practice limits). In addition to draw-bench operations, we must also consider the processing time and yield losses due to intermediate annealing and materials handling operations. Each drawing pass and every intermediate annealing operation entails one or more additional materials handling steps (e.g., using cranes or forklifts) for the batch. Shortage of oven capacity might create bottlenecks in annealing. Both annealing and materials handling introduce additional defects. To improve the tube mill's performance metrics such as throughput, yield, and productivity, tube drawing managers strongly prefer process plans that require few drawing passes and no intermediate annealing steps.

3.3 The Bloom Sizing problem

Flexibility in tube manufacturing impacts long-term capacity planning, medium-term tooling, and short-term lot planning decisions. This section focuses on the medium-term decision of selecting a set of standard bloom sizes to address the following tradeoff. The downstream (tube drawing) stage prefers to select, for each of its finished tube sizes, a tailored bloom size in the 1-draw feasible region (Figure 4) for that tube in order to minimize the number of draws and eliminate intermediate annealing steps. However, this strategy requires a large number of bloom sizes, with relatively low annual demand for each bloom and possibly low extrusion rates. On the other hand, the extrusion plant prefers to produce a limited set of standard bloom sizes that have high effective extrusion speeds. A single bloom can "serve" k different finished products if it lies in the intersection of the feasible drawing areas for these k products (see Figure 5). Choosing fewer and larger blooms that can each serve more products improves extrusion performance, but increases the total drawing and annealing effort. Vasko, et al. [1987], [1989] address a similar tradeoff in choosing standard ingot sizes for a steel mill.

Given the projected product mix and volumes, the *bloom sizing problem* consists of selecting a limited set of standard bloom sizes and assigning each product to a chosen bloom. Selecting standard bloom sizes is a special case of the more general *commonality selection* problem of choosing a set of standard initial flow paths for all end-products. To capture the extrusion-drawing tradeoff, we might minimize total production "cost" which is a weighted sum of the total extrusion, tube drawing, and annealing effort. Instead, we minimize tube drawing effort, but impose an upper limit on the total extrusion effort. This model has the advantage of generating many different solutions along the efficient frontier (by varying the extrusion upper limit) that managers can choose from, and avoids controversies associated with the accuracy and relevance of costs derived from conventional management accounting systems. Technically, the bloom sizes are continuous variables that can take any values in the region enclosed by the extrusion constraints on the tube reduction diagram. We discretize the problem by superimposing a rectangular grid on this feasible region, and treating each grid point as a candidate standard bloom size. An alternative approach would be to overlap the feasible areas for various products as in Figure 5, and select as candidate bloom sizes points that can serve many end products. Planners might prefer this intuitive approach since they are accustomed to the geometric interpretation of draw planning on the tube reduction diagram; furthermore, the number of candidate sizes and so the dimensionality of the optimization problem is smaller.

Let i = 1, 2, ..., n denote the index of the n products (OD-WT combinations) that the facility expects to produce. Let j = 1, 2, ..., m be the candidate set of bloom sizes that the extrusion plant can produce. For each product, we are given the projected demand and production frequency. The planning model requires two "engineering" inputs: the parameters δCSA_{max} and so on that define the tube drawing restrictions, and procedures to calculate extrusion effort and tube drawing effort as functions of bloom and tube sizes. The effort models must incorporate variations in processing speed and quality with workpiece dimensions. For each product i and bloom j, we use these inputs to: (i) determine if product i can be drawn from bloom j, and (ii) if so, determine the appropriate process plan. Let d_{ij} and e_{ij} respectively denote the total tube drawing effort and extrusion effort to meet all of the demand for product i if we produce this tube using bloom j. The parameter d_{ij} might include the cost of annealing, materials handling, and scrap reprocessing, and the effects of inflated batch sizes to compensate for yield losses.

We can formulate the bloom sizing problem as an integer program using two sets of binary decision variables: y_j which takes the value of 1 if we select size j as one of the standard sizes, and is 0 otherwise, and x_{ij} which is 1 if we produce tube i using bloom j, and 0 otherwise. The variable x_{ij} represents the preferred medium-term tube-to-bloom assignment. In the short term, the planner might use a different bloom to produce product i if its preferred bloom is not available in stock. The bloom size optimization model [BSO] has the following form:

[BSO] minimize $$\sum_{i=1}^{n} \sum_{j=1}^{m} d_{ij}\, x_{ij} \qquad (3.1)$$

subject to

Bloom-to-tube assignment: $$\sum_{j=1}^{m} x_{ij} = 1 \quad \text{for all } i = 1,2,\ldots,n, \qquad (3.2)$$

Forcing: $$x_{ij} \leq y_j \quad \text{for all } i=1,2,\ldots,n,\ j=1,2,\ldots m, \qquad (3.3)$$

Extrusion limit: $$\sum_{i=1}^{n} \sum_{j=1}^{m} e_{ij}\, x_{ij} \leq E\text{, and} \qquad (3.4)$$

No. of standard sizes: $$\sum_{j=1}^{m} y_j \leq p\,, \qquad (3.5)$$

Integrality: $$y_j,\ x_{ij} = 0 \text{ or } 1 \quad \text{for all } i=1,2,\ldots,n,\ j=1,2,\ldots m. \qquad (3.6)$$

The objective function (3.1) minimizes the total drawing effort of all tube-to-bloom assignments. Each product must be assigned to one bloom (constraint (3.2)), and we can assign tube i to bloom j only if we select candidate size j as one of the standard sizes (constraint (3.3)). Constraint (3.3) imposes the parametric upper limit E on total extrusion effort. The model does not explicitly capture setup and safety stock scale economies at the extrusion stage, but instead imposes (in constraint (3.3)) a user-specified upper limit p on the number of standard bloom sizes, thus avoiding non-linearities in the model. For medium-term planning, this constraint might be an adequate surrogate, especially if the extrusion facility uses a periodic scheduling policy (e.g., produce each bloom size once a week). By varying the parameters p and E, the planner can generate a variety of bloom sizing solutions with varying extrusion-drawing characteristics. Subsequent exploration of each scenario using a detailed simulation model incorporating scheduling, setup and safety stock considerations can lead to effective medium-term decisions.

Formulation [BSO] is a "capacitated p-median problem" that is related to several classical optimization models. It differs from the traditional p-median problem (see, for instance, Mirchandani and Francis [1990]) because of the additional "knapsack" or capacity constraint

(3.4). If instead of imposing the constraint (3.5), we assign a fixed cost F_j for selecting size j as a standard bloom size, then the model reduces to a facility location model with a side constraint. If a set of p or less standard bloom sizes is prespecified, then the problem reduces to a capacitated assignment model. Bloom sizing can also be viewed as a generalization of the assortment problem (e.g., Sadowski [1959]) which has been applied to the problem of selecting standard lengths of, say, steel bars (e.g., Wolfson [1965]).

Vasko, Wolf, and Stott [1987] describe a related bi-criteria set covering model to select an optimal set of ingot sizes, motivated by the acquisition of new equipment in the ingot plant of a steel mill. In this context, ingot casting and blooming are the upstream and downstream operations. The problem requires selecting a subset of standard ingot sizes from a candidate set of sizes determined by the facility's ingot molding capabilities. The primary objective is to minimize the number of standard ingot sizes, and the secondary objective is to minimize the total yield loss at the blooming mill for the chosen product-to-ingot assignments. This model implicitly assumes that the economies of scale at the ingot casting stage far outweigh the downstream costs. In the tube manufacturing context, however, extrusion and tube drawing have comparable costs, and so minimizing the number of standard bloom sizes might not be appropriate. Vasko et al.'s model does not contain an explicit capacity constraint such as (3.4), nor does it contain constraint (3.5) since it minimizes the number of standard sizes. To solve the model quickly, the authors apply a heuristic that first approximately solves the minimum cardinality set covering problem (to find the fewest number of ingot sizes necessary) and then applies local improvement to reduce the second (blooming yield loss) objective. They also noted that the bi-criteria model is equivalent to an uncapacitated plant location model with a large fixed cost for choosing each ingot.

3.4 Solution methods for bloom sizing

The bloom sizing problem is NP-hard, and so we might consider developing tailored optimization-based methods that exploit the problem's special structure to generate good heuristic solutions as well as tight lower bounds to verify the quality of the solutions. Consider, for instance, the following two Lagrangian relaxation schemes. If we dualize the p-median constraint (3.5), then the problem reduces to a plant location model with a single side constraint (3.4). A search procedure similar to Handler and Zang's [1980] solution method for constrained shortest path problems solves this Lagrangian subproblem by iteratively applying an uncapacitated facility location algorithm. Note that dualizing the p-median constraint using a multiplier ϕ corresponds to assigning a fixed cost ϕ for choosing each standard bloom size. Alternatively, if we dualize the extrusion limit (3.4) using a multiplier λ, the residual

Lagrangian subproblem is a p-median problem that we can solve using one of several well-known algorithms (e.g., Mirchandani, Oudjit, and Wong [1985]). The multiplier λ represents the "shadow price" of extrusion capacity. For both relaxations, we might use subgradient optimization to update the Lagrange multiplier and improve the lower bound. The Lagrangian subproblem solutions at each iteration are near-feasible; by adjusting these solutions and applying local improvement we can get good sets of standard bloom sizes.

Since we are interested in generating many different "pareto-optimal" bloom sizing scenarios by varying the parameters p and E, the following "multi-objective" approach is more promising. Suppose we dualize both the constraints (3.4) and (3.5) using multipliers λ and ϕ. The subproblem becomes the uncapacitated plant location model which we can solve using, say, Erlenkotter's [1978] dual ascent method. Instead of updating the multiplier values using subgradient methods, starting with $\lambda = \phi = 0$ we iteratively increase λ and ϕ by fixed or adaptive step sizes (or apply binary search) until we reach suitably large values λ_{max} and ϕ_{max} (beyond which neither the number of standard sizes nor the extrusion effort decreases in the subproblem solution). The overall computational requirements might decrease if, at each iteration, we use the previous dual solution to initialize the dual ascent algorithm. At each iteration k, we obtain a subproblem solution $\{Y^k, X^k\}$ with p^k standard blooms, and tube drawing and extrusion effort of D^k and E^k respectively. Eliminating duplicated and dominated solutions in this set, we get a subset of "efficient" bloom sizes and corresponding tube-to-bloom assignments. Although this method does not guarantee finding all the solutions on the efficient frontier, it can generate a wide range of promising ones. This methodology extends to the case when we wish to separately consider the two components–drawing and annealing–of tube effort, or impose explicit constraints requiring that a certain minimum percentage of tubes must be produced with, say, one or no intermediate annealing steps.

The engineering-planning iterations that we describe in the next section requires repeated bloom size optimization to perform sensitivity analyses with respect to process paramters. For this purpose, getting optimal solutions is less important than getting quick estimates of the relative improvement due to changes in various process parameters. So, instead of applying the search procedure, we might solve [BSO] approximately using efficient myopic or hybrid heuristics (Vasko and Wilson [1986]). In one of many possible versions, the procedure selects one bloom at a time, choosing at each step the bloom size that covers the largest percentage (in terms of pounds shipped) of remaining products within a prespecified number of draws. An alternate heuristic consists of clustering the products into the required number of groups (equal to the number of standard bloom sizes) on the tube reduction diagram, and selecting the best bloom size for each group. Simple methods such as these that can be implemented using spreadsheet programs, permit human interaction, and exploit the geometric intuition provided by tube reduction diagram will likely gain quicker and wider acceptance among managers, planners, and process engineers.

We describe the architecture of such a user-friendly system; we have partially implemented a prototype of this system for a tube manufacturing plant. The core of the system is a spreadsheet containing a "tube-to-bloom assigner and effort evaluator". For a given choice of blooms, a spreadsheet macro assigns each tube to its closest feasible bloom (an enhanced version might even solve an LP with constraints (3.2) and (3.4), assuming fractional assignments are permitted) and computes appropriate metrics for drawing , annealing, and extrusion effort. To complement this spreadsheet, an "electronic" tube reduction diagram displays the products (all or high volume only), and the current bloom serving each group of products; enhanced version might also display the overlapped feasible areas for products that are not covered by current blooms within a specified number of drawing and annealing steps. Based upon the current coverage pattern, the user can add a new bloom size to the spreadsheet, and observe the impact on the effort metrics. The spreadsheet also permits changes in the standard practice and effort parameters.

3.5 Planning-Engineering Iterations

The planning model [BSO] requires the process parameters as input to identify feasible tube-to-bloom assignments, and to calculate extrusion, drawing and annealing effort for each feasible processing path. A more accurate representation of constraints and better characterization of processing speeds, obtained through better process understanding, can improve the quality of the process planning decisions. Conversely, the planning model can help to prioritize process modeling and improvement efforts. To utilize their time effectively, process engineers need to know which process constraints are critical in terms of improving overall manufacturing performance (cost, lead time, quality). Consider, for instance, the max reduction per draw constraint described in Section 2.2. Should the process engineer first explore the possibility of increasing the CSA limit δCSA_{max} in the max reduction per draw constraint, or should he focus on refining one of the other four constraints? What is the economic impact of increasing the CSA limit by, say, 1 percentage point, and how does this impact compare to reducing the lower drawing angle by 1 degree? A parametric analysis using the planning model can provide some insights into these questions.

For a given set of standard bloom sizes and tube-to-bloom assignments, increasing the CSA limit by $\delta\%$ might possibly reduce the number of draws for certain products, and hence reduce the drawing effort. Adding these savings over all the current tube-to-bloom assignments provides a lower bound on the total reduction in drawing effort if we increase the CSA reduction per draw limit. However, further savings might be possible by reassigning tubes to other blooms or even choosing alternate standard bloom sizes. To accurately estimate this total savings, we must re-solve the planning model with the new CSA limit. Figure 6 shows how we might represent the results of this type of sensitivity analysis to provide insights to process engineers and managers; the extrusion-drawing tradeoff curve shifts downward as the maximum CSA reduction per draw increases. Similarly, the planning model can show how the curve shifts with changes in other process parameters. Figure 7 shows the linkage between planning and process improvement, recognizing that good process understanding is a prerequisite for effective planning, while the economic considerations derived from planning must drive process engineering. Vasko et al. [1987] discuss this type of interaction between engineering and planning during the development of their ingot sizing model to explore the limits of product length, ingot pour height range, and taper. We emphasize that the planning-engineering iterations must become an integral part of ongoing continuous improvement efforts, going beyond the normal consultations between engineers and planners while developing the initial planning model or making capital investment decisions. Furthermore, in addition to addressing equipment changes, they must also consider changes to standard practice in order to extend the processing limits.

3.6 Some observations from practice

We have had considerable contact with several tube and sheet manufacturing plants in the aluminum industry, including a joint two-year collaborative project with a tube manufacturing facility. This project provided us the opportunity to observe and interact closely with planners and production supervisors; we performed extensive analysis of actual practice for over 300 products that together accounted for over a million pounds of annual tube production. The origins, process, challenges, and outcomes of this collaboration are described in a recent paper (Balakrishnan, Brown, Dunlap, and Pahl [1993]). We summarize below our observations based upon this experience and our interactions with other plants.

Process planning was viewed mainly as an operational activity, namely, the task of (manually) choosing the processing path and preparing the lot ticket for each incoming order, as described in Section 2.4.1. Tactical decisions such as bloom sizing appeared to be ad hoc and incremental: if sales of a particular tubular product grew to a large enough volume, a new "tailored" bloom size would be introduced. Over the years, the plant had introduced 37 different standard bloom sizes to produce the 300+ products we studied. The plant did not have a systematic process to periodically review the entire mix of blooms and products or study extrusion-tube workload balancing issues. The complementary use of planning and process engineering models, described in Section 3.5, certainly appeared to be a new paradigm for the organization's engineers and planners.

For the product group that we studied, our analysis revealed the following improvement opportunities:

- better short-term and medium-term process planning can reduce total tube drawing effort by more than 20% while maintaining total extrusion effort at current levels, or decrease extrusion effort by over 30% with current levels of tube drawing effort;
- in one illustrative example, decreasing the OD and WT of a bloom reduced the total drawing effort for all the products it served by over 10%;
- replacing the 37 standard bloom sizes with just 10 new sizes (identified using myopic bloom sizing heuristics) can simultaneously decrease extrusion, tube drawing, and annealing effort;
- of the 37 current blooms, just 8 blooms can cover over 90% of the products with at most one intermediate annealing step;
- increasing the max CSA reduction per draw parameter δCSA_{max} provides greater leverage than changing the standard practice parameters for drawing angle. A 5-percentage point increase in δCSA_{max} can decrease total tube drawing effort by over 13% (keeping extrusion effort constant) or reduce total extrusion effort by over 20% (for the current level of drawing effort).

These results suggest that the plant did not fully exploit the leverage of medium-term decisions, and of incorporating a systems view in the planning process. Results were presented to management in the form of tradeoff curves and different bloom sizing scenarios. Two decision support tools–an "electronic" tube area chart viewer and a spreadsheet program for interactive bloom size optimization–were developed. The plant has since consolidated the planning functions for the extrusion press and tube drawing operations into a single department, ordered tooling for new bloom sizes, and initiated process improvement studies for tube reducing and drawing operations.

4. Concluding Remarks

We believe that there are substantial opportunities for planning and process improvement in the metal working industry by taking advantage of the inherent process flexibility, and by coupling engineering activities with the short, medium, and long-term planning efforts. The improvements we illustrated derive from some fundamental characteristics of continuous metal forming, namely, the highly interdependent upstream (hot forming) and downstream (cold forming) operations with wide lattitude in selecting both the upstream and the downstream process paths. Organizations that mainly emphasize the operational aspects of process planning, or those in which the upstream and downstream operations function independently, pursuing local objectives without consideration for overall efficiency, miss an important opportunity to gain strategic advantage by exploiting the inherent process flexibility. Other industries, particularly those involving large capital equipment and continuous processing such as the paper, food, and structural polymer products industries, can also benefit from the concepts presented in this paper.

The BSO model represents an improvement over current practice in the aluminum tube manufacturing industry. It is a prototype for a more general medium-term, multi-stage planning framework (incorporating all stages from ingot casting to shipping) to choose an appropriate level of upstream commonality in the process plans for multiple products, taking into account the process constraints and the upstream versus downstream workload tradeoffs. This approach can have far-reaching benefits including operations streamlining, inventory and flow time reductions, reduced setup times, and improved quality. The exact structure of the model depends on the organization structure, cost models, capacity limits, and ease of application. Commonality selection is constrained by and provides input to long-term capacity planning, technology choice as well as cellular manufacturing decisions.

The planning model can help to focus process engineering efforts; in turn, better process understanding leads to more effective process plans. The feasible area representation of tube drawing uses the engineering constraints to define the region of process flexibility for the planning model, eliminating the need to rely on either previous process history or a single process plan. Similarly, the sensitivity of system performance to process constraints enables engineers to pursue improvements that provide the greatest economic benefit.

We believe that the interdisciplinary approaches described in this article provide fertile ground for new research–new optimization models and algorithms, inventory management issues, and process modeling opportunities. We next outline some of these opportunities.

Planning model enhancements and solution methods

The BSO model captures the essential tradeoffs in medium-term planning, but uses the p-median constraint as a surrogate for scale economies due to setups and safety stocks, considers only a single demand scenario, and does not incorporate short-term flexibility. The following model enhancements merit further study and algorithmic development:

- Selecting a "robust" set of blooms: one that minimizes manufacturing effort for the preferred tube-to-bloom assignments, but also provides an alternate bloom when the preferred bloom is in short supply. del Callar [1992] has proposed and tested genetic algorithms for this model.
- Selecting a "stable" set of blooms: one that is effective for the projected demand, and does not change significantly when the product mix changes (e.g., increasing proportion of thinner wall tubes).
- Explicitly incorporating the savings in safety stocks due to greater commonality of blooms. Pentico [1988] considers a two-dimensional assortment model to decide how much of each size to keep in stock assuming a concave stocking cost function and a substitution cost that is additive and proportional. Tube manufacturing poses more complex substitution constraints and costs, but a variant of this model might apply.
- Incorporating the congestion effects (higher lead times and WIP inventories) due to the redistribution of workload between extrusion and tube drawing operations when we select standard bloom sizes.

Because draw planning and bloom sizing have intuitive geometric interpretations in terms of the tube reduction diagram, this context also motivates some interesting Euclidean location problems. For instance, finding the best bloom(s) for a given set of products corresponds to finding one or more "medians" in the intersection of the feasible areas (Figure 5) corresponding to different products. Computer scientists and location theorists have analyzed simple versions of this problem for certain special metrics (e.g., Shamos [1978]). Similarly, the problem of determining the minimum number of blooms needed to cover all products (with k or fewer draws each) in a specified region of the tube reduction diagram defines a new class of *oriented location problems*. Gopalan [1992] analyzes the performance of heuristics for certain special cases in this problem class.

Inventory Models for common and substitutable components

When blooms are made to stock, managing bloom inventories presents a challenging modeling opportunity. Bloom size optimization introduces commonality: several products have the same bloom as their preferred starting stock. In the short-term, however, blooms are also substitutable, i.e., if a bloom runs out the planner might substitute it with a larger (higher OD and WT) bloom. This substitution possibility can reduce safety stocks since it permits risk pooling, but also entails higher drawing and annealing effort and lower yield. Previous research in the inventory management literature has studied policies for systems having common components or with substitutable products (e.g., Baker, Magazine, and Nuttle [1986], Gerchak and Henig [1989], Gerchak, Magazine and Gamble [1988], Bitran and Dasu [1989], Bassok, Anupindi, and Akella [1991], and Ou and Wein [1991]).

Long-term Process Development and Improvement

While incremental adjustments and experimentation around current operating parameters might suffice for reactive problem-solving to address day-to-day process difficulties, longer term process improvement requires deeper process understanding. The true underlying constraints in tube drawing are currently not well-understood, presenting many opportunities for modeling and characterization to characterize the effects of die geometries, interfaces, machine setups, material properties, and process path on process yield (e.g., Rowe [1983]). For instance, if engineering analysis can provide a functional description of how recovery varies with, say, drawing angle or CSA reduction per draw, then the planning model can readily incorporate the differential yields to choose effective draw plans. Friction, lubrication, and the effect of surface condition are all imperfectly accomodated within simulation models, and computational capabilities limit the model size if we wish to represent three dimensional forming operations. Another arena concerns the formulation of inexpensive lubricants that provide maximum lubrication with the least environmental impact. We also require guidelines or a structured approach to combine model-based methods with experimentation and experience (e.g., Altan, Lahoti, and Nagpal [1980]) so that process engineers can identify and address process improvement opportunities efficiently.

Finally, a fruitful research direction concerns the direct integration of the cost of process engineering analysis within the planning model. Instead of specifying process restrictions as hard constraints in the planning model, suppose we permit relaxing the constraints at a cost (to cover the costs of process analysis, experimentation and lower yield). Then, we can evaluate the return on investment for different types of process engineering efforts, and directly identify constraints that are critical or cost effective from a planning perspective.

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<u>Figure 1</u>: Tube Manufacturing Process Flow

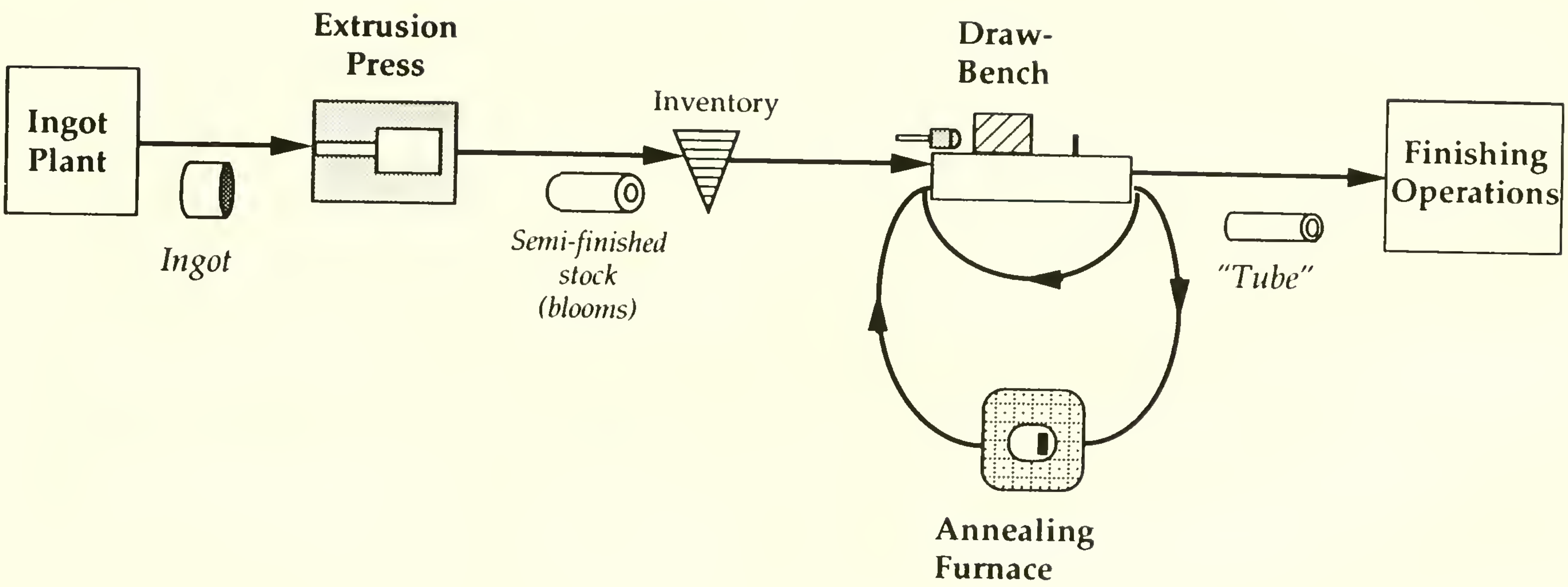


Figure 2: Draw Bench Schematic

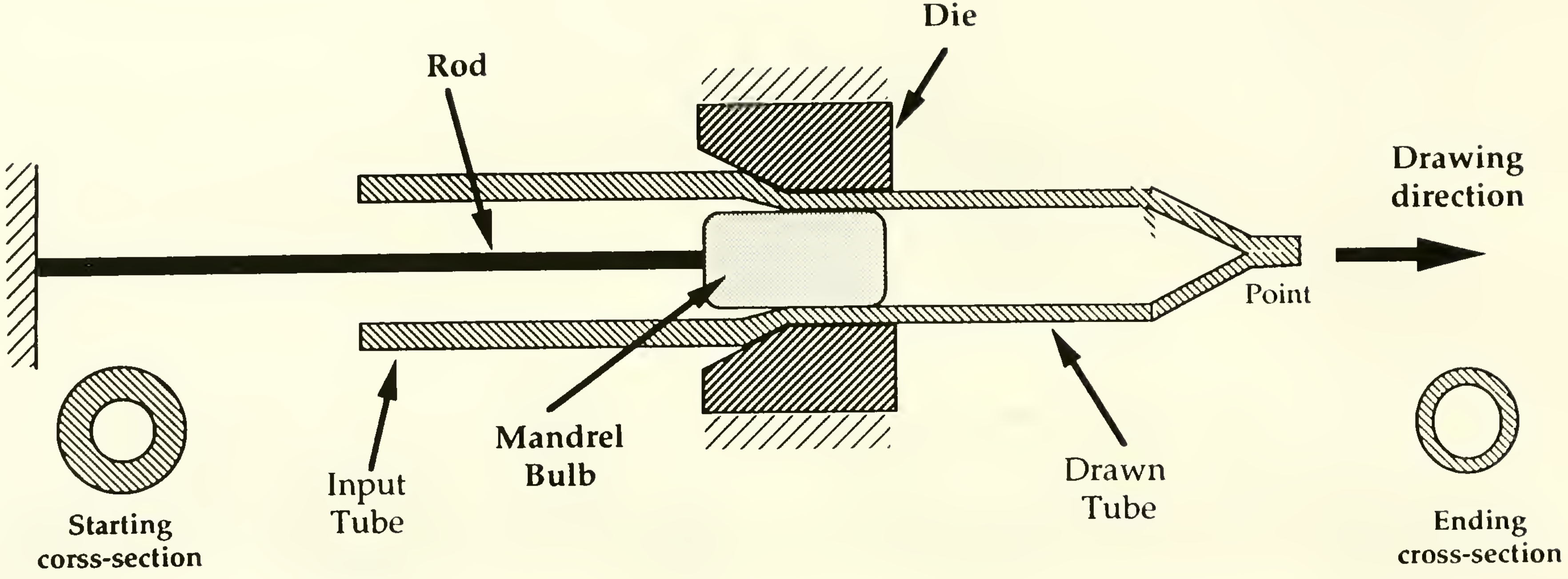


Figure 3: Tube Reduction Diagram

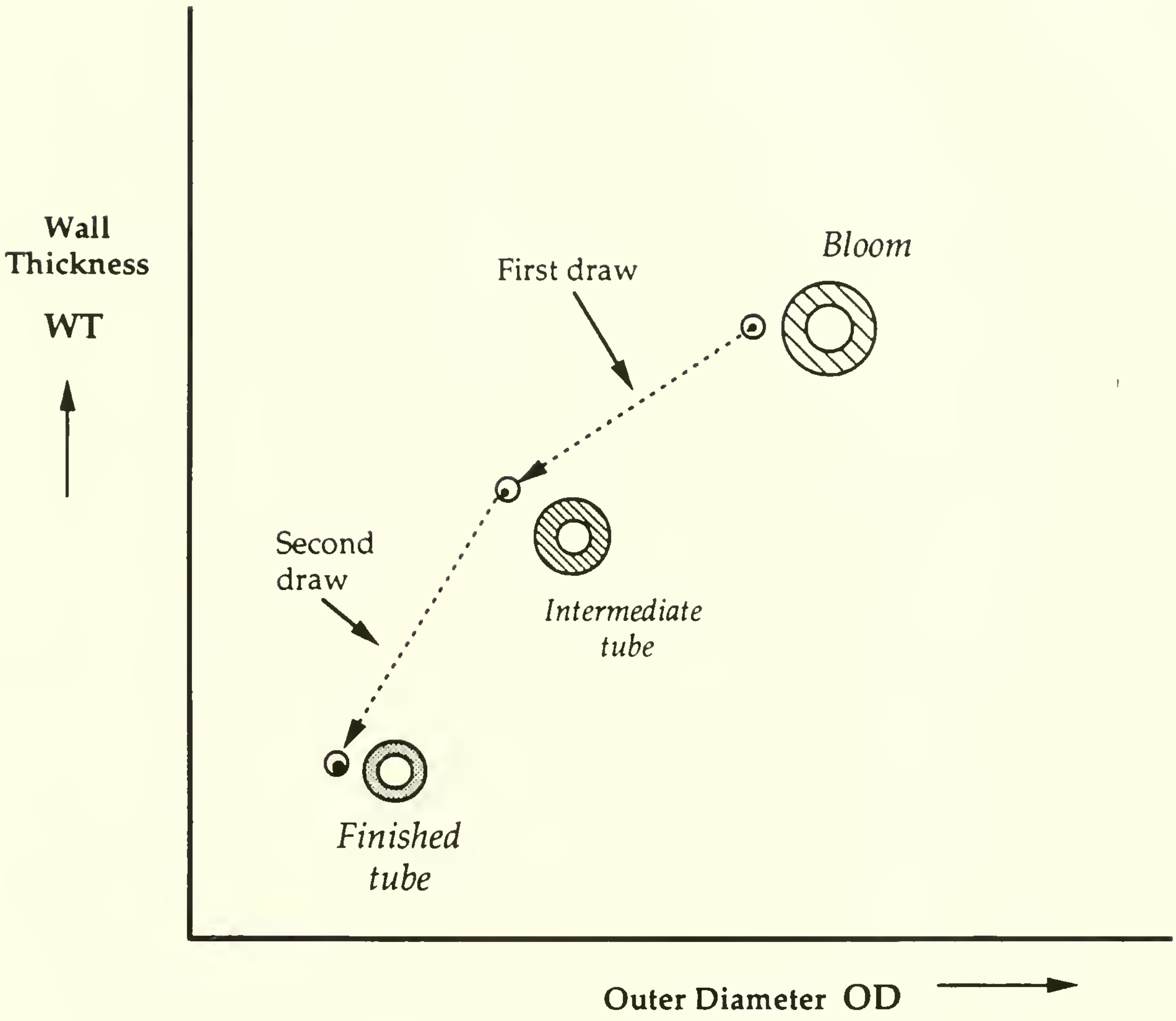


Figure 4: Tube Drawing Constraints

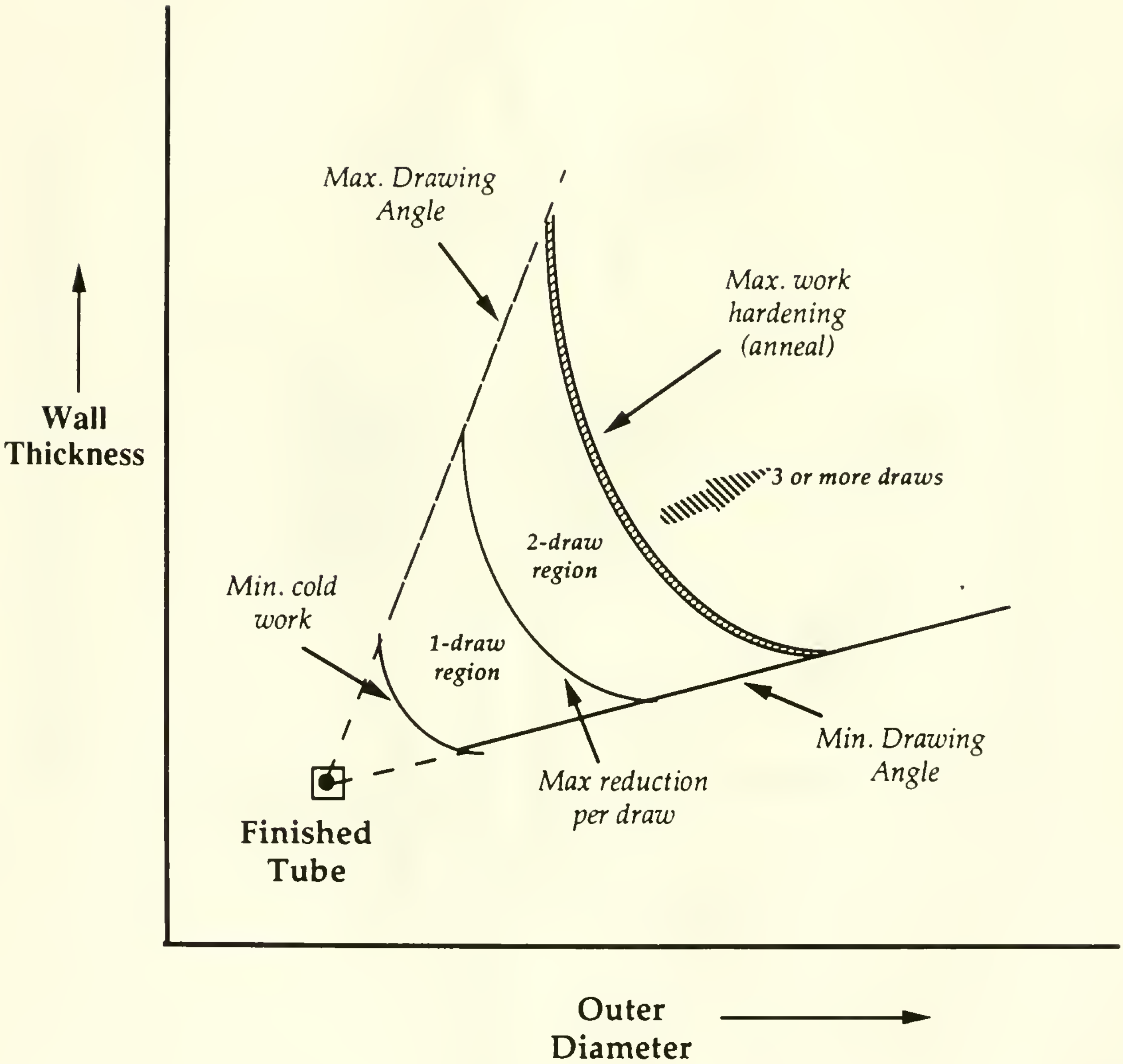
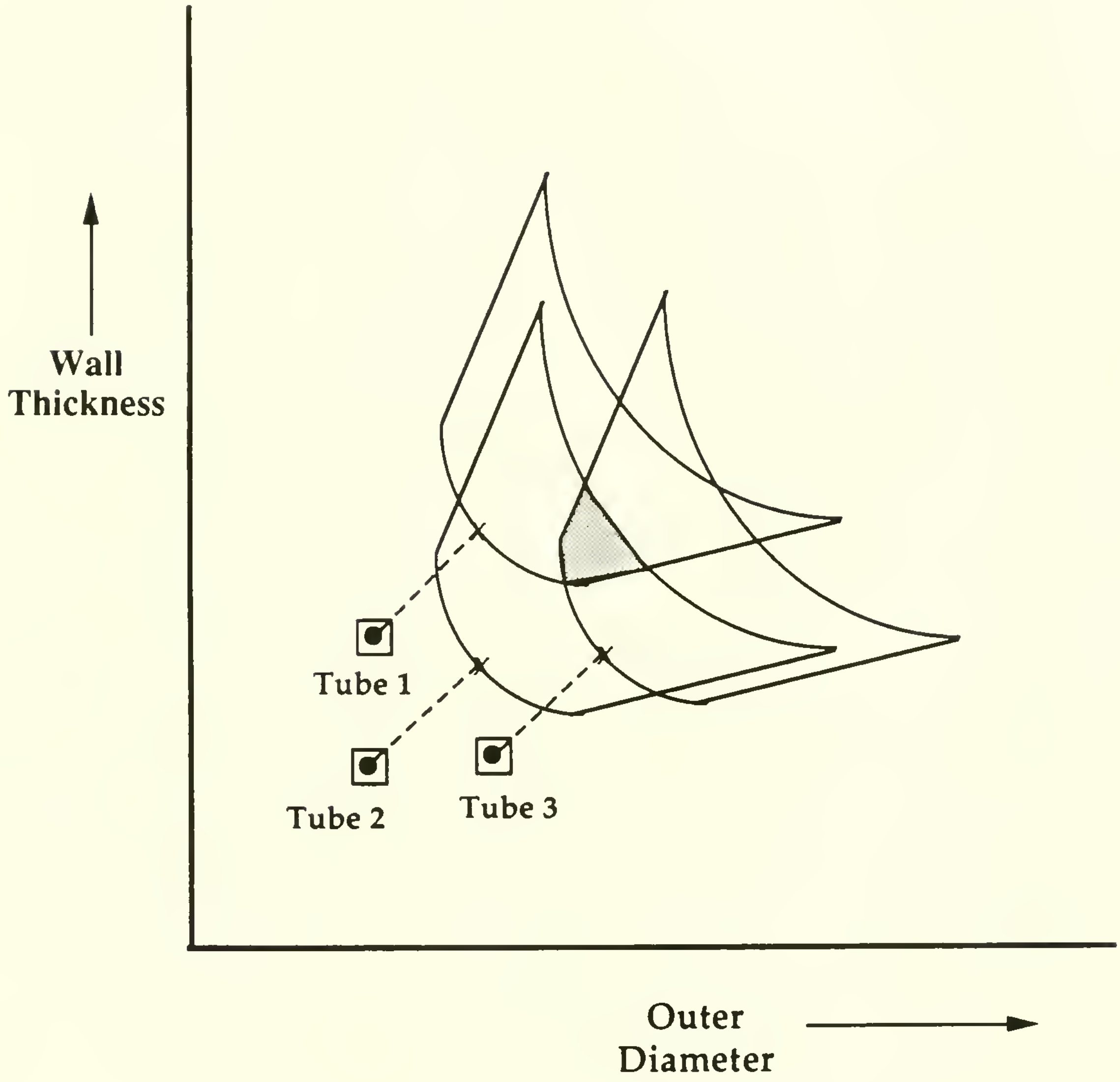


Figure 5: Overlapping Feasible Areas



<u>Figure 6</u>: Extrusion versus Draw effort Tradeoff Curves and Sensitivity Analysis

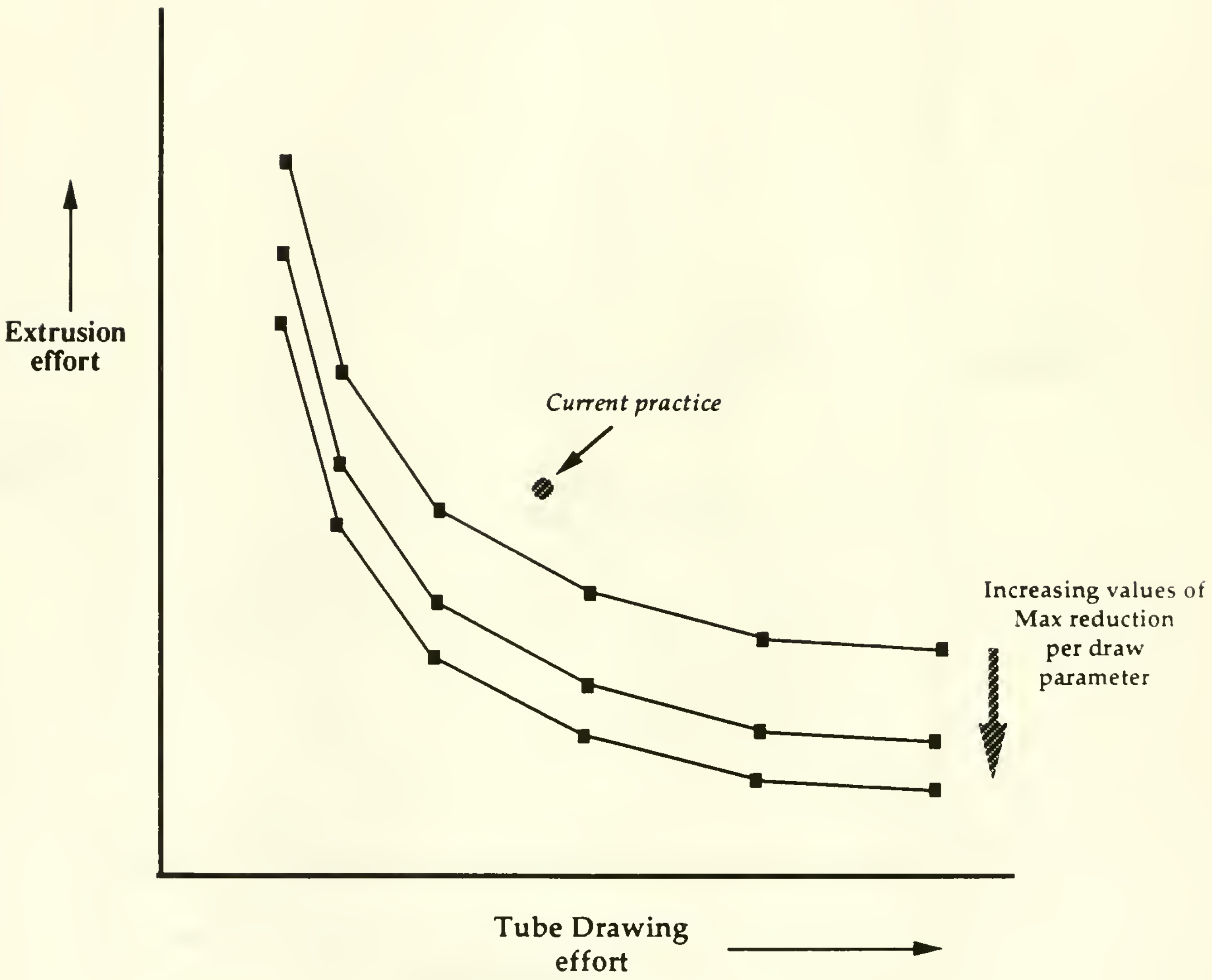
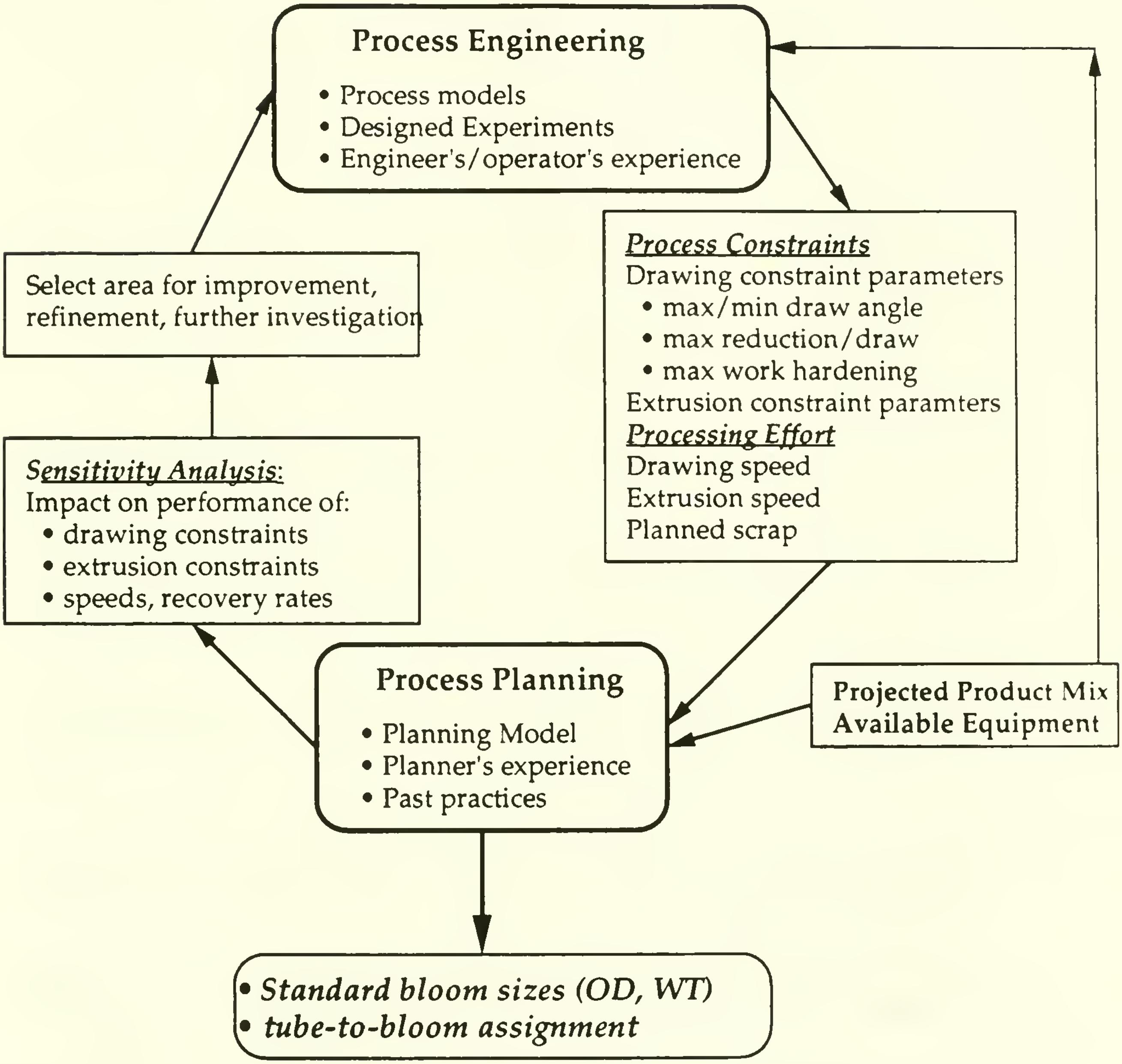


Figure 7: Planning–Engineering Iterations



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