

INTERACTIVE GRAPHICS SOFTWARE FOR
COMPUTER AIDED MANUFACTURE OF
SHEET METAL DUCTWORK

by

Peter Thompson

Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the
Requirements of the
Degree of

MECHANICAL ENGINEER

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1982

© Massachusetts Institute of Technology 1982

Signature of Author _____
Department of Mechanical Engineering
May 12, 1982

Certified by _____
Thesis Supervisor

Accepted by _____
Department Thesis Committee

Archives
MASSACHUSETTS INSTITUTE
OF TECHNOLOGY

JUN 21 1982

LIBRARIES

ABSTRACT

This report describes a software project called CALCUDUCT which is on file in the MIT CAD Lab. The program is written in Fortran and demonstrates how the fabrication of sheet metal ductwork can be expedited by computer. Through an interactive process, the user describes certain critical dimensions on a standard fitting such as a reducer or elbow. The program then calculates the exact shapes of the flat panels which comprise the fitting and draws them in a format which is analagous to actual sheet metal shop practice.

Table of Contents

	page
I. Introduction	
A. Statement of problem	4
B. Objective of project	4
II. Duct Layout	
A. State of the industry	
1. Definition of terms	5
2. Applications	7
3. Current methods	7
B. Tasks to be aided by computer	
1. Calculation	9
2. Drawing	9
3. Bookkeeping	10
III. CALCUDUCT program	
A. The TERAk minicomputer	11
B. Program overview	
1. Flow	11
2. Modules and files	13
3. Execution format	16
C. Features	
1. Validation loops	17
2. Scrap minimization	18
3. Screen overflow	18
D. User interface	19
IV. Conclusions and recommendations	
A. Marketing restrictions	
1. Operating speed	20
2. Cost	20
B. Project extensions	
1. Software	21
2. Hardware	22
3. Total HVAC by CAD/CAM	23

I. Introduction

A. Statement of problem

Ductwork for heating and air conditioning systems is custom-fabricated for each job by sheet metal shopworkers. To make three-dimensional ducts from sheet metal, they project the exact shapes of orthogonal surfaces onto flat metal by any of a number of manual techniques. These may involve geometric construction, chart referencing or numerical calculation. This process has remained virtually unchanged throughout the history of the industry. Unlike product-oriented manufacturing, ductwork production is dominated by labor rather than equipment expenditures.

Problems which stem from this situation involve productivity, communication and a dependence on highly skilled workers whose numbers are declining. Some complex shapes are seldom even attempted because of the high labor costs involved. The result has been a decline in the industry's ability to custom-fabricate the ductwork that it needs at prices that it can afford.

B. Objective of the project

The objective is to eliminate much of the human factor in duct fabrication. The calculation of shapes and the drawing of these shapes can be accomplished by computerized means. The software project, which is on file in the MIT CAD Lab, demonstrates this concept and allows a user to

participate in the duct layout process. The demonstration can be used as a base for further hardware/software development or it may be shown to investors who are interested in equipment manufacturing.

II. Duct layout

A. State of the industry

1. Definition of terms

SHEET METAL DUCTWORK - Air conduit for heating, ventilating or air conditioning (HVAC). Cross-dimensions range from 2 inches to several feet and cross-sections are usually round or rectangular. Most ducts are made from galvanized steel but some applications call for aluminum, stainless steel or copper. Non-metallic duct materials include PVC, fiberglass and thin foils.

FITTING - Piece of duct which accomplishes a change of direction, size or shape.

LAYOUT - The process of developing the flat panels which comprise a three-dimensional fitting. A layout person receives a sketch which describes the fitting, usually in one view. He then calculates true lengths, circumferences, radii etc. and transcribes these dimensions onto flat metal. He cuts these out by hand and passes them to other workers who bend and assemble them.

COIL LINE - Numerically controlled (NC) device for manufacture of straight duct only. A coil of sheet metal approximately four feet by two hundred feet is fed through a table-level machine which cuts the sheet at duct perimeter length and bends it automatically.

JOB - A collection of straight duct and fittings which comprises all or part of an air distribution system.

2. Applications

Ducts are employed as HVAC conduits in buildings of every size. In residential applications the main (or trunk) duct generally has dimensions which range from eight inches to twenty-four inches. Smaller ducts branch off at the trunk duct. Residential-size ductwork is mass produced and is available at HVAC supply houses.

Larger commercial applications require much larger trunk ducts and the wide range of building configurations leads to a very large variety of duct shapes. Therefore, ductwork for all commercial applications must be custom-designed and constructed. Although some sizes are common, it is seldom economical to mass produce and store these for future use. Fittings (reducers, offsets, etc.) are especially application dependent. While other conduit-based trades such as plumbing and electrical utilize pre-manufactured fittings and straight pipes, the ductwork trade employs about one third of its workers as manufacturers of conduit.

3. Current Methods

Since sheet metal shops range in size from a few workers to several hundred, there has developed a wide range of duct manufacturing methods. In order to remain competitive, a small contractor must be able to produce the same fittings as a large, automated shop.

In a very small shop the workers may alternate between field installation and shop fabrication. This minimizes bookkeeping and communication problems between shop and field. The man who decides, on a given afternoon, that he needs an offset fitting can fabricate it himself the following morning. However, since shop equipment is unmanned at least half of the time, sophisticated machines are too expensive for the small operator.

In larger sheet metal operations, field installers never do shop work and vice versa. A list of required fittings is submitted by the field foreman who draws simple sketches when necessary. Straight ducts are usually produced on an NC coil line while fittings are diverted to layout men, each of whom works at his own bench.

Working with with a 4' X 8' sheet of metal, ruler, compass etc., this "specialist" can develop and cut the flat panels for a standard fitting in two to five minutes. Lesser skilled workers take these pre-cut blanks and bend and form them into three-dimensional shapes. The system works very well for large shops but leads to some worker dissatisfaction because of repetition, emphasis on speed and frequent layoffs when fabrication demand declines. This system also leads to voluminous bookkeeping as lists and sketches are passed among the many individuals concerned. When an especially complicated fitting is required, the system bogs down severely. A fitting which must accomplish a change of cross section as well as direction may take an hou to lay out.

The process of laying out fittings is identical for shops of any size and in fact the process has remained unchanged throughout the history of the industry. Straight duct manufacturing however has long been aided by the NC coil line because of the simplicity of calculating a perimeter and making a single cut.

B. Tasks to be aided by computer

1. Calculation

Many of the dimensions which describe a fitting are not the primary dimensions which are specified by the installer. Perimeters, circumferences, true lengths of sloped sides, etc., have traditionally been derived from charts or geometric construction. Some layout persons use only a calculator and knowledge of trigonometry to derive these secondary dimensions. A computer of course would expedite this aspect of the job tremendously. Once the field installer has determined the parameters of his fitting, no further math need be utilized by the tradesmen.

2. Drawing

A layout person "scribes" the metal with a sharp instrument in order to generate very fine lines. He must pause often to acquire flat metal, calculate dimensions or pick up hand tools. A flatbed plotter can draw continuously at a rate of speed and degree of accuracy far in excess of the manual

method. If the drawing surface is a continuous, coil-based sheet, an entire job may be drawn with no manual assistance.

Another aspect of the drawing process pertains to the efficient allocation of metal. Given material costs of approximately twenty-five cents per square foot, the value of material is not high compared to the value of labor required to fabricate finished products. Still it is important to arrange the blanks in a manner which wastes as little metal as possible. Computer subroutines can accomplish this very reliably thereby eliminating one of the more tedious aspects of duct layout.

3. Bookkeeping

Cross referencing lists by jobname, HVAC system name, fitting number or installer's name can lead to excessive paperwork especially when sketches are involved. The computer's ability to store information can be useful in this field as it is in many others. Data files generated in the production process can be shared by accounting or time study programs.

Most shops weigh ductwork prior to loading and trucking. This weight figure is used to monitor job costs and productivity. A computerized layout system however can easily calculate area and weight of raw material used, eliminating an additional manual procedure.

III. The CALCUDUCT Program

A. The TERAk minicomputer

Among the devices employed by the MIT CAD Lab is a TERAk minicomputer system with graphics capabilities. The system is manufactured by :

Terak Corporation
14405 North Scottsdale Road
Scottsdale, Arizona 85254

The components utilized by this project were :

- Model 8510 CPU and Disk Drive (24K memory)
- Model 8512 Disk Drive
- CRT Display Monitor
- ASCII Keyboard
- Software including graphics support and Fortran IV compiler

B. Program overview

1. Flow

A flow diagram of the program operation appears in Figure 1. Note that this is not an exact depiction of a single executable program but rather the net flow characteristics of the total software package.

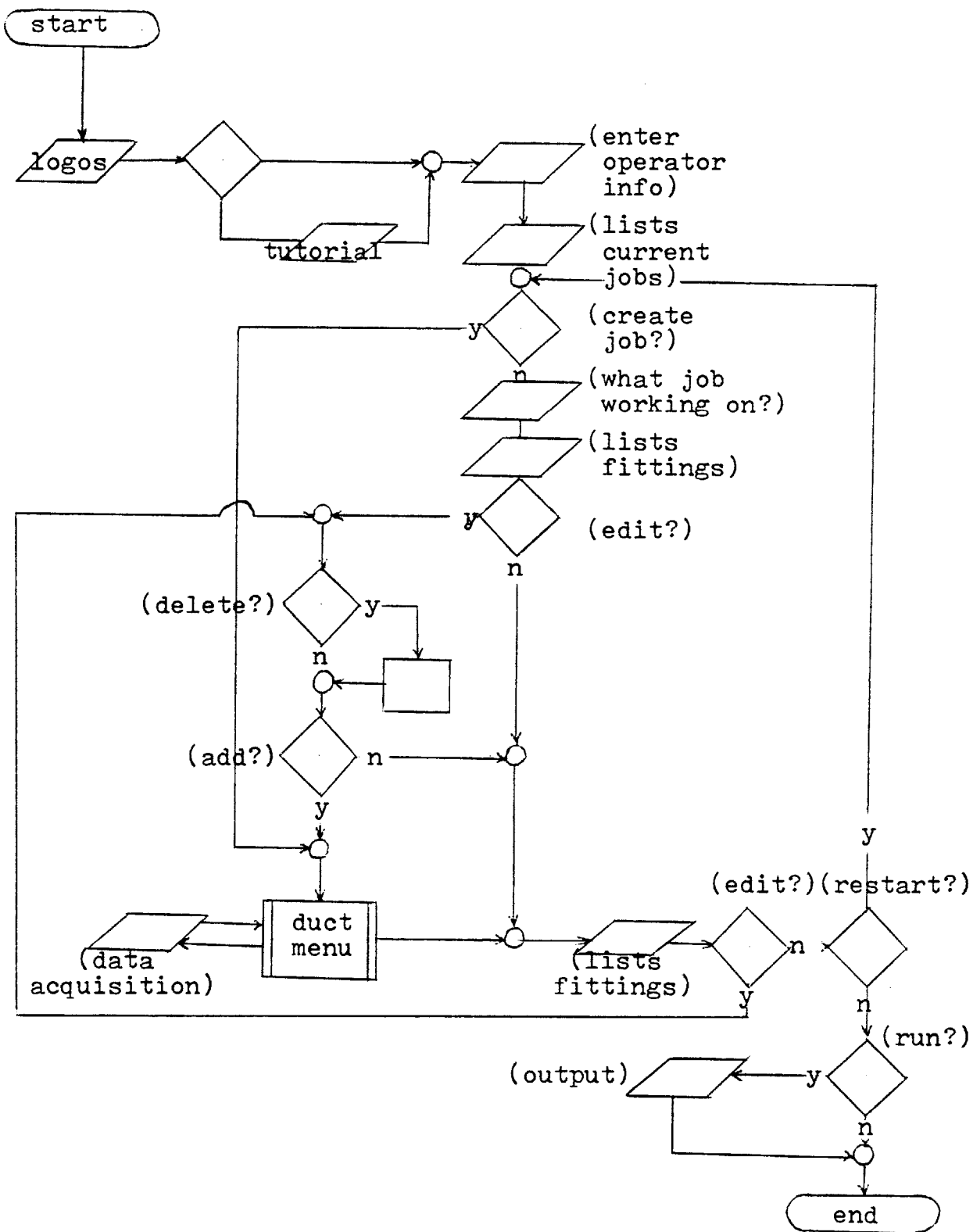


FIGURE 1 - FLOW DIAGRAM

2. Modules and files

There are sixteen source programs. All are available in the MIT CAD Lab on a disk labeled, "Calcuduct". The following is an overview of the programs and their functions.

- LOGO -Draws MIT logo
 -Draws CALCUDUCT logo
 -Calls tutorial if requested
- TUTOR -Displays explanatory paragraphs regarding
 duct layout and gives introduction to duct
 fitting terminology
 -Displays isometric of elbow fitting
 -Displays same elbow in its flat component form
 -Invites user to describe similar elbow
 with different dimensions
 -Displays user's creation in flat component
 form
 -User may practice on more elbow fittings
 until ready to continue with actual program.
- DUCTIN -Main input program
 -Displays current job information and associated
 names and dates
 -Contains all of the necessary prompts for
 creating, editing and erasing jobs
 -Calls MENU when user wishes to describe a
 new fitting
- MENU -See Figure 2
 -Calls appropriate input subroutines
 >Returns to DUCTIN upon exit

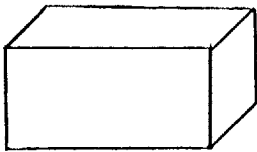
rectangular duct

ENTER THE ONE LETTER CODE

X

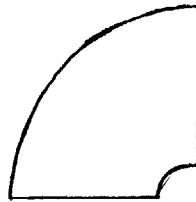
EXIT

S



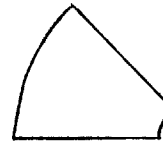
STRAIGHT

L



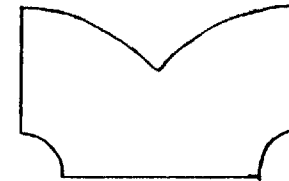
ELBOW

B



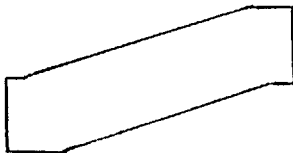
BEVEL

T



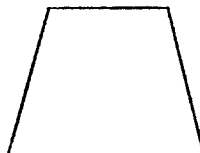
TEE

O



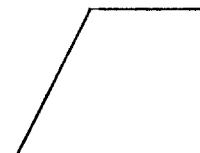
OFFSET

C



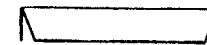
REDUCER ON CENTER

F



REDUCER FLAT SIDE

E



END CAP

FIGURE 2 - DUCT MENU

INPUT SUBROUTINES

- There is one subroutine for each of the available fitting types.
- A generic graphic of the pre-selected fitting is displayed.
- One dimension at a time, the user is asked to insert the parameters which describe the piece.
- When the fitting has been described to the program's satisfaction, a return to MENU is called.
- The following are the input subroutines :

STRAIN	Straight duct
ELBOIN	90° elbow
BEVEIN	45° bevel
TEEIN	Tee
OFFSIN	Offset
CENRIN	Reducer on center
FLTRIN	Reducer flat side
ECAPIN	End cap

- DUCTOT
- Main output program.
 - Draws a representative 3 foot by 12 foot segment of a continuous sheet of metal.
 - Passes dimensional data to the output subroutines.
 - Waits for "return" key before continuing on to next fitting.
 - Calls appropriate output subroutine.

OUTPUT SUBROUTINES:

STRAOT	Straight duct
ELBOOT	90° elbow
BEVEOT	45° bevel
TEEOT	Tee
OFFSOT	Offset
CENROT	Reducer on center
FLTROT	Reducer flat side
ECAPOT	End cap
CURVOT	Curved lines
DOTLNV	Dotted vertical lines (bend lines)
DOTLNH	Dotted horizontal lines (bend lines)

3. Execution format

Because the TERAk's 24K dynamic memory cannot accommodate all of the executable programs, the project was broken into three roughly equal segments. These programs are called automatically by an indirect command file. The filetype .SAV refers to an executable file.

LOGO.SAV - This program reads coordinates for the MIT logo from a file called MIT.DAT and uses them to generate the first logo. This segment was taken from the BEZIER PATCH program which is also on file in the CAD Lab. LOGO.SAV also includes variations of ELBOIN and ELBOOT which allow the user to practice fitting creation and see the results immediately. This program does not communicate with subsequent programs. It displays logos and titles, introduces concepts and allows the user to practice interfacing.

DUCTIN.SAV - This is the executable input program. It reads old job information from a file called DUCT.DAT which can accommodate four jobs of eight fittings each and associated job data. DUCTIN allows the user to create and/or alter jobs. Before ending, this program always asks the question, "Restart the input program?" thereby allowing the user to go back to the beginning of DUCTIN before moving on to the output program.

The last question that this program asks is whether to RUN the job on which the operator is working. The answer to this question is written on DUCT.DAT along with all new job data.

DUCTOT.SAV - This executable file reads the answer to the RUN question then displays the flat projections on the CRT. The program pauses and waits for a "return" after each fitting is displayed. At the conclusion of the DUCTOT segment the system returns to monitor. Restarting requires a simple rebooting.

C. Features

1. Validation loops

Every response provided by the user is subject to a validation check. Dimensions beyond the designated range, missing decimal points, unrecognized job or fitting numbers and answers other than Y or N will all result in error messages and a restatement of the question. Error messages define the exact format of the required response. Dimensions must fall between 8. and 24. inches inclusive (the range for residential applications.)

2. Scrap Minimization

Each output subroutine, along with its drawing function, has the task of squeezing the panels into the leftmost region of the sheet. A fitting is never drawn on axes which are not orthogonal with the sheet itself because this would complicate the cutting process. Similarly, fittings are separated by an imaginary vertical line so that each may be sheared off individually and handed to an assembler.

Scrap minimization requires a decision-tree which arranges the panels in the leftmost region while trying to adhere to the three outside edges at the end of the sheet. This eliminates some manual cutting. The software problem is easier than with the case of odd-shaped pastry wherein the raw material cost is relatively high and axes may be set at any angle. A typical application appears in Fig. 3.

3. Screen overflow

The representation of a twelve foot sheet segment is too small for full display of very large fittings. Therefore the program allows for screen overflow, a function which reinforces the concept of a continuous sheet. When an overflow occurs, the user is informed that the remainder of the fitting is displayed on the next screen image. It is accessed by pressing the "return" key.

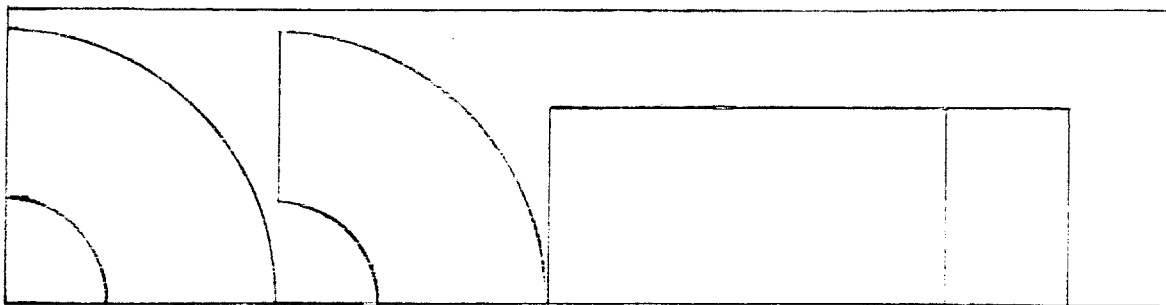
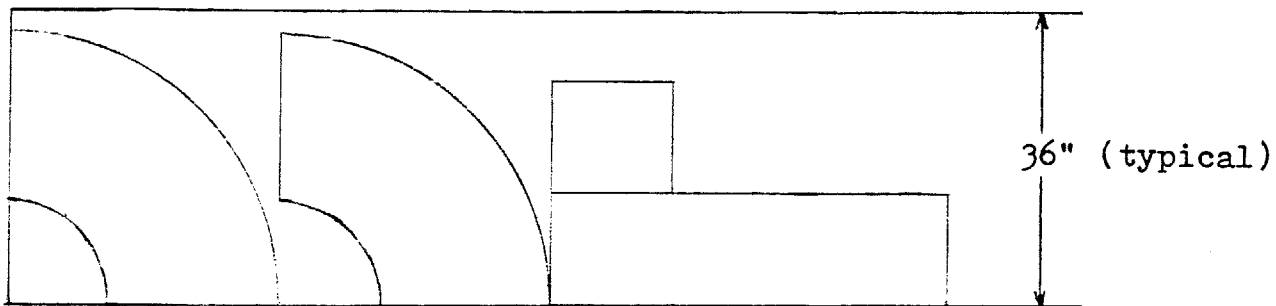
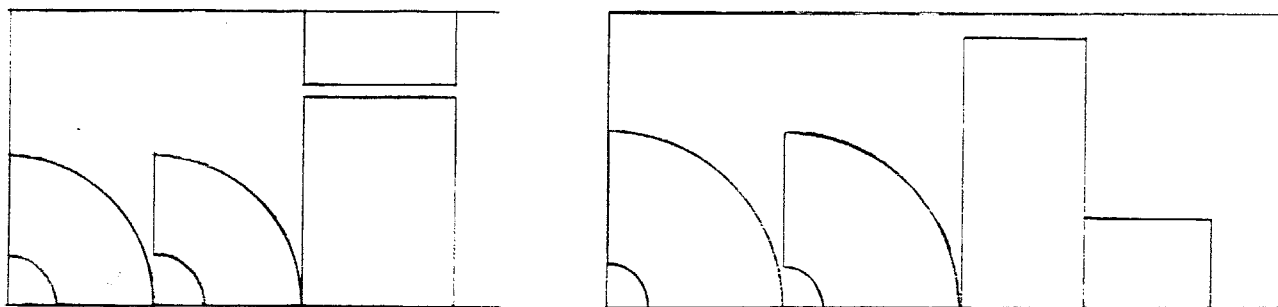
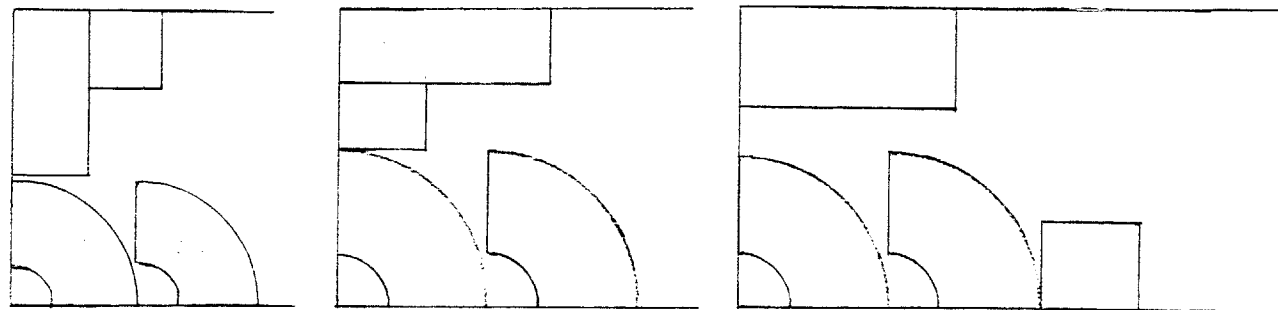


Figure 3 - SCRAP MINIMIZATION (Elbow Fitting)

D. User interface

Since the project is meant as a demonstration rather than a saleable product, it is aimed at those who are unfamiliar with HVAC ductwork. The tutorial provides sufficient information to convey the problem, the solution and the user's part in the process. However, the program has enough sophistication to make a strong impression on a sheet metal contractor. In fact, anyone who has been through the manual layout process is likely to experience some degree of thrill when that process is accomplished "magically" at the push of a button.

The blue-collar atmosphere of a sheet metal shop is not conducive to computer training and documentation checking. Moreover, in a field where the status quo has remained unchanged for decades there may be some resistance to foreign methods. Therefore user-friendliness is critical and in this case the users are accustomed to dealing with sketches. Graphics software that identically reflects the user's experience can make the transition smooth and even enjoyable. For that reason the program employs pictures whenever possible to show the user what he is working on.

The flow of the program is such that the user is constantly prompted to make YES or NO decisions. This relieves him of the responsibility of knowing whether he is in a tutorial or an edit mode or any other particular segment. He does not have to request a list of jobs or a list of fittings because the program displays them automatically. When he tries to add to an array that is already full, the program politely informs him of the problem and what can be done about it. A complete computer novice could probably learn everything that he needs to know about the program in 10 - 15 minutes without referring to any documentation.

IV. Conclusions and recommendations

A. Marketing restrictions

1. Operating speed

Distributors of sheet metal shop equipment point to one operating disadvantage regarding this system. To understand the problem it is necessary to introduce the concept of a squaring shear. This device resembles a table-level guillotine and is used to make fast, clean cuts across a metal sheet. A layout person often begins by using a squaring shear to create a rectangular blank which has the exact length and width of his final piece. He then makes notches and cuts to finish the procedure. The calculations that he made before square shearing the blank allow him to "back into" the final geometry with minimal measuring.

Suppose then that the same piece has just been drawn in the middle of a flat sheet. It cannot be accessed by a squaring shear without cutting across the adjacent panel(s). The best way to remove it is with hand-held shears. This process is not as slow as it sounds since there does exist a power hand tool called the unishear which can follow any scribed line at almost one foot per second. It is apparent then that research is needed so that the exact time from the sketch presentation to the end of the cutting process can be documented.

2. Cost

A fully functioning system (flatbed plotter, coil spindle, computer, software and cutoff shear) will probably be priced at \$150,000. or more. For firms which build housings for computers, this is no more than a standard investment.

However, for HVAC ductwork shops this device would be the single largest equipment investment that the company could make.

Automation is usually slow to take hold in construction-related industries because, in essence, construction workers are not replaceable. No matter how automated a sheet metal shop becomes, its prime functions will still be performed by tradesmen who stand on ladders and carry hand tools. But the general trends of rising labor costs and increased robotization assure that the larger shops, at least, will seek alternative fabrication methods.

B. Project extensions

1. Software

It would take perhaps two man-years to compose all of the necessary software for a marketable system. Some additions which must be made to the demonstration module include :

a. Fitting variety - Besides the eight fitting types discussed so far, there are a few others which should be included. Fittings with curved bends must be complemented by fittings with square bends and internal turning vanes, a common option. There is also a complete assortment of round ductwork which is extremely time consuming to lay out manually.

b. Fitting complexity - For the sake of the demonstration each fitting can be specified by 2 - 3 user inputs and all other dimensions are assumed by the program. In fact however, some complex fittings may require up to eight specified dimensions in order to accommodate the installer's need. A single fitting may start with a rectangular cross-section, turn ninety degrees, offset downward and finish with a round cross-section. The number of layout men who would even attempt such a fitting has decreased to a handful but such artistry could be reinstated with the help of CAD/CAM.

c. Categorizing by metal gauge - To reduce buckling and vibration, wider ducts are made of heavier gauges. The program would have to create separate queues for each gauge and divert them to separate plotters or to appropriate coils run on the same plotter.

d. Defaults - Judicious use of defaults can greatly decrease input time. A preliminary module with limited access should be used to preset certain values. Some shops, for instance, try to make all reducers 24 inches long or all inside elbow radii one half of the fitting width. Of course the opportunity to override a default should also exist.

2. Hardware

The product in question is basically a turnkey system. It would consist of the following :

- A computer in the size range of the PDP-11.
- A heavy-duty flatbed plotter.

- Two video display terminals, ideally one in the shop and one in the office.
- Disk drive.
- A coil spindle and automatic advance, similar to those already in use on straight-duct coil lines.
- An automatic squaring shear to isolate each fitting after it has been drawn.
- A software package.

One very challenging hardware problem pertains to automatic cutting of the metal. The drawing step could be eliminated if the metal blanks could be cut to size without causing excessive edge roughness.

3. Total HVAC by CAD/CAM

It is generally accepted that the process must become manual after the duct leaves the shop. The start of the process however is wide open to computerization in the professional fields involved. Architects design the building, engineers design the HVAC system and draftsmen provide the contractor with a set of plans. Every facet of this scenario has already been exposed to some computerization and the following sequence of automated events requires only a turnkey system for the construction.

- The building is designed structurally, aesthetically and functionally according to the client's specifications
- Heating and cooling loads are calculated from local weather information.
- An air distribution system which maximizes comfort and minimizes cost is selected.
- Individual components of the duct system are manufactured using a CALCUDUCT system.