

# Multiple Regression—I

Multiple regression analysis is one of the most widely used of all statistical methods. In this chapter, we first discuss a variety of multiple regression models. Then we present the basic statistical results for multiple regression in matrix form. Since the matrix expressions for multiple regression are the same as for simple linear regression, we state the results without much discussion. We conclude the chapter with an example, illustrating a variety of inferences and residual analyses in multiple regression analysis.

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## 6.1 Multiple Regression Models

### *Need for Several Predictor Variables*

When we first introduced regression analysis in Chapter 1, we spoke of regression models containing a number of predictor variables. We mentioned a regression model where the response variable was direct operating cost for a branch office of a consumer finance chain, and four predictor variables were considered, including average number of loans outstanding at the branch and total number of new loan applications processed by the branch. We also mentioned a tractor purchase study where the response variable was volume of tractor purchases in a sales territory, and the nine predictor variables included number of farms in the territory and quantity of crop production in the territory. In addition, we mentioned a study of short children where the response variable was the peak plasma growth hormone level, and the 14 predictor variables included gender, age, and various body measurements. In all these examples, a single predictor variable in the model would have provided an inadequate description since a number of key variables affect the response variable in important and distinctive ways. Furthermore, in situations of this type, we frequently find that predictions of the response variable based on a model containing only a single predictor variable are too imprecise to be useful. We noted the imprecise predictions with a single predictor variable in the Toluca Company example in Chapter 2. A more complex model, containing additional predictor variables, typically is more helpful in providing sufficiently precise predictions of the response variable.

In each of the examples just mentioned, the analysis was based on observational data because the predictor variables were not controlled, usually because they were not susceptible to direct control. Multiple regression analysis is also highly useful in experimental

situations where the experimenter can control the predictor variables. An experimenter typically will wish to investigate a number of predictor variables simultaneously because almost always more than one key predictor variable influences the response. For example, in a study of productivity of work crews, the experimenter may wish to control both the size of the crew and the level of bonus pay. Similarly, in a study of responsiveness to a drug, the experimenter may wish to control both the dose of the drug and the method of administration.

The multiple regression models which we now describe can be utilized for either observational data or for experimental data from a completely randomized design.

### First-Order Model with Two Predictor Variables

When there are two predictor variables  $X_1$  and  $X_2$ , the regression model:

$$(6.1) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i$$

is called a first-order model with two predictor variables. A first-order model, as we noted in Chapter 1, is linear in the predictor variables.  $Y_i$  denotes as usual the response in the  $i$ th trial, and  $X_{i1}$  and  $X_{i2}$  are the values of the two predictor variables in the  $i$ th trial. The parameters of the model are  $\beta_0$ ,  $\beta_1$ , and  $\beta_2$ , and the error term is  $\varepsilon_i$ .

Assuming that  $E\{\varepsilon_i\} = 0$ , the regression function for model (6.1) is:

$$(6.2) \quad E\{Y\} = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

Analogous to simple linear regression, where the regression function  $E\{Y\} = \beta_0 + \beta_1 X$  is a line, regression function (6.2) is a plane. Figure 6.1 contains a representation of a portion of the response plane:

$$(6.3) \quad E\{Y\} = 10 + 2X_1 + 5X_2$$

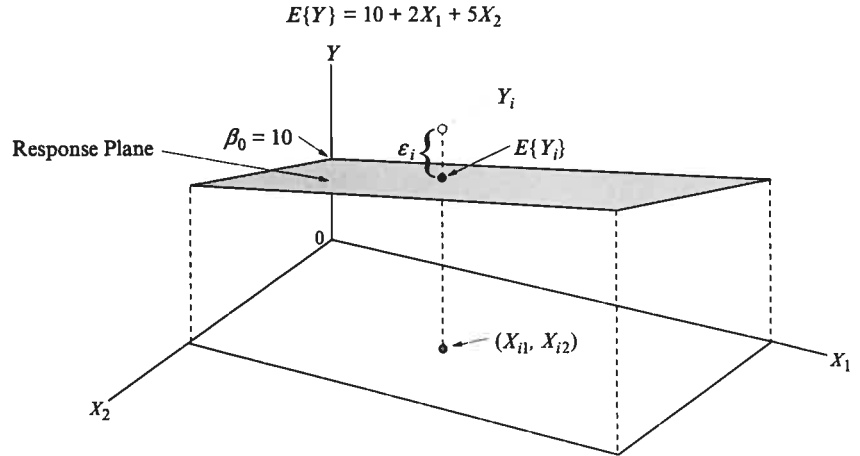
Note that any point on the response plane (6.3) corresponds to the mean response  $E\{Y\}$  at the given combination of levels of  $X_1$  and  $X_2$ .

Figure 6.1 also shows an observation  $Y_i$  corresponding to the levels  $(X_{i1}, X_{i2})$  of the two predictor variables. Note that the vertical rule in Figure 6.1 between  $Y_i$  and the response plane represents the difference between  $Y_i$  and the mean  $E\{Y_i\}$  of the probability distribution of  $Y$  for the given  $(X_{i1}, X_{i2})$  combination. Hence, the vertical distance from  $Y_i$  to the response plane represents the error term  $\varepsilon_i = Y_i - E\{Y_i\}$ .

Frequently the regression function in multiple regression is called a *regression surface* or a *response surface*. In Figure 6.1, the response surface is a plane, but in other cases the response surface may be more complex in nature.

**Meaning of Regression Coefficients.** Let us now consider the meaning of the regression coefficients in the multiple regression function (6.3). The parameter  $\beta_0 = 10$  is the  $Y$  intercept of the regression plane. If the scope of the model includes  $X_1 = 0$ ,  $X_2 = 0$ , then  $\beta_0 = 10$  represents the mean response  $E\{Y\}$  at  $X_1 = 0$ ,  $X_2 = 0$ . Otherwise,  $\beta_0$  does not have any particular meaning as a separate term in the regression model.

The parameter  $\beta_1$  indicates the change in the mean response  $E\{Y\}$  per unit increase in  $X_1$  when  $X_2$  is held constant. Likewise,  $\beta_2$  indicates the change in the mean response per

**FIGURE 6.1** Response Function is a Plane—Sales Promotion Example.

unit increase in  $X_2$  when  $X_1$  is held constant. To see this for our example, suppose  $X_2$  is held at the level  $X_2 = 2$ . The regression function (6.3) now is:

$$(6.4) \quad E\{Y\} = 10 + 2X_1 + 5(2) = 20 + 2X_1 \quad X_2 = 2$$

Note that this response function is a straight line with slope  $\beta_1 = 2$ . The same is true for any other value of  $X_2$ ; only the intercept of the response function will differ. Hence,  $\beta_1 = 2$  indicates that the mean response  $E\{Y\}$  increases by 2 with a unit increase in  $X_1$  when  $X_2$  is constant, no matter what the level of  $X_2$ . We confirm therefore that  $\beta_1$  indicates the change in  $E\{Y\}$  with a unit increase in  $X_1$  when  $X_2$  is held constant.

Similarly,  $\beta_2 = 5$  in regression function (6.3) indicates that the mean response  $E\{Y\}$  increases by 5 with a unit increase in  $X_2$  when  $X_1$  is held constant.

When the effect of  $X_1$  on the mean response does not depend on the level of  $X_2$ , and correspondingly the effect of  $X_2$  does not depend on the level of  $X_1$ , the two predictor variables are said to have *additive effects* or *not to interact*. Thus, the first-order regression model (6.1) is designed for predictor variables whose effects on the mean response are additive or do not interact.

The parameters  $\beta_1$  and  $\beta_2$  are sometimes called *partial regression coefficients* because they reflect the partial effect of one predictor variable when the other predictor variable is included in the model and is held constant.

**Example.** The response plane (6.3) shown in Figure 6.1 is for a regression model relating test market sales ( $Y$ , in 10 thousand dollars) to point-of-sale expenditures ( $X_1$ , in thousand dollars) and TV expenditures ( $X_2$ , in thousand dollars). Since  $\beta_1 = 2$ , if point-of-sale expenditures in a locality are increased by one unit (1 thousand dollars) while TV expenditures are held constant, expected sales increase by 2 units (20 thousand dollars). Similarly, since  $\beta_2 = 5$ , if TV expenditures in a locality are increased by 1 thousand dollars and point-of-sale expenditures are held constant, expected sales increase by 50 thousand dollars.

### Comments

1. A regression model for which the response surface is a plane can be used either in its own right when it is appropriate, or as an approximation to a more complex response surface. Many complex response surfaces can be approximated well by a plane for limited ranges of  $X_1$  and  $X_2$ .

2. We can readily establish the meaning of  $\beta_1$  and  $\beta_2$  by calculus, taking partial derivatives of the response surface (6.2) with respect to  $X_1$  and  $X_2$  in turn:

$$\frac{\partial E\{Y\}}{\partial X_1} = \beta_1 \quad \frac{\partial E\{Y\}}{\partial X_2} = \beta_2$$

The partial derivatives measure the rate of change in  $E\{Y\}$  with respect to one predictor variable when the other is held constant. ■

### First-Order Model with More than Two Predictor Variables

We consider now the case where there are  $p - 1$  predictor variables  $X_1, \dots, X_{p-1}$ . The regression model:

$$(6.5) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i$$

is called a first-order model with  $p - 1$  predictor variables. It can also be written:

$$(6.5a) \quad Y_i = \beta_0 + \sum_{k=1}^{p-1} \beta_k X_{ik} + \varepsilon_i$$

or, if we let  $X_{i0} \equiv 1$ , it can be written as:

$$(6.5b) \quad Y_i = \sum_{k=0}^{p-1} \beta_k X_{ik} + \varepsilon_i \quad \text{where } X_{i0} \equiv 1$$

Assuming that  $E\{\varepsilon_i\} = 0$ , the response function for regression model (6.5) is:

$$(6.6) \quad E\{Y\} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{p-1} X_{p-1}$$

This response function is a *hyperplane*, which is a plane in more than two dimensions. It is no longer possible to picture this response surface, as we were able to do in Figure 6.1 for the case of two predictor variables. Nevertheless, the meaning of the parameters is analogous to the case of two predictor variables. The parameter  $\beta_k$  indicates the change in the mean response  $E\{Y\}$  with a unit increase in the predictor variable  $X_k$ , when all other predictor variables in the regression model are held constant. Note again that the effect of any predictor variable on the mean response is the same for regression model (6.5) no matter what are the levels at which the other predictor variables are held. Hence, first-order regression model (6.5) is designed for predictor variables whose effects on the mean response are additive and therefore do not interact.

**Note**

When  $p - 1 = 1$ , regression model (6.5) reduces to:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \varepsilon_i$$

which is the simple linear regression model considered in earlier chapters. ■

**General Linear Regression Model**

In general, the variables  $X_1, \dots, X_{p-1}$  in a regression model do not need to represent different predictor variables, as we shall shortly see. We therefore define the general linear regression model, with normal error terms, simply in terms of  $X$  variables:

$$(6.7) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i$$

where:

$\beta_0, \beta_1, \dots, \beta_{p-1}$  are parameters

$X_{i1}, \dots, X_{i,p-1}$  are known constants

$\varepsilon_i$  are independent  $N(0, \sigma^2)$

$i = 1, \dots, n$

If we let  $X_{i0} \equiv 1$ , regression model (6.7) can be written as follows:

$$(6.7a) \quad Y_i = \beta_0 X_{i0} + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i \quad \text{where } X_{i0} \equiv 1$$

or:

$$(6.7b) \quad Y_i = \sum_{k=0}^{p-1} \beta_k X_{ik} + \varepsilon_i \quad \text{where } X_{i0} \equiv 1$$

The response function for regression model (6.7) is, since  $E\{\varepsilon_i\} = 0$ :

$$(6.8) \quad E\{Y\} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{p-1} X_{p-1}$$

Thus, the general linear regression model with normal error terms implies that the observations  $Y_i$  are independent normal variables, with mean  $E\{Y_i\}$  as given by (6.8) and with constant variance  $\sigma^2$ .

This general linear model encompasses a vast variety of situations. We consider a few of these now.

**$p - 1$  Predictor Variables.** When  $X_1, \dots, X_{p-1}$  represent  $p - 1$  different predictor variables, general linear regression model (6.7) is, as we have seen, a first-order model in which there are no interaction effects between the predictor variables. The example in Figure 6.1 involves a first-order model with two predictor variables.

**Qualitative Predictor Variables.** The general linear regression model (6.7) encompasses not only quantitative predictor variables but also qualitative ones, such as gender (male, female) or disability status (not disabled, partially disabled, fully disabled). We use indicator variables that take on the values 0 and 1 to identify the classes of a qualitative variable.

Consider a regression analysis to predict the length of hospital stay ( $Y$ ) based on the age ( $X_1$ ) and gender ( $X_2$ ) of the patient. We define  $X_2$  as follows:

$$X_2 = \begin{cases} 1 & \text{if patient female} \\ 0 & \text{if patient male} \end{cases}$$

The first-order regression model then is as follows:

$$(6.9) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i$$

where:

$X_{i1}$  = patient's age

$$X_{i2} = \begin{cases} 1 & \text{if patient female} \\ 0 & \text{if patient male} \end{cases}$$

The response function for regression model (6.9) is:

$$(6.10) \quad E\{Y\} = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

For male patients,  $X_2 = 0$  and response function (6.10) becomes:

$$(6.10a) \quad E\{Y\} = \beta_0 + \beta_1 X_1 \quad \text{Male patients}$$

For female patients,  $X_2 = 1$  and response function (6.10) becomes:

$$(6.10b) \quad E\{Y\} = (\beta_0 + \beta_2) + \beta_1 X_1 \quad \text{Female patients}$$

These two response functions represent parallel straight lines with different intercepts.

In general, we represent a qualitative variable with  $c$  classes by means of  $c - 1$  indicator variables. For instance, if in the hospital stay example the qualitative variable disability status is to be added as another predictor variable, it can be represented as follows by the two indicator variables  $X_3$  and  $X_4$ :

$$X_3 = \begin{cases} 1 & \text{if patient not disabled} \\ 0 & \text{otherwise} \end{cases}$$

$$X_4 = \begin{cases} 1 & \text{if patient partially disabled} \\ 0 & \text{otherwise} \end{cases}$$

The first-order model with age, gender, and disability status as predictor variables then is:

$$(6.11) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \beta_4 X_{i4} + \varepsilon_i$$

where:

$X_{i1}$  = patient's age

$$X_{i2} = \begin{cases} 1 & \text{if patient female} \\ 0 & \text{if patient male} \end{cases}$$

$$X_{i3} = \begin{cases} 1 & \text{if patient not disabled} \\ 0 & \text{otherwise} \end{cases}$$

$$X_{i4} = \begin{cases} 1 & \text{if patient partially disabled} \\ 0 & \text{otherwise} \end{cases}$$

In Chapter 11 we present a comprehensive discussion of how to model qualitative predictor variables and how to interpret regression models containing qualitative predictor variables.

**Polynomial Regression.** Polynomial regression models are special cases of the general linear regression model. They contain squared and higher-order terms of the predictor variable(s), making the response function curvilinear. The following is a polynomial regression model with one predictor variable:

$$(6.12) \quad Y_i = \beta_0 + \beta_1 X_i + \beta_2 X_i^2 + \varepsilon_i$$

Figure 1.3 shows an example of a polynomial regression function with one predictor variable.

Despite the curvilinear nature of the response function for regression model (6.12), it is a special case of general linear regression model (6.7). If we let  $X_{i1} = X_i$  and  $X_{i2} = X_i^2$ , we can write (6.12) as follows:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i$$

which is in the form of general linear regression model (6.7). While (6.12) illustrates a curvilinear regression model where the response function is quadratic, models with higher-degree polynomial response functions are also particular cases of the general linear regression model. We shall discuss polynomial regression models in more detail in Chapter 7.

**Transformed Variables.** Models with transformed variables involve complex, curvilinear response functions, yet still are special cases of the general linear regression model. Consider the following model with a transformed  $Y$  variable:

$$(6.13) \quad \log Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i$$

Here, the response surface is complex, yet model (6.13) can still be treated as a general linear regression model. If we let  $Y'_i = \log Y_i$ , we can write regression model (6.13) as follows:

$$Y'_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i$$

which is in the form of general linear regression model (6.7). The response variable just happens to be the logarithm of  $Y$ .

Many models can be transformed into the general linear regression model. For instance, the model:

$$(6.14) \quad Y_i = \frac{1}{\beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i}$$

can be transformed to the general linear regression model by letting  $Y'_i = 1/Y_i$ . We then have:

$$Y'_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i$$

**Interaction Effects.** When the effects of the predictor variables on the response variable are not additive, the effect of one predictor variable depends on the levels of the other predictor variables. The general linear regression model (6.7) encompasses regression models with nonadditive or interacting effects. An example of a nonadditive regression model with two predictor variables  $X_1$  and  $X_2$  is the following:

$$(6.15) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1} X_{i2} + \varepsilon_i$$

Here, the response function is complex because of the interaction term  $\beta_3 X_{i1} X_{i2}$ . Yet regression model (6.15) is a special case of the general linear regression model. Let  $X_{i3} = X_{i1} X_{i2}$  and then write (6.15) as follows:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i$$

We see that this model is in the form of general linear regression model (6.7). We shall discuss regression models with interaction effects in more detail in Chapter 7.

**Combination of Cases.** A regression model may combine several of the elements we have just noted and still be treated as a general linear regression model. Consider the following regression model containing linear and quadratic terms for each of two predictor variables and an interaction term represented by the cross-product term:

$$(6.16) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i1}^2 + \beta_3 X_{i2} + \beta_4 X_{i2}^2 + \beta_5 X_{i1} X_{i2} + \varepsilon_i$$

Let us define:

$$Z_{i1} = X_{i1} \quad Z_{i2} = X_{i1}^2 \quad Z_{i3} = X_{i2} \quad Z_{i4} = X_{i2}^2 \quad Z_{i5} = X_{i1} X_{i2}$$

We can then write regression model (6.16) as follows:

$$Y_i = \beta_0 + \beta_1 Z_{i1} + \beta_2 Z_{i2} + \beta_3 Z_{i3} + \beta_4 Z_{i4} + \beta_5 Z_{i5} + \varepsilon_i$$

which is in the form of general linear regression model (6.7).

The general linear regression model (6.7) includes many complex models, some of which may be highly complex. Figure 6.2 illustrates two complex response surfaces when there are two predictor variables, that can be represented by general linear regression model (6.7).

**Meaning of Linear in General Linear Regression Model.** It should be clear from the various examples that general linear regression model (6.7) is not restricted to linear response surfaces. The term *linear model* refers to the fact that model (6.7) is linear in the parameters; it does not refer to the shape of the response surface.

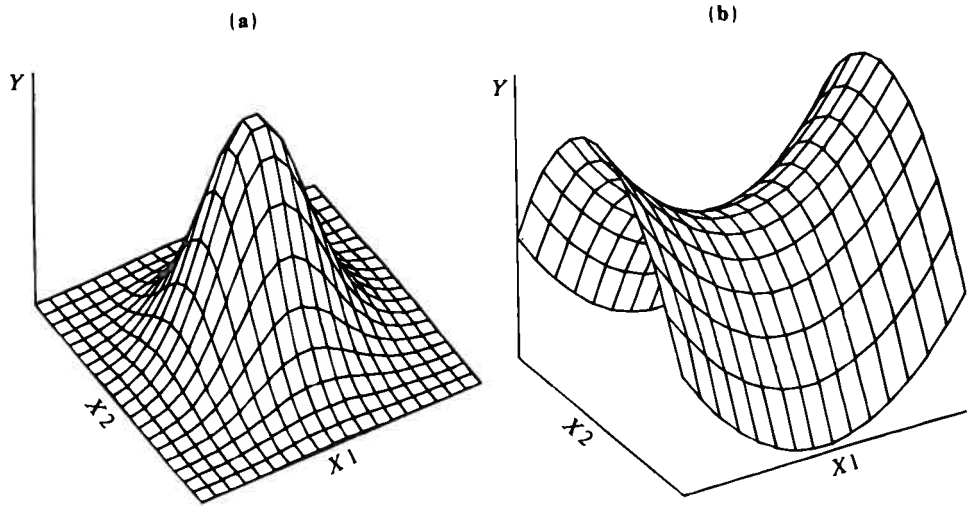
We say that a regression model is linear in the parameters when it can be written in the form:

$$(6.17) \quad Y_i = c_{i0}\beta_0 + c_{i1}\beta_1 + c_{i2}\beta_2 + \cdots + c_{i,p-1}\beta_{p-1} + \varepsilon_i$$

where the terms  $c_{i0}$ ,  $c_{i1}$ , etc., are coefficients involving the predictor variables. For example, first-order model (6.1) in two predictor variables:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i$$



**FIGURE 6.2 Additional Examples of Response Functions.**

is linear in the parameters, with  $c_{i0} = 1$ ,  $c_{i1} = X_{i1}$ , and  $c_{i2} = X_{i2}$ .

An example of a nonlinear regression model is the following:

$$Y_i = \beta_0 \exp(\beta_1 X_i) + \varepsilon_i$$

This is a nonlinear regression model because it cannot be expressed in the form of (6.17). We shall discuss nonlinear regression models in Part III.

## 6.2 General Linear Regression Model in Matrix Terms

We now present the principal results for the general linear regression model (6.7) in matrix terms. This model, as noted, encompasses a wide variety of particular cases. The results to be presented are applicable to all of these.

It is remarkable property of matrix algebra that the results for the general linear regression model (6.7) in matrix notation appear exactly as those for the simple linear regression model (5.53). Only the degrees of freedom and other constants related to the number of  $X$  variables and the dimensions of some matrices are different. Hence, we are able to present the results very concisely.

The matrix notation, to be sure, may hide enormous computational complexities. To find the inverse of a  $10 \times 10$  matrix  $A$  requires a tremendous amount of computation, yet it is simply represented as  $A^{-1}$ . Our reason for emphasizing matrix algebra is that it indicates the essential conceptual steps in the solution. The actual computations will, in all but the very simplest cases, be done by programmable calculator or computer. Hence, it does not matter to us whether  $(X'X)^{-1}$  represents finding the inverse of a  $2 \times 2$  or a  $10 \times 10$  matrix. The important point is to know what the inverse of the matrix represents.

To express general linear regression model (6.7):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i$$

in matrix terms, we need to define the following matrices:

$$(6.18a) \quad \mathbf{Y}_{n \times 1} = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} \quad (6.18)$$

$$(6.18b) \quad \mathbf{X}_{n \times p} = \begin{bmatrix} 1 & X_{11} & X_{12} & \cdots & X_{1,p-1} \\ 1 & X_{21} & X_{22} & \cdots & X_{2,p-1} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & X_{n1} & X_{n2} & \cdots & X_{n,p-1} \end{bmatrix}$$

$$(6.18c) \quad \boldsymbol{\beta}_{p \times 1} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_{p-1} \end{bmatrix}$$

$$(6.18d) \quad \boldsymbol{\varepsilon}_{n \times 1} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}$$

Note that the  $\mathbf{Y}$  and  $\boldsymbol{\varepsilon}$  vectors are the same as for simple linear regression. The  $\boldsymbol{\beta}$  vector contains additional regression parameters, and the  $\mathbf{X}$  matrix contains a column of 1s as well as a column of the  $n$  observations for each of the  $p - 1$   $X$  variables in the regression model. The row subscript for each element  $X_{ik}$  in the  $\mathbf{X}$  matrix identifies the trial or case, and the column subscript identifies the  $X$  variable.

In matrix terms, the general linear regression model (6.7) is:

$$(6.19) \quad \mathbf{Y}_{n \times 1} = \mathbf{X}_{n \times p} \boldsymbol{\beta}_{p \times 1} + \boldsymbol{\varepsilon}_{n \times 1}$$

where:

$\mathbf{Y}$  is a vector of responses

$\boldsymbol{\beta}$  is a vector of parameters

$\mathbf{X}$  is a matrix of constants

$\boldsymbol{\varepsilon}$  is a vector of independent normal random variables with expectation

$E\{\boldsymbol{\varepsilon}\} = \mathbf{0}$  and variance-covariance matrix:

$$\sigma^2\{\boldsymbol{\varepsilon}\}_{n \times n} = \begin{bmatrix} \sigma^2 & 0 & \cdots & 0 \\ 0 & \sigma^2 & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & \sigma^2 \end{bmatrix} = \sigma^2 \mathbf{I}$$

Consequently, the random vector  $\mathbf{Y}$  has expectation:

$$(6.20) \quad E\{\mathbf{Y}\}_{n \times 1} = \mathbf{X}\boldsymbol{\beta}$$

and the variance-covariance matrix of  $\mathbf{Y}$  is the same as that of  $\boldsymbol{\varepsilon}$ :

$$(6.21) \quad \sigma^2\{\mathbf{Y}\}_{n \times n} = \sigma^2 \mathbf{I}$$

## 6.3 Estimation of Regression Coefficients

The least squares criterion (1.8) is generalized as follows for general linear regression model (6.7):

$$(6.22) \quad Q = \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_{i1} - \cdots - \beta_{p-1} X_{i,p-1})^2$$

The least squares estimators are those values of  $\beta_0, \beta_1, \dots, \beta_{p-1}$  that minimize  $Q$ . Let us denote the vector of the least squares estimated regression coefficients  $b_0, b_1, \dots, b_{p-1}$  as  $\mathbf{b}$ :

$$(6.23) \quad \underset{p \times 1}{\mathbf{b}} = \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_{p-1} \end{bmatrix}$$

The least squares normal equations for the general linear regression model (6.19) are:

$$(6.24) \quad \mathbf{X}'\mathbf{X}\mathbf{b} = \mathbf{X}'\mathbf{Y}$$

and the least squares estimators are:

$$(6.25) \quad \underset{p \times 1}{\mathbf{b}} = \underset{p \times p}{(\mathbf{X}'\mathbf{X})}^{-1} \underset{p \times 1}{(\mathbf{X}'\mathbf{Y})}$$

The method of maximum likelihood leads to the same estimators for normal error regression model (6.19) as those obtained by the method of least squares in (6.25). The likelihood function in (1.26) generalizes directly for multiple regression as follows:

$$(6.26) \quad L(\boldsymbol{\beta}, \sigma^2) = \frac{1}{(2\pi\sigma^2)^{n/2}} \exp \left[ -\frac{1}{2\sigma^2} \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_{i1} - \cdots - \beta_{p-1} X_{i,p-1})^2 \right]$$

Maximizing this likelihood function with respect to  $\beta_0, \beta_1, \dots, \beta_{p-1}$  leads to the estimators in (6.25). These estimators are least squares and maximum likelihood estimators and have all the properties mentioned in Chapter 1: they are minimum variance unbiased, consistent, and sufficient.

## 6.4 Fitted Values and Residuals

Let the vector of the fitted values  $\hat{Y}_i$  be denoted by  $\hat{\mathbf{Y}}$  and the vector of the residual terms  $e_i = Y_i - \hat{Y}_i$  be denoted by  $\mathbf{e}$ :

$$(6.27) \quad \underset{n \times 1}{\hat{\mathbf{Y}}} = \begin{bmatrix} \hat{Y}_1 \\ \hat{Y}_2 \\ \vdots \\ \hat{Y}_n \end{bmatrix} \quad (6.27a) \quad \underset{n \times 1}{\mathbf{e}} = \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} \quad (6.27b)$$

The fitted values are represented by:

$$(6.28) \quad \underset{n \times 1}{\hat{\mathbf{Y}}} = \mathbf{X}\mathbf{b}$$

and the residual terms by:

$$(6.29) \quad \underset{n \times 1}{\mathbf{e}} = \mathbf{Y} - \hat{\mathbf{Y}} = \mathbf{Y} - \mathbf{X}\mathbf{b}$$

The vector of the fitted values  $\hat{\mathbf{Y}}$  can be expressed in terms of the hat matrix  $\mathbf{H}$  as follows:

$$(6.30) \quad \underset{n \times 1}{\hat{\mathbf{Y}}} = \mathbf{H}\mathbf{Y}$$

where:

$$(6.30a) \quad \underset{n \times n}{\mathbf{H}} = \mathbf{X}(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'$$

Similarly, the vector of residuals can be expressed as follows:

$$(6.31) \quad \underset{n \times 1}{\mathbf{e}} = (\mathbf{I} - \mathbf{H})\mathbf{Y}$$

The variance-covariance matrix of the residuals is:

$$(6.32) \quad \underset{n \times n}{\sigma^2\{\mathbf{e}\}} = \sigma^2(\mathbf{I} - \mathbf{H})$$

which is estimated by:

$$(6.33) \quad \underset{n \times n}{s^2\{\mathbf{e}\}} = MSE(\mathbf{I} - \mathbf{H})$$

---

## 6.5 Analysis of Variance Results

### *Sums of Squares and Mean Squares*

The sums of squares for the analysis of variance in matrix terms are:

$$(6.34) \quad SSTO = \mathbf{Y}'\mathbf{Y} - \left(\frac{1}{n}\right)\mathbf{Y}'\mathbf{J}\mathbf{Y} = \mathbf{Y}'\left[\mathbf{I} - \left(\frac{1}{n}\right)\mathbf{J}\right]\mathbf{Y}$$

**TABLE 6.1** ANOVA Table for General Linear Regression Model (6.19).

| Source of Variation | $SS$   | $df$    | $MS$                      |
|---------------------|--|---------|---------------------------|
| Regression          | $SSR = \mathbf{b}'\mathbf{X}'\mathbf{Y} - \left(\frac{1}{n}\right)\mathbf{Y}'\mathbf{J}\mathbf{Y}$ | $p - 1$ | $MSR = \frac{SSR}{p - 1}$ |
| Error               | $SSE = \mathbf{Y}'\mathbf{Y} - \mathbf{b}'\mathbf{X}'\mathbf{Y}$                                   | $n - p$ | $MSE = \frac{SSE}{n - p}$ |
| Total               | $SSTO = \mathbf{Y}'\mathbf{Y} - \left(\frac{1}{n}\right)\mathbf{Y}'\mathbf{J}\mathbf{Y}$           | $n - 1$ |                           |

$$(6.35) \quad SSE = \mathbf{e}'\mathbf{e} = (\mathbf{Y} - \mathbf{X}\mathbf{b})'(\mathbf{Y} - \mathbf{X}\mathbf{b}) = \mathbf{Y}'\mathbf{Y} - \mathbf{b}'\mathbf{X}'\mathbf{Y} = \mathbf{Y}'(\mathbf{I} - \mathbf{H})\mathbf{Y}$$

$$(6.36) \quad SSR = \mathbf{b}'\mathbf{X}'\mathbf{Y} - \left(\frac{1}{n}\right)\mathbf{Y}'\mathbf{J}\mathbf{Y} = \mathbf{Y}'\left[\mathbf{H} - \left(\frac{1}{n}\right)\mathbf{J}\right]\mathbf{Y}$$

where  $\mathbf{J}$  is an  $n \times n$  matrix of 1s defined in (5.18) and  $\mathbf{H}$  is the hat matrix defined in (6.30a).

$SSTO$ , as usual, has  $n - 1$  degrees of freedom associated with it.  $SSE$  has  $n - p$  degrees of freedom associated with it since  $p$  parameters need to be estimated in the regression function for model (6.19). Finally,  $SSR$  has  $p - 1$  degrees of freedom associated with it, representing the number of  $X$  variables  $X_1, \dots, X_{p-1}$ .

Table 6.1 shows these analysis of variance results, as well as the mean squares  $MSR$  and  $MSE$ :

$$(6.37) \quad MSR = \frac{SSR}{p - 1}$$

$$(6.38) \quad MSE = \frac{SSE}{n - p}$$

The expectation of  $MSE$  is  $\sigma^2$ , as for simple linear regression. The expectation of  $MSR$  is  $\sigma^2$  plus a quantity that is nonnegative. For instance, when  $p - 1 = 2$ , we have:

$$E\{MSR\} = \sigma^2 + \frac{1}{2} \left[ \beta_1^2 \sum (X_{i1} - \bar{X}_1)^2 + \beta_2^2 \sum (X_{i2} - \bar{X}_2)^2 + 2\beta_1\beta_2 \sum (X_{i1} - \bar{X}_1)(X_{i2} - \bar{X}_2) \right]$$

Note that if both  $\beta_1$  and  $\beta_2$  equal zero,  $E\{MSR\} = \sigma^2$ . Otherwise  $E\{MSR\} > \sigma^2$ .

### F Test for Regression Relation

To test whether there is a regression relation between the response variable  $Y$  and the set of  $X$  variables  $X_1, \dots, X_{p-1}$ , i.e., to choose between the alternatives:

$$(6.39a) \quad \begin{aligned} H_0: & \beta_1 = \beta_2 = \dots = \beta_{p-1} = 0 \\ H_a: & \text{not all } \beta_k \text{ } (k = 1, \dots, p - 1) \text{ equal zero} \end{aligned}$$

we use the test statistic:

$$(6.39b) \quad F^* = \frac{MSR}{MSE}$$

The decision rule to control the Type I error at  $\alpha$  is:

$$(6.39c) \quad \begin{aligned} &\text{If } F^* \leq F(1 - \alpha; p - 1, n - p), \text{ conclude } H_0 \\ &\text{If } F^* > F(1 - \alpha; p - 1, n - p), \text{ conclude } H_a \end{aligned}$$

The existence of a regression relation by itself does not, of course, ensure that useful predictions can be made by using it.

Note that when  $p - 1 = 1$ , this test reduces to the  $F$  test in (2.60) for testing in simple linear regression whether or not  $\beta_1 = 0$ .

### Coefficient of Multiple Determination

The coefficient of multiple determination, denoted by  $R^2$ , is defined as follows:

$$(6.40) \quad R^2 = \frac{SSR}{SSTO} = 1 - \frac{SSE}{SSTO}$$

It measures the proportionate reduction of total variation in  $Y$  associated with the use of the set of  $X$  variables  $X_1, \dots, X_{p-1}$ . The coefficient of multiple determination  $R^2$  reduces to the coefficient of simple determination  $r^2$  in (2.72) for simple linear regression when  $p - 1 = 1$ , i.e., when one  $X$  variable is in regression model (6.19). Just as for  $r^2$ , we have:

$$(6.41) \quad 0 \leq R^2 \leq 1$$

where  $R^2$  assumes the value 0 when all  $b_k = 0$  ( $k = 1, \dots, p - 1$ ), and the value 1 when all  $Y$  observations fall directly on the fitted regression surface, i.e., when  $Y_i = \hat{Y}_i$  for all  $i$ .

#### Comments

1. To distinguish between the coefficients of determination for simple and multiple regression, we shall from now on call  $r^2$  the coefficient of simple determination.
2. It can be shown that the coefficient of multiple determination  $R^2$  can be viewed as a coefficient of simple determination  $r^2$  between the responses  $Y_i$  and the fitted values  $\hat{Y}_i$ .
3. A large value of  $R^2$  does not necessarily imply that the fitted model is a useful one. For instance, observations may have been taken at only a few levels of the predictor variables. Despite a high  $R^2$  in this case, the fitted model may not be useful if most predictions require extrapolations outside the region of observations. Again, even though  $R^2$  is large,  $MSE$  may still be too large for inferences to be useful when high precision is required.
4. Adding more  $X$  variables to the regression model can only increase  $R^2$  and never reduce it, because  $SSE$  can never become larger with more  $X$  variables and  $SSTO$  is always the same for a given set of responses. Since  $R^2$  usually can be made larger by including a larger number of predictor variables, it is sometimes suggested that a modified measure be used that adjusts for the number of  $X$  variables in the model. The *adjusted coefficient of multiple determination*,

denoted by  $R_a^2$ , adjusts  $R^2$  by dividing each sum of squares by its associated degrees of freedom:

$$(6.42) \quad R_a^2 = 1 - \frac{\frac{SSE}{n-p}}{\frac{SSTO}{n-1}} = 1 - \left( \frac{n-1}{n-p} \right) \frac{SSE}{SSTO}$$

This adjusted coefficient of multiple determination may actually become smaller when another  $X$  variable is introduced into the model, because any decrease in  $SSE$  may be more than offset by the loss of a degree of freedom in the denominator  $n-p$ . ■

### Coefficient of Multiple Correlation

The coefficient of multiple correlation  $R$  is the positive square root of  $R^2$ :

$$(6.43) \quad R = \sqrt{R^2}$$

When there is one  $X$  variable in regression model (6.19), i.e., when  $p-1 = 1$ , the coefficient of multiple correlation  $R$  equals in absolute value the correlation coefficient  $r$  in (2.74) for simple correlation.

#### Note

From now on, we call  $r$  the *coefficient of simple correlation* to distinguish it from the coefficient of multiple correlation. ■

## 6.6 Inferences about Regression Parameters

The least squares and maximum likelihood estimators in  $\mathbf{b}$  are unbiased:

$$(6.44) \quad E\{\mathbf{b}\} = \boldsymbol{\beta}$$

The variance-covariance matrix  $\boldsymbol{\sigma}^2\{\mathbf{b}\}$ :

$$(6.45) \quad \boldsymbol{\sigma}^2\{\mathbf{b}\}_{p \times p} = \begin{bmatrix} \sigma^2\{b_0\} & \sigma\{b_0, b_1\} & \cdots & \sigma\{b_0, b_{p-1}\} \\ \sigma\{b_1, b_0\} & \sigma^2\{b_1\} & \cdots & \sigma\{b_1, b_{p-1}\} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma\{b_{p-1}, b_0\} & \sigma\{b_{p-1}, b_1\} & \cdots & \sigma^2\{b_{p-1}\} \end{bmatrix}$$

is given by:

$$(6.46) \quad \boldsymbol{\sigma}^2\{\mathbf{b}\}_{p \times p} = \sigma^2(\mathbf{X}'\mathbf{X})^{-1}$$

The estimated variance-covariance matrix  $\mathbf{s}^2\{\mathbf{b}\}$ :

$$(6.47) \quad \mathbf{s}^2_{p \times p}\{\mathbf{b}\} = \begin{bmatrix} s^2\{b_0\} & s\{b_0, b_1\} & \cdots & s\{b_0, b_{p-1}\} \\ s\{b_1, b_0\} & s^2\{b_1\} & \cdots & s\{b_1, b_{p-1}\} \\ \vdots & \vdots & & \vdots \\ s\{b_{p-1}, b_0\} & s\{b_{p-1}, b_1\} & \cdots & s^2\{b_{p-1}\} \end{bmatrix}$$

is given by:

$$(6.48) \quad \mathbf{s}^2_{p \times p}\{\mathbf{b}\} = MSE(\mathbf{X}'\mathbf{X})^{-1}$$

From  $\mathbf{s}^2\{\mathbf{b}\}$ , one can obtain  $s^2\{b_0\}$ ,  $s^2\{b_1\}$ , or whatever other variance is needed, or any needed covariances.

### Interval Estimation of $\beta_k$

For the normal error regression model (6.19), we have:

$$(6.49) \quad \frac{b_k - \beta_k}{s\{b_k\}} \sim t(n - p) \quad k = 0, 1, \dots, p - 1$$

Hence, the confidence limits for  $\beta_k$  with  $1 - \alpha$  confidence coefficient are:

$$(6.50) \quad b_k \pm t(1 - \alpha/2; n - p)s\{b_k\}$$

### Tests for $\beta_k$

Tests for  $\beta_k$  are set up in the usual fashion. To test:

$$(6.51a) \quad \begin{aligned} H_0: & \beta_k = 0 \\ H_a: & \beta_k \neq 0 \end{aligned}$$

we may use the test statistic:

$$(6.51b) \quad t^* = \frac{b_k}{s\{b_k\}}$$

and the decision rule:

$$(6.51c) \quad \begin{aligned} & \text{If } |t^*| \leq t(1 - \alpha/2; n - p), \text{ conclude } H_0 \\ & \text{Otherwise conclude } H_a \end{aligned}$$

The power of the  $t$  test can be obtained as explained in Chapter 2, with the degrees of freedom modified to  $n - p$ .

As with simple linear regression, an  $F$  test can also be conducted to determine whether or not  $\beta_k = 0$  in multiple regression models. We discuss this test in Chapter 7.



## Joint Inferences

The Bonferroni joint confidence intervals can be used to estimate several regression coefficients simultaneously. If  $g$  parameters are to be estimated jointly (where  $g \leq p$ ), the confidence limits with family confidence coefficient  $1 - \alpha$  are:

$$(6.52) \quad b_k \pm Bs\{b_k\}$$

where:

$$(6.52a) \quad B = t(1 - \alpha/2g; n - p)$$

In Chapter 7, we discuss tests concerning subsets of the regression parameters.

---

## 6.7 Estimation of Mean Response and Prediction of New Observation

### Interval Estimation of $E\{Y_h\}$

For given values of  $X_1, \dots, X_{p-1}$ , denoted by  $X_{h1}, \dots, X_{h,p-1}$ , the mean response is denoted by  $E\{Y_h\}$ . We define the vector  $\mathbf{X}_h$ :

$$(6.53) \quad \mathbf{X}_h = \begin{bmatrix} 1 \\ X_{h1} \\ \vdots \\ X_{h,p-1} \end{bmatrix}$$

so that the mean response to be estimated is:

$$(6.54) \quad E\{Y_h\} = \mathbf{X}_h' \boldsymbol{\beta}$$

The estimated mean response corresponding to  $\mathbf{X}_h$ , denoted by  $\hat{Y}_h$ , is:

$$(6.55) \quad \hat{Y}_h = \mathbf{X}_h' \mathbf{b}$$

This estimator is unbiased:

$$(6.56) \quad E\{\hat{Y}_h\} = \mathbf{X}_h' \boldsymbol{\beta} = E\{Y_h\}$$

and its variance is:

$$(6.57) \quad \sigma^2\{\hat{Y}_h\} = \sigma^2 \mathbf{X}_h' (\mathbf{X}' \mathbf{X})^{-1} \mathbf{X}_h$$

This variance can be expressed as a function of the variance-covariance matrix of the estimated regression coefficients:

$$(6.57a) \quad \sigma^2\{\hat{Y}_h\} = \mathbf{X}_h' \boldsymbol{\sigma}^2\{\mathbf{b}\} \mathbf{X}_h$$

Note from (6.57a) that the variance  $\sigma^2\{\hat{Y}_h\}$  is a function of the variances  $\sigma^2\{b_k\}$  of the regression coefficients and of the covariances  $\sigma\{b_k, b_{k'}\}$  between pairs of regression coefficients, just as in simple linear regression. The estimated variance  $s^2\{\hat{Y}_h\}$  is given by:

$$(6.58) \quad s^2\{\hat{Y}_h\} = \text{MSE}(\mathbf{X}'_h(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}_h) = \mathbf{X}'_h\mathbf{s}^2\{\mathbf{b}\}\mathbf{X}_h$$

The  $1 - \alpha$  confidence limits for  $E\{Y_h\}$  are:

$$(6.59) \quad \hat{Y}_h \pm t(1 - \alpha/2; n - p)s\{\hat{Y}_h\}$$

### Confidence Region for Regression Surface

The  $1 - \alpha$  confidence region for the entire regression surface is an extension of the Working-Hotelling confidence band (2.40) for the regression line when there is one predictor variable. Boundary points of the confidence region at  $\mathbf{X}_h$  are obtained from:

$$(6.60) \quad \hat{Y}_h \pm Ws\{\hat{Y}_h\}$$

where:

$$(6.60a) \quad W^2 = pF(1 - \alpha; p, n - p)$$

The confidence coefficient  $1 - \alpha$  provides assurance that the region contains the entire regression surface over all combinations of values of the  $X$  variables.

### Simultaneous Confidence Intervals for Several Mean Responses

To estimate a number of mean responses  $E\{Y_h\}$  corresponding to different  $\mathbf{X}_h$  vectors with family confidence coefficient  $1 - \alpha$ , we can employ two basic approaches:

1. Use the Working-Hotelling confidence region bounds (6.60) for the several  $\mathbf{X}_h$  vectors of interest:

$$(6.61) \quad \hat{Y}_h \pm Ws\{\hat{Y}_h\}$$

where  $\hat{Y}_h$ ,  $W$ , and  $s\{\hat{Y}_h\}$  are defined in (6.55), (6.60a), and (6.58), respectively. Since the Working-Hotelling confidence region covers the mean responses for all possible  $\mathbf{X}_h$  vectors with confidence coefficient  $1 - \alpha$ , the selected boundary values will cover the mean responses for the  $\mathbf{X}_h$  vectors of interest with family confidence coefficient greater than  $1 - \alpha$ .

2. Use Bonferroni simultaneous confidence intervals. When  $g$  interval estimates are to be made, the Bonferroni confidence limits are:

$$(6.62) \quad \hat{Y}_h \pm Bs\{\hat{Y}_h\}$$

where:

$$(6.62a) \quad B = t(1 - \alpha/2g; n - p)$$

For any particular application, we can compare the  $W$  and  $B$  multiples to see which procedure will lead to narrower confidence intervals. If the  $\mathbf{X}_h$  levels are not specified in advance but are determined as the analysis proceeds, it is better to use the Working-Hotelling limits (6.61) since the family for this procedure includes all possible  $\mathbf{X}_h$  levels.

### Prediction of New Observation $Y_{h(\text{new})}$

The  $1 - \alpha$  prediction limits for a new observation  $Y_{h(\text{new})}$  corresponding to  $\mathbf{X}_h$ , the specified values of the  $X$  variables, are:

$$(6.63) \quad \hat{Y}_h \pm t(1 - \alpha/2; n - p)s\{\text{pred}\}$$

where:

$$(6.63a) \quad s^2\{\text{pred}\} = MSE + s^2\{\hat{Y}_h\} = MSE(1 + \mathbf{X}_h'(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}_h)$$

and  $s^2\{\hat{Y}_h\}$  is given by (6.58).

### Prediction of Mean of $m$ New Observations at $\mathbf{X}_h$

When  $m$  new observations are to be selected at the same levels  $\mathbf{X}_h$  and their mean  $\bar{Y}_{h(\text{new})}$  is to be predicted, the  $1 - \alpha$  prediction limits are:

$$(6.64) \quad \hat{Y}_h \pm t(1 - \alpha/2; n - p)s\{\text{predmean}\}$$

where:

$$(6.64a) \quad s^2\{\text{predmean}\} = \frac{MSE}{m} + s^2\{\hat{Y}_h\} = MSE \left( \frac{1}{m} + \mathbf{X}_h'(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}_h \right)$$

### Predictions of $g$ New Observations

Simultaneous Scheffé prediction limits for  $g$  new observations at  $g$  different levels  $\mathbf{X}_h$  with family confidence coefficient  $1 - \alpha$  are given by:

$$(6.65) \quad \hat{Y}_h \pm Ss\{\text{pred}\}$$

where:

$$(6.65a) \quad S^2 = gF(1 - \alpha; g, n - p)$$

and  $s^2\{\text{pred}\}$  is given by (6.63a).

Alternatively, Bonferroni simultaneous prediction limits can be used. For  $g$  predictions with family confidence coefficient  $1 - \alpha$ , they are:

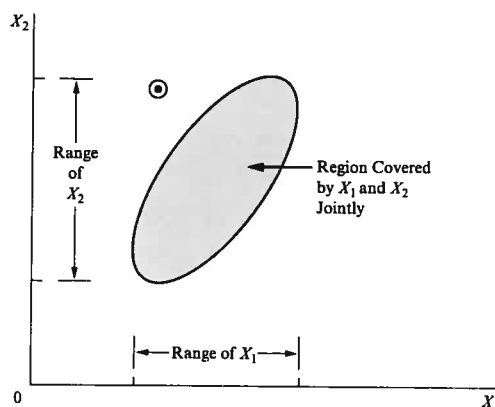
$$(6.66) \quad \hat{Y}_h \pm Bs\{\text{pred}\}$$

where:

$$(6.66a) \quad B = t(1 - \alpha/2g; n - p)$$

A comparison of  $S$  and  $B$  in advance of any particular use will indicate which procedure will lead to narrower prediction intervals.

**FIGURE 6.3** Region of Observations on  $X_1$  and  $X_2$  Jointly, Compared with Ranges of  $X_1$  and  $X_2$  Individually.



### Caution about Hidden Extrapolations

When estimating a mean response or predicting a new observation in multiple regression, one needs to be particularly careful that the estimate or prediction does not fall outside the scope of the model. The danger, of course, is that the model may not be appropriate when it is extended outside the region of the observations. In multiple regression, it is particularly easy to lose track of this region since the levels of  $X_1, \dots, X_{p-1}$  jointly define the region. Thus, one cannot merely look at the ranges of each predictor variable. Consider Figure 6.3, where the shaded region is the region of observations for a multiple regression application with two predictor variables and the circled dot represents the values  $(X_{h1}, X_{h2})$  for which a prediction is to be made. The circled dot is within the ranges of the predictor variables  $X_1$  and  $X_2$  individually, yet is well outside the joint region of observations. It is easy to spot this extrapolation when there are only two predictor variables, but it becomes much more difficult when the number of predictor variables is large. We discuss in Chapter 9 a procedure for identifying hidden extrapolations when there are more than two predictor variables.

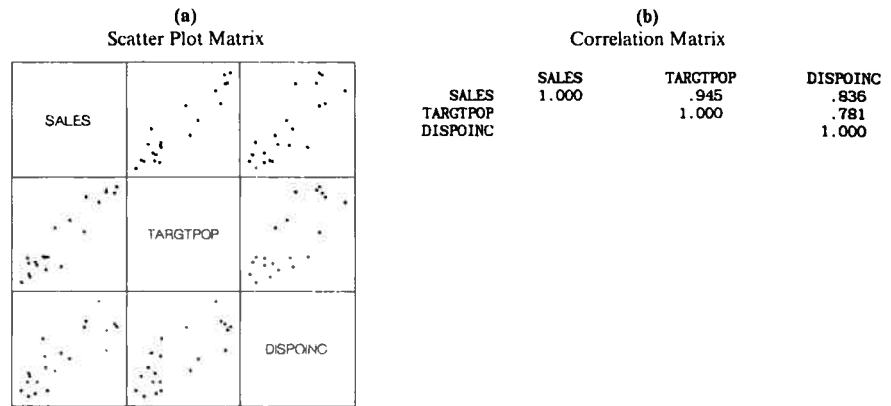
## 6.8 Diagnostics and Remedial Measures

Diagnostics play an important role in the development and evaluation of multiple regression models. Most of the diagnostic procedures for simple linear regression that we described in Chapter 3 carry over directly to multiple regression. We review these diagnostic procedures now, as well as the remedial measures for simple linear regression that carry over directly to multiple regression.

Many specialized diagnostics and remedial procedures for multiple regression have also been developed. Some important ones will be discussed in Chapters 9 and 10.

### Scatter Plot Matrix

Box plots, sequence plots, stem-and-leaf plots, and dot plots for each of the predictor variables and for the response variable can provide helpful, preliminary univariate information

**FIGURE 6.4 SYGRAPH Scatter Plot Matrix and Correlation Matrix—Dwayne Studios Example.**

about these variables. Scatter plots of the response variable against each predictor variable can aid in determining the nature and strength of the bivariate relationships between each of the predictor variables and the response variable and in identifying gaps in the data points as well as outlying data points. Scatter plots of each predictor variable against each of the other predictor variables are helpful for studying the bivariate relationships among the predictor variables and for finding gaps and detecting outliers.

Analysis is facilitated if these scatter plots are assembled in a *scatter plot matrix*, such as in Figure 6.4. In this figure, the  $Y$  variable for any one scatter plot is the name found in its row, and the  $X$  variable is the name found in its column. Thus, the scatter plot matrix in Figure 6.4 shows in the first row the plots of  $Y$  (SALES) against  $X_1$  (TARGETPOP) and  $X_2$  (DISPOINC), of  $X_1$  against  $Y$  and  $X_2$  in the second row, and of  $X_2$  against  $Y$  and  $X_1$  in the third row. Alternatively, by viewing the first column, one can compare the plots of  $X_1$  and  $X_2$  each against  $Y$ , and similarly for the other two columns. A scatter plot matrix facilitates the study of the relationships among the variables by comparing the scatter plots within a row or a column. Examples in this and subsequent chapters will illustrate the usefulness of scatter plot matrices.

A complement to the scatter plot matrix that may be useful at times is the correlation matrix. This matrix contains the coefficients of simple correlation  $r_{Y1}, r_{Y2}, \dots, r_{Y,p-1}$  between  $Y$  and each of the predictor variables, as well as all of the coefficients of simple correlation among the predictor variables— $r_{12}$  between  $X_1$  and  $X_2$ ,  $r_{13}$  between  $X_1$  and  $X_3$ , etc. The format of the correlation matrix follows that of the scatter plot matrix:

$$(6.67) \quad \begin{bmatrix} 1 & r_{Y1} & r_{Y2} & \cdots & r_{Y,p-1} \\ r_{Y1} & 1 & r_{12} & \cdots & r_{1,p-1} \\ \vdots & \vdots & \vdots & & \vdots \\ r_{Y,p-1} & r_{1,p-1} & r_{2,p-1} & \cdots & 1 \end{bmatrix}$$

Note that the correlation matrix is symmetric and that its main diagonal contains 1s because the coefficient of correlation between a variable and itself is 1. Many statistics packages

provide the correlation matrix as an option. Since this matrix is symmetric, the lower (or upper) triangular block of elements is frequently omitted in the output.

Some interactive statistics packages enable the user to employ *brushing* with scatter plot matrices. When a point in a scatter plot is brushed, it is given a distinctive appearance on the computer screen in each scatter plot in the matrix. The case corresponding to the brushed point may also be identified. Brushing is helpful to see whether a case that is outlying in one scatter plot is also outlying in some or all of the other plots. Brushing may also be applied to a group of points to see, for instance, whether a group of cases that does not fit the relationship for the remaining cases in one scatter plot also follows a distinct pattern in any of the other scatter plots.

### Three-Dimensional Scatter Plots

Some interactive statistics packages provide *three-dimensional scatter plots* or *point clouds*, and permit spinning of these plots to enable the viewer to see the point cloud from different perspectives. This can be very helpful for identifying patterns that are only apparent from certain perspectives. Figure 6.6 on page 242 illustrates a three-dimensional scatter plot and the use of spinning.

### Residual Plots

A plot of the residuals against the fitted values is useful for assessing the appropriateness of the multiple regression function and the constancy of the variance of the error terms, as well as for providing information about outliers, just as for simple linear regression. Similarly, a plot of the residuals against time or against some other sequence can provide diagnostic information about possible correlations between the error terms in multiple regression. Box plots and normal probability plots of the residuals are useful for examining whether the error terms are reasonably normally distributed.

In addition, residuals should be plotted against each of the predictor variables. Each of these plots can provide further information about the adequacy of the regression function with respect to that predictor variable (*e.g.*, whether a curvature effect is required for that variable) and about possible variation in the magnitude of the error variance in relation to that predictor variable.

Residuals should also be plotted against important predictor variables that were omitted from the model, to see if the omitted variables have substantial additional effects on the response variable that have not yet been recognized in the regression model. Also, residuals should be plotted against interaction terms for potential interaction effects not included in the regression model, such as against  $X_1X_2$ ,  $X_1X_3$ , and  $X_2X_3$ , to see whether some or all of these interaction terms are required in the model.

A plot of the absolute residuals or the squared residuals against the fitted values is useful for examining the constancy of the variance of the error terms. If nonconstancy is detected, a plot of the absolute residuals or the squared residuals against each of the predictor variables may identify one or several of the predictor variables to which the magnitude of the error variability is related.

### Correlation Test for Normality

The correlation test for normality described in Chapter 3 carries forward directly to multiple regression. The expected values of the ordered residuals under normality are calculated according to (3.6), and the coefficient of correlation between the residuals and the expected

values under normality is then obtained. Table B.6 is employed to assess whether or not the magnitude of the correlation coefficient supports the reasonableness of the normality assumption.

### **Modified Levene Test for Constancy of Error Variance**

The modified Levene test statistic (3.9) for assessing the constancy of the error variance can be used readily in multiple regression when the error variance increases or decreases with one of the predictor variables. To conduct the Levene test, we divide the data set into two groups, as for simple linear regression, where one group consists of cases where the level of the predictor variable is relatively low and the other group consists of cases where the level of the predictor variable is relatively high. The Levene test then proceeds as for simple linear regression.

### **Breusch-Pagan Test for Constancy of Error Variance**

The Breusch-Pagan test (3.11) for constancy of the error variance in multiple regression is carried out exactly the same as for simple linear regression when the error variance increases or decreases with one of the predictor variables. The squared residuals are simply regressed against the predictor variable to obtain the regression sum of squares  $SSR^*$ , and the test proceeds as before, using the error sum of squares  $SSE$  for the full multiple regression model.

When the error variance is a function of more than one predictor variable, a multiple regression of the squared residuals against these predictor variables is conducted and the regression sum of squares  $SSR^*$  is obtained. The test statistic again uses  $SSE$  for the full multiple regression model, but now the chi-square distribution involves  $q$  degrees of freedom, where  $q$  is the number of predictor variables against which the squared residuals are regressed.

### **F Test for Lack of Fit**

The lack of fit  $F$  test described in Chapter 3 for simple linear regression can be carried over to test whether the multiple regression response function:

$$E\{Y\} = \beta_0 + \beta_1 X_1 + \cdots + \beta_{p-1} X_{p-1}$$

is an appropriate response surface. Repeat observations in multiple regression are replicate observations on  $Y$  corresponding to levels of each of the  $X$  variables that are constant from trial to trial. Thus, with two predictor variables, repeat observations require that  $X_1$  and  $X_2$  each remain at given levels from trial to trial.

Once the ANOVA table, shown in Table 6.1, has been obtained,  $SSE$  is decomposed into pure error and lack of fit components. The pure error sum of squares  $SSPE$  is obtained by first calculating for each replicate group the sum of squared deviations of the  $Y$  observations around the group mean, where a replicate group has the same values for each of the  $X$  variables. Let  $c$  denote the number of groups with distinct sets of levels for the  $X$  variables, and let the mean of the  $Y$  observations for the  $j$ th group be denoted by  $\bar{Y}_j$ . Then the sum of squares for the  $j$ th group is given by (3.17), and the pure error sum of squares is the sum of these sums of squares, as given by (3.16). The lack of fit sum of squares  $SSLF$  equals the difference  $SSE - SSPE$ , as indicated by (3.24).

The number of degrees of freedom associated with  $SSPE$  is  $n - c$ , and the number of degrees of freedom associated with  $SSLF$  is  $(n - p) - (n - c) = c - p$ . Thus, for testing the alternatives:

$$(6.68a) \quad \begin{aligned} H_0: E\{Y\} &= \beta_0 + \beta_1 X_1 + \cdots + \beta_{p-1} X_{p-1} \\ H_a: E\{Y\} &\neq \beta_0 + \beta_1 X_1 + \cdots + \beta_{p-1} X_{p-1} \end{aligned}$$

the appropriate test statistic is:

$$(6.68b) \quad F^* = \frac{SSLF}{c - p} \div \frac{SSPE}{n - c} = \frac{MSLF}{MSPE}$$

where  $SSLF$  and  $SSPE$  are given by (3.24) and (3.16), respectively, and the appropriate decision rule is:

$$(6.68c) \quad \begin{aligned} \text{If } F^* &\leq F(1 - \alpha; c - p, n - c), \text{ conclude } H_0 \\ \text{If } F^* &> F(1 - \alpha; c - p, n - c), \text{ conclude } H_a \end{aligned}$$

### Note

When replicate observations are not available, an approximate lack of fit test can be conducted if there are cases that have similar  $\mathbf{X}_h$  vectors. These cases are grouped together and treated as pseudoreplicates, and the test for lack of fit is then carried out using these groupings of similar cases. ■

## Remedial Measures

The remedial measures described in Chapter 3 are also applicable to multiple regression. When a more complex model is required to recognize curvature or interaction effects, the multiple regression model can be expanded to include these effects. For example,  $X_2^2$  might be added as a variable to take into account a curvature effect of  $X_2$ , or  $X_1 X_3$  might be added as a variable to recognize an interaction effect between  $X_1$  and  $X_3$  on the response variable. Alternatively, transformations on the response and/or the predictor variables can be made, following the principles discussed in Chapter 3, to remedy model deficiencies. Transformations on the response variable  $Y$  may be helpful when the distributions of the error terms are quite skewed and the variance of the error terms is not constant. Transformations of some of the predictor variables may be helpful when the effects of these variables are curvilinear. In addition, transformations on  $Y$  and/or the predictor variables may be helpful in eliminating or substantially reducing interaction effects.

As with simple linear regression, the usefulness of potential transformations needs to be examined by means of residual plots and other diagnostic tools to determine whether the multiple regression model for the transformed data is appropriate.

**Box-Cox Transformations.** The Box-Cox procedure for determining an appropriate power transformation on  $Y$  for simple linear regression models described in Chapter 3 is also applicable to multiple regression models. The standardized variable  $W$  in (3.36) is again obtained for different values of the parameter  $\lambda$  and is now regressed against the set of  $X$  variables in the multiple regression model to find that value of  $\lambda$  that minimizes the error sum of squares  $SSE$ .



**FIGURE 6.5** SYSTAT Multiple Regression Output and Basic Data—Dwayne Studios Example.

| (a) Multiple Regression Output    |                                     |                   |                           |           |         |           | (b) Basic Data |      |      |       |         |          |  |
|-----------------------------------|-------------------------------------|-------------------|---------------------------|-----------|---------|-----------|----------------|------|------|-------|---------|----------|--|
| DEP VAR: SALES                    | N: 21                               | MULTIPLE R: 0.957 | SQUARED MULTIPLE R: 0.917 |           |         |           | CASE           | X1   | X2   | Y     | FITTED  | RESIDUAL |  |
| ADJUSTED SQUARED MULTIPLE R: .907 | STANDARD ERROR OF ESTIMATE: 11.0074 |                   |                           |           |         |           | 1              | 68.5 | 16.7 | 174.4 | 187.184 | -12.7841 |  |
|                                   |                                     |                   |                           |           |         |           | 2              | 45.2 | 16.8 | 164.4 | 154.229 | 10.1706  |  |
|                                   |                                     |                   |                           |           |         |           | 3              | 91.3 | 18.2 | 244.2 | 234.396 | 9.8037   |  |
|                                   |                                     |                   |                           |           |         |           | 4              | 47.8 | 16.3 | 154.6 | 153.329 | 1.2715   |  |
|                                   |                                     |                   |                           |           |         |           | 5              | 46.9 | 17.3 | 181.6 | 161.385 | 20.2151  |  |
|                                   |                                     |                   |                           |           |         |           | 6              | 66.1 | 18.2 | 207.5 | 197.741 | 9.7586   |  |
|                                   |                                     |                   |                           |           |         |           | 7              | 49.5 | 15.9 | 152.8 | 152.055 | 0.7449   |  |
|                                   |                                     |                   |                           |           |         |           | 8              | 52.0 | 17.2 | 163.2 | 167.867 | -4.6666  |  |
|                                   |                                     |                   |                           |           |         |           | 9              | 48.9 | 16.6 | 145.4 | 157.738 | -12.3382 |  |
| VARIABLE                          | COEFFICIENT                         | STD ERROR         | STD COEF                  | TOLERANCE | T       | P(2 TAIL) | 10             | 38.4 | 16.0 | 137.2 | 136.846 | 0.3540   |  |
| CONSTANT                          | -68.8571                            | 60.0170           | 0.0000                    | .         | -1.1473 | 0.2663    | 11             | 87.9 | 18.3 | 241.9 | 230.387 | 11.5126  |  |
| TARGETPOP                         | 1.4546                              | 0.2118            | 0.7484                    | 0.3896    | 6.8682  | 0.0000    | 12             | 72.8 | 17.1 | 191.1 | 197.185 | -6.0849  |  |
| DISPOINC                          | 9.3655                              | 4.0640            | 0.2511                    | 0.3896    | 2.3045  | 0.0333    | 13             | 88.4 | 17.4 | 232.0 | 222.686 | 9.3143   |  |
|                                   |                                     |                   |                           |           |         |           | 14             | 42.9 | 15.8 | 145.3 | 141.518 | 3.7816   |  |
|                                   |                                     |                   |                           |           |         |           | 15             | 52.5 | 17.8 | 161.1 | 174.213 | -13.1132 |  |
|                                   |                                     |                   |                           |           |         |           | 16             | 85.7 | 18.4 | 209.7 | 228.124 | -18.4239 |  |
|                                   |                                     |                   |                           |           |         |           | 17             | 41.3 | 16.5 | 146.4 | 145.747 | 0.6530   |  |
|                                   |                                     |                   |                           |           |         |           | 18             | 51.7 | 16.3 | 144.0 | 159.001 | -15.0013 |  |
|                                   |                                     |                   |                           |           |         |           | 19             | 89.6 | 18.1 | 232.6 | 230.987 | 1.6130   |  |
|                                   |                                     |                   |                           |           |         |           | 20             | 82.7 | 19.1 | 224.1 | 230.316 | -6.2160  |  |
|                                   |                                     |                   |                           |           |         |           | 21             | 52.3 | 16.0 | 166.5 | 157.064 | 9.4356   |  |
| ANALYSIS OF VARIANCE              |                                     |                   |                           |           |         |           |                |      |      |       |         |          |  |
| SOURCE                            | SUM-OF-SQUARES                      | DF                | MEAN-SQUARE               | F-RATIO   | P       |           |                |      |      |       |         |          |  |
| REGRESSION                        | 24015.2821                          | 2                 | 12007.6411                | 99.1035   | 0.0000  |           |                |      |      |       |         |          |  |
| RESIDUAL                          | 2180.9274                           | 18                | 121.1626                  |           |         |           |                |      |      |       |         |          |  |
| INVERSE (X'X)                     |                                     |                   |                           |           |         |           |                |      |      |       |         |          |  |
|                                   | 1                                   | 2                 | 3                         |           |         |           |                |      |      |       |         |          |  |
| 1                                 | 29.7289                             |                   |                           |           |         |           |                |      |      |       |         |          |  |
| 2                                 | 0.0722                              | 0.00037           |                           |           |         |           |                |      |      |       |         |          |  |
| 3                                 | -1.9926                             | -0.0056           | 0.1363                    |           |         |           |                |      |      |       |         |          |  |

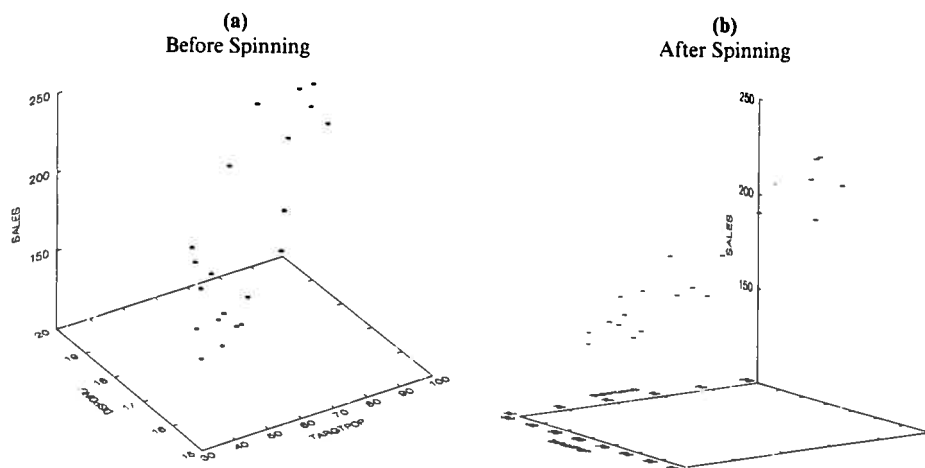
Box and Tidwell (Ref. 6.1) have also developed an iterative approach for ascertaining appropriate power transformations for each predictor variable in a multiple regression model when transformations on the predictor variables may be required.

## 6.9 An Example—Multiple Regression with Two Predictor Variables

In this section, we shall develop a multiple regression application with two predictor variables. We shall illustrate several diagnostic procedures and several types of inferences that might be made for this application. We shall set up the necessary calculations in matrix format but, for ease of viewing, show fewer significant digits for the elements of the matrices than are used in the actual calculations.

### Setting

Dwayne Studios, Inc., operates portrait studios in 21 cities of medium size. These studios specialize in portraits of children. The company is considering an expansion into other cities of medium size and wishes to investigate whether sales ( $Y$ ) in a community can be predicted from the number of persons aged 16 or younger in the community ( $X_1$ ) and the per capita disposable personal income in the community ( $X_2$ ). Data on these variables for the most recent year for the 21 cities in which Dwayne Studios is now operating are shown in Figure 6.5b. Sales are expressed in thousands of dollars and are labeled  $Y$  or SALES; the number of persons aged 16 or younger is expressed in thousands of persons and is labeled  $X_1$  or TARGTPOP for target population; and per capita disposable personal income is expressed in thousands of dollars and labeled  $X_2$  or DISPOINC for disposable income.

**FIGURE 6.6** SYGRAPH Plot of Point Cloud before and after Spinning—Dwayne Studios Example.

The first-order regression model:

$$(6.69) \quad Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i$$

with normal error terms is expected to be appropriate, based on the SYGRAPH scatter plot matrix in Figure 6.4a. Note the linear relation between target population and sales and between disposable income and sales. Also note that there is more scatter in the latter relationship. Finally note that there is also some linear relationship between the two predictor variables. The correlation matrix in Figure 6.4b bears out these visual impressions from the scatter plot matrix.

A SYGRAPH plot of the point cloud is shown in Figure 6.6a. By spinning the axes, we obtain the perspective in Figure 6.6b which supports the tentative conclusion that a response plane may be a reasonable regression function to utilize here.

### Basic Calculations

The  $\mathbf{X}$  and  $\mathbf{Y}$  matrices for the Dwayne Studios example are as follows:

$$(6.70) \quad \mathbf{X} = \begin{bmatrix} 1 & 68.5 & 16.7 \\ 1 & 45.2 & 16.8 \\ \vdots & \vdots & \vdots \\ 1 & 52.3 & 16.0 \end{bmatrix} \quad \mathbf{Y} = \begin{bmatrix} 174.4 \\ 164.4 \\ \vdots \\ 166.5 \end{bmatrix}$$

We require:

1.

$$\mathbf{X}'\mathbf{X} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 68.5 & 45.2 & \cdots & 52.3 \\ 16.7 & 16.8 & \cdots & 16.0 \end{bmatrix} \quad \begin{bmatrix} 1 & 68.5 & 16.7 \\ 1 & 45.2 & 16.8 \\ \vdots & \vdots & \vdots \\ 1 & 52.3 & 16.0 \end{bmatrix}$$

which yields:

$$(6.71) \quad \mathbf{X}'\mathbf{X} = \begin{bmatrix} 21.0 & 1,302.4 & 360.0 \\ 1,302.4 & 87,707.9 & 22,609.2 \\ 360.0 & 22,609.2 & 6,190.3 \end{bmatrix}$$

2.

$$\mathbf{X}'\mathbf{Y} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 68.5 & 45.2 & \cdots & 52.3 \\ 16.7 & 16.8 & \cdots & 16.0 \end{bmatrix} \begin{bmatrix} 174.4 \\ 164.4 \\ \vdots \\ 166.5 \end{bmatrix}$$

which yields:

$$(6.72) \quad \mathbf{X}'\mathbf{Y} = \begin{bmatrix} 3,820 \\ 249,643 \\ 66,073 \end{bmatrix}$$

3.

$$(\mathbf{X}'\mathbf{X})^{-1} = \begin{bmatrix} 21.0 & 1,302.4 & 360.0 \\ 1,302.4 & 87,707.9 & 22,609.2 \\ 360.0 & 22,609.2 & 6,190.3 \end{bmatrix}^{-1}$$

Using (5.23), we obtain:

$$(6.73) \quad (\mathbf{X}'\mathbf{X})^{-1} = \begin{bmatrix} 29.7289 & .0722 & -1.9926 \\ .0722 & .00037 & -.0056 \\ -1.9926 & -.0056 & .1363 \end{bmatrix}$$

**Algebraic Equivalents.** Note that  $\mathbf{X}'\mathbf{X}$  for the first-order regression model (6.69) with two predictor variables is:

$$\mathbf{X}'\mathbf{X} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ X_{11} & X_{21} & \cdots & X_{n1} \\ X_{12} & X_{22} & \cdots & X_{n2} \end{bmatrix} \begin{bmatrix} 1 & X_{11} & X_{12} \\ 1 & X_{21} & X_{22} \\ \vdots & \vdots & \vdots \\ 1 & X_{n1} & X_{n2} \end{bmatrix}$$

or:

$$(6.74) \quad \mathbf{X}'\mathbf{X} = \begin{bmatrix} n & \Sigma X_{i1} & \Sigma X_{i2} \\ \Sigma X_{i1} & \Sigma X_{i1}^2 & \Sigma X_{i1}X_{i2} \\ \Sigma X_{i2} & \Sigma X_{i2}X_{i1} & \Sigma X_{i2}^2 \end{bmatrix}$$

For the Dwaine Studios example, we have:

$$n = 21$$

$$\Sigma X_{i1} = 68.5 + 45.2 + \cdots = 1,302.4$$

$$\Sigma X_{i1}X_{i2} = 68.5(16.7) + 45.2(16.8) + \cdots = 22,609.2$$

etc.

These elements are found in (6.71).

Also note that  $\mathbf{X}'\mathbf{Y}$  for the first-order regression model (6.69) with two predictor variables is:

$$(6.75) \quad \mathbf{X}'\mathbf{Y} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ X_{11} & X_{21} & \cdots & X_{n1} \\ X_{12} & X_{22} & \cdots & X_{n2} \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} = \begin{bmatrix} \sum Y_i \\ \sum X_{i1}Y_i \\ \sum X_{i2}Y_i \end{bmatrix}$$

For the Dwaine Studios example, we have:

$$\begin{aligned} \sum Y_i &= 174.4 + 164.4 + \cdots = 3,820 \\ \sum X_{i1}Y_i &= 68.5(174.4) + 45.2(164.4) + \cdots = 249,643 \\ \sum X_{i2}Y_i &= 16.7(174.4) + 16.8(164.4) + \cdots = 66,073 \end{aligned}$$

These are the elements found in (6.72).

### Estimated Regression Function

The least squares estimates  $\mathbf{b}$  are readily obtained by (6.25), using our basic calculations in (6.72) and (6.73):

$$\mathbf{b} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y} = \begin{bmatrix} 29.7289 & .0722 & -1.9926 \\ .0722 & .00037 & -.0056 \\ -1.9926 & -.0056 & .1363 \end{bmatrix} \begin{bmatrix} 3,820 \\ 249,643 \\ 66,073 \end{bmatrix}$$

which yields:

$$(6.76) \quad \mathbf{b} = \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} -68.857 \\ 1.455 \\ 9.366 \end{bmatrix}$$

and the estimated regression function is:

$$\hat{Y} = -68.857 + 1.455X_1 + 9.366X_2$$

This estimated regression function indicates that mean sales are expected to increase by 1.455 thousand dollars when the target population increases by 1 thousand persons aged 16 years or younger, holding per capita disposable personal income constant, and that mean sales are expected to increase by 9.366 thousand dollars when per capita income increases by 1 thousand dollars, holding the target population constant.

Figure 6.5a contains SYSTAT multiple regression output for the Dwaine Studios example. The estimated regression coefficients are shown in the column labeled COEFFICIENT; the output shows one more decimal place than we have shown.

The SYSTAT output also contains the inverse of the  $\mathbf{X}'\mathbf{X}$  matrix that we calculated earlier; only the lower portion of the symmetric matrix is shown. The results are the same as in (6.73).

**Algebraic Version of Normal Equations.** The normal equations in algebraic form for the case of two predictor variables can be obtained readily from (6.74) and (6.75). We have:

$$(\mathbf{X}'\mathbf{X})\mathbf{b} = \mathbf{X}'\mathbf{Y}$$

$$\begin{bmatrix} n & \Sigma X_{i1} & \Sigma X_{i2} \\ \Sigma X_{i1} & \Sigma X_{i1}^2 & \Sigma X_{i1}X_{i2} \\ \Sigma X_{i2} & \Sigma X_{i2}X_{i1} & \Sigma X_{i2}^2 \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} \Sigma Y_i \\ \Sigma X_{i1}Y_i \\ \Sigma X_{i2}Y_i \end{bmatrix}$$

from which we obtain the normal equations:

$$\begin{aligned} \Sigma Y_i &= nb_0 + b_1 \Sigma X_{i1} + b_2 \Sigma X_{i2} \\ (6.77) \quad \Sigma X_{i1}Y_i &= b_0 \Sigma X_{i1} + b_1 \Sigma X_{i1}^2 + b_2 \Sigma X_{i1}X_{i2} \\ \Sigma X_{i2}Y_i &= b_0 \Sigma X_{i2} + b_1 \Sigma X_{i1}X_{i2} + b_2 \Sigma X_{i2}^2 \end{aligned}$$

### Fitted Values and Residuals

To examine the appropriateness of regression model (6.69) for the data at hand, we require the fitted values  $\hat{Y}_i$  and the residuals  $e_i = Y_i - \hat{Y}_i$ . We obtain by (6.28):

$$\hat{\mathbf{Y}} = \mathbf{X}\mathbf{b}$$

$$\begin{bmatrix} \hat{Y}_1 \\ \hat{Y}_2 \\ \vdots \\ \hat{Y}_{21} \end{bmatrix} = \begin{bmatrix} 1 & 68.5 & 16.7 \\ 1 & 45.2 & 16.8 \\ \vdots & \vdots & \vdots \\ 1 & 52.3 & 16.0 \end{bmatrix} \begin{bmatrix} -68.857 \\ 1.455 \\ 9.366 \end{bmatrix} = \begin{bmatrix} 187.2 \\ 154.2 \\ \vdots \\ 157.1 \end{bmatrix}$$

Further, by (6.29) we find:

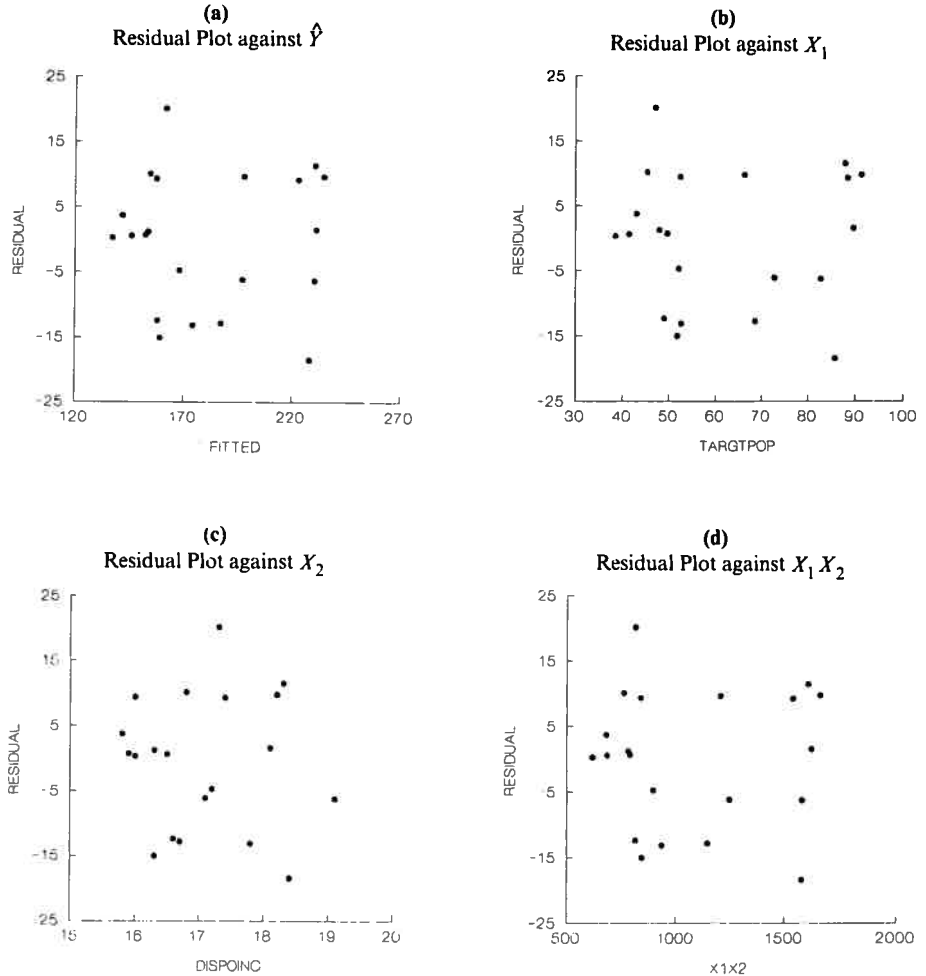
$$\mathbf{e} = \mathbf{Y} - \hat{\mathbf{Y}}$$

$$\begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_{21} \end{bmatrix} = \begin{bmatrix} 174.4 \\ 164.4 \\ \vdots \\ 166.5 \end{bmatrix} - \begin{bmatrix} 187.2 \\ 154.2 \\ \vdots \\ 157.1 \end{bmatrix} = \begin{bmatrix} -12.8 \\ 10.2 \\ \vdots \\ 9.4 \end{bmatrix}$$

Figure 6.5b shows the computer output for the fitted values and residuals to more decimal places than we have presented.

### Analysis of Appropriateness of Model

We begin our analysis of the appropriateness of regression model (6.69) for the Dwaine Studios example by considering the plot of the residuals  $e$  against the fitted values  $\hat{Y}$  in Figure 6.7a. This plot does not suggest any systematic deviations from the response plane, nor that the variance of the error terms varies with the level of  $\hat{Y}$ . Plots of the residuals  $e$

**FIGURE 6.7 SYGRAPH Diagnostic Plots—Dwaine Studios Example.**

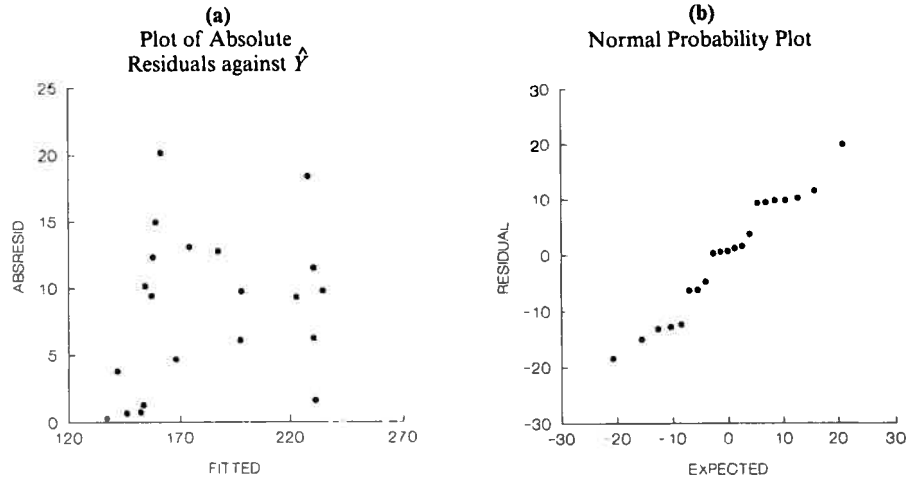
against  $X_1$  and  $X_2$  in Figures 6.7b and 6.7c, respectively, are entirely consistent with the conclusions of good fit by the response function and constant variance of the error terms.

In multiple regression applications, there is frequently the possibility of interaction effects being present. To examine this for the Dwaine Studios example, we plotted the residuals  $e$  against the interaction term  $X_1 X_2$  in Figure 6.7d. A systematic pattern of this plot would suggest that an interaction effect may be present, so that a response function of the type:

$$E\{Y\} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2$$

might be more appropriate. Figure 6.7d does not exhibit any systematic pattern; hence, no interaction effects reflected by the model term  $\beta_3 X_1 X_2$  appear to be present.

Figure 6.8 contains two additional diagnostic plots. Figure 6.8a presents a plot of the absolute residuals against the fitted values. There is no indication of nonconstancy of the error variance. Figure 6.8b contains a normal probability plot of the residuals. The pattern

**FIGURE 6.8** Additional Diagnostic Plots—Dwayne Studios Example.

is moderately linear. The coefficient of correlation between the ordered residuals and their expected values under normality is .980. This high value (the interpolated critical value in Table B.6 for  $n = 21$  and  $\alpha = .05$  is .9525) helps to confirm the reasonableness of the conclusion that the error terms are fairly normally distributed.

Since the Dwayne Studios data are cross-sectional and do not involve a time sequence, a time sequence plot is not relevant here. Thus, all of the diagnostics support the use of regression model (6.69) for the Dwayne Studios example.

### Analysis of Variance

To test whether sales are related to target population and per capita disposable income, we require the ANOVA table. The basic quantities needed are:

$$\begin{aligned}
 \mathbf{Y}'\mathbf{Y} &= [174.4 \quad 164.4 \quad \cdots \quad 166.5] \begin{bmatrix} 174.4 \\ 164.4 \\ \vdots \\ 166.5 \end{bmatrix} \\
 &= 721,072.40 \\
 \left(\frac{1}{n}\right) \mathbf{Y}'\mathbf{J}\mathbf{Y} &= \frac{1}{21} [174.4 \quad 164.4 \quad \cdots \quad 166.5] \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1 & \cdots & 1 \\ \vdots & \vdots & & \vdots \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} 174.4 \\ 164.4 \\ \vdots \\ 166.5 \end{bmatrix} \\
 &= \frac{(3,820.0)^2}{21} = 694,876.19
 \end{aligned}$$

Thus:

$$SSTO = \mathbf{Y}'\mathbf{Y} - \left(\frac{1}{n}\right) \mathbf{Y}'\mathbf{J}\mathbf{Y} = 721,072.40 - 694,876.19 = 26,196.21$$

and, using our results in (6.72) and (6.76):

$$\begin{aligned}
 SSE &= \mathbf{Y}'\mathbf{Y} - \mathbf{b}'\mathbf{X}'\mathbf{Y} \\
 &= 721,072.40 - [-68.857 \quad 1.455 \quad 9.366] \begin{bmatrix} 3,820 \\ 249,643 \\ 66,073 \end{bmatrix} \\
 &= 721,072.40 - 718,891.47 = 2,180.93
 \end{aligned}$$

Finally, we obtain by subtraction:

$$SSR = SSTO - SSE = 26,196.21 - 2,180.93 = 24,015.28$$

These sums of squares are shown in the SYSTAT ANOVA table in Figure 6.5a. Also shown in the ANOVA table are degrees of freedom and mean squares. Note that three regression parameters had to be estimated; hence,  $21 - 3 = 18$  degrees of freedom are associated with  $SSE$ . Also, the number of degrees of freedom associated with  $SSR$  is 2—the number of  $X$  variables in the model.

**Test of Regression Relation.** To test whether sales are related to target population and per capita disposable income:

$$H_0: \beta_1 = 0 \text{ and } \beta_2 = 0$$

$$H_a: \text{not both } \beta_1 \text{ and } \beta_2 \text{ equal zero}$$

we use test statistic (6.39b):

$$F^* = \frac{MSR}{MSE} = \frac{12,007.64}{121.1626} = 99.1$$

This test statistic is labeled F-RATIO in the SYSTAT output. For  $\alpha = .05$ , we require  $F(.95; 2, 18) = 3.55$ . Since  $F^* = 99.1 > 3.55$ , we conclude  $H_a$ , that sales are related to target population and per capita disposable income. The  $P$ -value for this test is .0000, as shown in the SYSTAT output labeled P.

Whether the regression relation is useful for making predictions of sales or estimates of mean sales still remains to be seen.

**Coefficient of Multiple Determination.** For our example, we have by (6.40):

$$R^2 = \frac{SSR}{SSTO} = \frac{24,015.28}{26,196.21} = .917$$

Thus, when the two predictor variables, target population and per capita disposable income, are considered, the variation in sales is reduced by 91.7 percent. The coefficient of multiple determination is shown in the SYSTAT output labeled SQUARED MULTIPLE R. Also shown in the output is the coefficient of multiple correlation  $R = .957$  and the adjusted coefficient of multiple determination (6.42),  $R_a^2 = .907$ , which is labeled in the output ADJUSTED SQUARED MULTIPLE R. Note that adjusting for the number of predictor variables in the model had only a small effect here on  $R^2$ .



## Estimation of Regression Parameters

Dwayne Studios is not interested in the parameter  $\beta_0$  since it falls far outside the scope of the model. It is desired to estimate  $\beta_1$  and  $\beta_2$  jointly with family confidence coefficient .90. We shall use the simultaneous Bonferroni confidence limits (6.52).

First, we need the estimated variance-covariance matrix  $s^2\{\mathbf{b}\}$ :

$$s^2\{\mathbf{b}\} = \text{MSE}(\mathbf{X}'\mathbf{X})^{-1}$$

$\text{MSE}$  is given in Figure 6.5a, and  $(\mathbf{X}'\mathbf{X})^{-1}$  was obtained in (6.73). Hence:

$$(6.78) \quad s^2\{\mathbf{b}\} = 121.1626 \begin{bmatrix} 29.7289 & .0722 & -1.9926 \\ .0722 & .00037 & -.0056 \\ -1.9926 & -.0056 & .1363 \end{bmatrix}$$

$$= \begin{bmatrix} 3,602.0 & 8.748 & -241.43 \\ 8.748 & .0448 & -.679 \\ -241.43 & -.679 & 16.514 \end{bmatrix}$$

The two estimated variances we require are:

$$s^2\{b_1\} = .0448 \quad \text{or} \quad s\{b_1\} = .212$$

$$s^2\{b_2\} = 16.514 \quad \text{or} \quad s\{b_2\} = 4.06$$

These estimated standard deviations are shown in the SYSTAT output in Figure 6.5a, labeled STD ERROR, to four decimal places.

Next, we require for  $g = 2$  simultaneous estimates:

$$B = t[1 - .10/2(2); 18] = t(.975; 18) = 2.101$$

The two pairs of simultaneous confidence limits therefore are  $1.455 \pm 2.101(.212)$  and  $9.366 \pm 2.101(4.06)$ , which yield the confidence intervals:

$$1.01 \leq \beta_1 \leq 1.90$$

$$.84 \leq \beta_2 \leq 17.9$$

With family confidence coefficient .90, we conclude that  $\beta_1$  falls between 1.01 and 1.90 and that  $\beta_2$  falls between .84 and 17.9.

Note that the simultaneous confidence intervals suggest that both  $\beta_1$  and  $\beta_2$  are positive, which is in accord with theoretical expectations that sales should increase with higher target population and higher per capita disposable income, the other variable being held constant.

## Estimation of Mean Response

Dwayne Studios would like to estimate expected (mean) sales in cities with target population  $X_{h1} = 65.4$  thousand persons aged 16 years or younger and per capita disposable income  $X_{h2} = 17.6$  thousand dollars with a 95 percent confidence interval. We define:

$$\mathbf{X}_h = \begin{bmatrix} 1 \\ 65.4 \\ 17.6 \end{bmatrix}$$

The point estimate of mean sales is by (6.55):

$$\hat{Y}_h = \mathbf{X}'_h \mathbf{b} = [1 \quad 65.4 \quad 17.6] \begin{bmatrix} -68.857 \\ 1.455 \\ 9.366 \end{bmatrix} = 191.10$$

The estimated variance by (6.58), using the results in (6.78), is:

$$\begin{aligned} s^2\{\hat{Y}_h\} &= \mathbf{X}'_h s^2\{\mathbf{b}\} \mathbf{X}_h \\ &= [1 \quad 65.4 \quad 17.6] \begin{bmatrix} 3,602.0 & 8.748 & -241.43 \\ 8.748 & .0448 & -.679 \\ -241.43 & -.679 & 16.514 \end{bmatrix} \begin{bmatrix} 1 \\ 65.4 \\ 17.6 \end{bmatrix} \\ &= 7.656 \end{aligned}$$

or:

$$s\{\hat{Y}_h\} = 2.77$$

For confidence coefficient .95, we need  $t(.975; 18) = 2.101$ , and we obtain by (6.59) the confidence limits  $191.10 \pm 2.101(2.77)$ . The confidence interval for  $E\{Y_h\}$  therefore is:

$$185.3 \leq E\{Y_h\} \leq 196.9$$

Thus, with confidence coefficient .95, we estimate that mean sales in cities with target population of 65.4 thousand persons aged 16 years or younger and per capita disposable income of 17.6 thousand dollars are somewhere between 185.3 and 196.9 thousand dollars. Dwaine Studios considers this confidence interval to provide information about expected (average) sales in communities of this size and income level that is precise enough for planning purposes.

**Algebraic Version of Estimated Variance  $s^2\{\hat{Y}_h\}$ .** Since by (6.58):

$$s^2\{\hat{Y}_h\} = \mathbf{X}'_h s^2\{\mathbf{b}\} \mathbf{X}_h$$

it follows for the case of two predictor variables in a first-order model:

$$\begin{aligned} (6.79) \quad s^2\{\hat{Y}_h\} &= s^2\{b_0\} + X_{h1}^2 s^2\{b_1\} + X_{h2}^2 s^2\{b_2\} + 2X_{h1}s\{b_0, b_1\} \\ &\quad + 2X_{h2}s\{b_0, b_2\} + 2X_{h1}X_{h2}s\{b_1, b_2\} \end{aligned}$$

### Prediction Limits for New Observations

Dwaine Studios as part of a possible expansion program would like to predict sales for two new cities, with the following characteristics:

|          | City A | City B |
|----------|--------|--------|
| $X_{h1}$ | 65.4   | 53.1   |
| $X_{h2}$ | 17.6   | 17.7   |

Prediction intervals with a 90 percent family confidence coefficient are desired. Note that the two new cities have characteristics that fall well within the pattern of the 21 cities on which the regression analysis is based.

To determine which simultaneous prediction intervals are best here, we find  $S$  as given in (6.65a) and  $B$  as given in (6.66a) for  $g = 2$  and  $1 - \alpha = .90$ :

$$S^2 = 2F(.90; 2, 18) = 2(2.62) = 5.24 \quad S = 2.29$$

and:

$$B = t[1 - .10/2(2); 18] = t(.975; 18) = 2.101$$

Hence, the Bonferroni limits are more efficient here.

For city A, we use the results obtained when estimating mean sales, since the levels of the predictor variables are the same here. We have from before:

$$\hat{Y}_h = 191.10 \quad s^2\{\hat{Y}_h\} = 7.656 \quad MSE = 121.1626$$

Hence, by (6.63a):

$$s^2\{\text{pred}\} = MSE + s^2\{\hat{Y}_h\} = 121.1626 + 7.656 = 128.82$$

or:

$$s\{\text{pred}\} = 11.35$$

In similar fashion, we obtain for city B (calculations not shown):

$$\hat{Y}_h = 174.15 \quad s\{\text{pred}\} = 11.93$$

We previously found that the Bonferroni multiple is  $B = 2.101$ . Hence, by (6.66) the simultaneous Bonferroni prediction limits with family confidence coefficient .90 are  $191.10 \pm 2.101(11.35)$  and  $174.15 \pm 2.101(11.93)$ , leading to the simultaneous prediction intervals:

$$\text{City A: } 167.3 \leq Y_{h(\text{new})} \leq 214.9$$

$$\text{City B: } 149.1 \leq Y_{h(\text{new})} \leq 199.2$$

With family confidence coefficient .90, we predict that sales in the two cities will be within the indicated limits. Dwaine Studios considers these prediction limits to be somewhat useful for planning purposes, but would prefer tighter intervals for predicting sales for a particular city. A consulting firm has been engaged to see if additional or alternative predictor variables can be found that will lead to tighter prediction intervals.

Note incidentally that even though the coefficient of multiple determination,  $R^2 = .917$ , is high, the prediction limits here are not fully satisfactory. This serves as another reminder that a high value of  $R^2$  does not necessarily indicate that precise predictions can be made.

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## Cited Reference

- 6.1. Box, G. E. P., and P. W. Tidwell. "Transformations of the Independent Variables," *Technometrics* 4 (1962), pp. 531-50.

## Problems

- 6.1. Set up the  $\mathbf{X}$  matrix and  $\boldsymbol{\beta}$  vector for each of the following regression models (assume  $i = 1, \dots, 4$ ):
- $Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i1} X_{i2} + \varepsilon_i$
  - $\log Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i$
- 6.2. Set up the  $\mathbf{X}$  matrix and  $\boldsymbol{\beta}$  vector for each of the following regression models (assume  $i = 1, \dots, 5$ ):
- $Y_i = \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1}^2 + \varepsilon_i$
  - $\sqrt{Y_i} = \beta_0 + \beta_1 X_{i1} + \beta_2 \log_{10} X_{i2} + \varepsilon_i$
- 6.3. A student stated: "Adding predictor variables to a regression model can never reduce  $R^2$ , so we should include all available predictor variables in the model." Comment.
- 6.4. Why is it not meaningful to attach a sign to the coefficient of multiple correlation  $R$ , although we do so for the coefficient of simple correlation  $r$ ?
- 6.5. **Brand preference.** In a small-scale experimental study of the relation between degree of brand liking ( $Y$ ) and moisture content ( $X_1$ ) and sweetness ( $X_2$ ) of the product, the following results were obtained from the experiment based on a completely randomized design (data are coded).

| $i$ :      | 1  | 2  | 3  | . . . | 14 | 15 | 16  |
|------------|----|----|----|-------|----|----|-----|
| $X_{i1}$ : | 4  | 4  | 4  | . . . | 10 | 10 | 10  |
| $X_{i2}$ : | 2  | 4  | 2  | . . . | 4  | 2  | 4   |
| $Y_i$ :    | 64 | 73 | 61 | . . . | 95 | 94 | 100 |

- Obtain the scatter plot matrix and the correlation matrix. What information do these diagnostic aids provide here?
  - Fit regression model (6.1) to the data. State the estimated regression function. How is  $b_1$  interpreted here?
  - Obtain the residuals and prepare a box plot of the residuals. What information does this plot provide?
  - Plot the residuals against  $\hat{Y}$ ,  $X_1$ ,  $X_2$ , and  $X_1 X_2$  on separate graphs. Also prepare a normal probability plot. Interpret the plots and summarize your findings.
  - Conduct the Breusch-Pagan test for constancy of the error variance, assuming  $\log \sigma_i^2 = \gamma_0 + \gamma_1 X_{i1} + \gamma_2 X_{i2}$ ; use  $\alpha = .01$ . State the alternatives, decision rule, and conclusion.
  - Conduct a formal test for lack of fit of the first-order regression function; use  $\alpha = .01$ . State the alternatives, decision rule, and conclusion.
- 6.6. Refer to **Brand preference** Problem 6.5. Assume that regression model (6.1) with independent normal error terms is appropriate.
- Test whether there is a regression relation, using  $\alpha = .01$ . State the alternatives, decision rule, and conclusion. What does your test imply about  $\beta_1$  and  $\beta_2$ ?
  - What is the  $P$ -value of the test in part (a)?

- c. Estimate  $\beta_1$  and  $\beta_2$  jointly by the Bonferroni procedure, using a 99 percent family confidence coefficient. Interpret your results.

6.7. Refer to **Brand preference** Problem 6.5.

- a. Calculate the coefficient of multiple determination  $R^2$ . How is it interpreted here?  
 b. Calculate the coefficient of simple determination  $r^2$  between  $Y_i$  and  $\hat{Y}_i$ . Does it equal  $R^2$ ?

6.8. Refer to **Brand preference** Problem 6.5. Assume that regression model (6.1) with independent normal error terms is appropriate.

- a. Obtain an interval estimate of  $E\{Y_h\}$  when  $X_{h1} = 5$  and  $X_{h2} = 4$ . Use a 99 percent confidence coefficient. Interpret your interval estimate.  
 b. Obtain a prediction interval for a new observation  $Y_{h(\text{new})}$  when  $X_{h1} = 5$  and  $X_{h2} = 4$ . Use a 99 percent confidence coefficient.

✓ 6.9. **Chemical shipment.** The data to follow, taken on 20 incoming shipments of chemicals in drums arriving at a warehouse, show number of drums in shipment ( $X_1$ ), total weight of shipment ( $X_2$ , in hundred pounds), and number of minutes required to handle shipment ( $Y$ ).

| $i$ :      | 1    | 2     | 3    | . . . | 18    | 19   | 20   |
|------------|------|-------|------|-------|-------|------|------|
| $X_{i1}$ : | 7    | 18    | 5    | . . . | 21    | 6    | 11   |
| $X_{i2}$ : | 5.11 | 16.72 | 3.20 | . . . | 15.21 | 3.64 | 9.57 |
| $Y_i$ :    | 58   | 152   | 41   | . . . | 155   | 39   | 90   |

- a. Prepare separate stem-and-leaf plots for the numbers of drums in the shipments  $X_{i1}$  and the weights of the shipments  $X_{i2}$ . Are there any outlying cases present? Are there any gaps in the data?  
 b. The cases are given in the order that the incoming shipments arrived. Prepare a time plot for each predictor variable. What do the plots show?  
 c. Obtain the scatter plot matrix and the correlation matrix. What information do these diagnostic aids provide here?

✓ 6.10. Refer to **Chemical shipment** Problem 6.9.

- a. Fit regression model (6.1) to the data. State the estimated regression function. How are  $b_1$  and  $b_2$  interpreted here?  
 b. Obtain the residuals and prepare a box plot of the residuals. What information does this plot provide?  
 c. Plot the residuals against  $\hat{Y}$ ,  $X_1$ ,  $X_2$ , and  $X_1X_2$  on separate graphs. Also prepare a normal probability plot. Interpret the plots and summarize your findings.  
 d. Prepare a time plot of the residuals. Is there any indication that the error terms are correlated? Discuss.  
 e. Divide the 20 cases into two groups, placing the 10 cases with the smallest fitted values  $\hat{Y}_i$  into group 1 and the other 10 cases into group 2. Conduct the modified Levene test for constancy of the error variance, using  $\alpha = .01$ . State the decision rule and conclusion.

✓ 6.11. Refer to **Chemical shipment** Problem 6.9. Assume that regression model (6.1) with independent normal error terms is appropriate.

- a. Test whether there is a regression relation, using level of significance .05. State the alternatives, decision rule, and conclusion. What does your test result imply about  $\beta_1$  and  $\beta_2$ ? What is the  $P$ -value of the test?
  - b. Estimate  $\beta_1$  and  $\beta_2$  jointly by the Bonferroni procedure, using a 95 percent family confidence coefficient. Interpret your results.
  - c. Calculate the coefficient of multiple determination  $R^2$ . How is this measure interpreted here?
- ✓ 6.12. Refer to **Chemical shipment** Problem 6.9. Assume that regression model (6.1) with independent normal error terms is appropriate.
- a. Management desires simultaneous interval estimates of the mean handling times for the following five typical shipments:

|         | 1    | 2    | 3    | 4     | 5     |
|---------|------|------|------|-------|-------|
| $X_1$ : | 5    | 6    | 10   | 14    | 20    |
| $X_2$ : | 3.20 | 4.80 | 7.00 | 10.00 | 18.00 |

Obtain the family of estimates using a 95 percent family confidence coefficient. Employ the Working-Hotelling or the Bonferroni procedure, whichever is more efficient.

- b. For the data in Problem 6.9 on which the regression fit is based, would you consider a shipment of 20 drums with a weight of 5 hundred pounds to be within the scope of the model? What about a shipment of 20 drums with a weight of 19 hundred pounds? Support your answers by preparing a relevant plot.
- ✓ 6.13. Refer to **Chemical shipment** Problem 6.9. Assume that regression model (6.1) with independent normal error terms is appropriate. Four separate shipments with the following characteristics will arrive in the next day or two:

|         | 1    | 2    | 3     | 4     |
|---------|------|------|-------|-------|
| $X_1$ : | 9    | 12   | 15    | 18    |
| $X_2$ : | 7.20 | 9.00 | 12.50 | 16.50 |

Management desires predictions of the handling times for these shipments so that the actual handling times can be compared with the predicted times to determine whether any are “out of line.” Develop the needed predictions, using the most efficient approach and a family confidence coefficient of 95 percent.

- ✓ 6.14. Refer to **Chemical shipment** Problem 6.9. Assume that regression model (6.1) with independent normal error terms is appropriate. Three new shipments are to be received, each with  $X_{h1} = 7$  and  $X_{h2} = 6$ .
- a. Obtain a 95 percent prediction interval for the mean handling time for these shipments.
  - b. Convert the interval obtained in part (a) into a 95 percent prediction interval for the total handling time for the three shipments.
- ✓ 6.15. **Patient satisfaction.** A hospital administrator wished to study the relation between patient satisfaction ( $Y$ ) and patient’s age ( $X_1$ , in years), severity of illness ( $X_2$ , an index), and anxiety level ( $X_3$ , an index). The administrator randomly selected 23 patients and collected the data presented below, where larger values of  $Y$ ,  $X_2$ , and  $X_3$  are, respectively, associated with more satisfaction, increased severity of illness, and more anxiety.

| $i:$      | 1   | 2   | 3   | . . . | 21  | 22  | 23  |
|-----------|-----|-----|-----|-------|-----|-----|-----|
| $X_{i1}:$ | 50  | 36  | 40  | . . . | 29  | 44  | 43  |
| $X_{i2}:$ | 51  | 46  | 48  | . . . | 52  | 58  | 50  |
| $X_{i3}:$ | 2.3 | 2.3 | 2.2 | . . . | 2.3 | 2.9 | 2.3 |
| $Y_i:$    | 48  | 57  | 66  | . . . | 77  | 52  | 60  |

- Prepare a stem-and-leaf plot for each of the predictor variables. Are any noteworthy features revealed by these plots?
- Obtain the scatter plot matrix and the correlation matrix. Interpret these and state your principal findings.
- Fit regression model (6.5) for three predictor variables to the data and state the estimated regression function. How is  $b_2$  interpreted here?
- Obtain the residuals and prepare a box plot of the residuals. Do there appear to be any outliers?
- Plot the residuals against  $\hat{Y}$ , each of the predictor variables, and each two-factor interaction term on separate graphs. Also prepare a normal probability plot. Interpret your plots and summarize your findings.
- Can you conduct a formal test for lack of fit here?
- Conduct the Breusch-Pagan test for constancy of the error variance, assuming  $\log \sigma_i^2 = \gamma_0 + \gamma_1 X_{i1} + \gamma_2 X_{i2} + \gamma_3 X_{i3}$ ; use  $\alpha = .01$ . State the alternatives, decision rule, and conclusion.

6.16. Refer to **Patient satisfaction** Problem 6.15. Assume that regression model (6.5) for three predictor variables with independent normal error terms is appropriate.

- Test whether there is a regression relation; use  $\alpha = .10$ . State the alternatives, decision rule, and conclusion. What does your test imply about  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ ? What is the  $P$ -value of the test?
- Obtain joint interval estimates of  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ , using a 90 percent family confidence coefficient. Interpret your results.
- Calculate the coefficient of multiple correlation. What does it indicate here?

6.17. Refer to **Patient satisfaction** Problem 6.15. Assume that regression model (6.5) for three predictor variables with independent normal error terms is appropriate.

- Obtain an interval estimate of the mean satisfaction when  $X_{h1} = 35$ ,  $X_{h2} = 45$ , and  $X_{h3} = 2.2$ . Use a 90 percent confidence coefficient. Interpret your confidence interval.
- Obtain a prediction interval for a new patient's satisfaction when  $X_{h1} = 35$ ,  $X_{h2} = 45$ , and  $X_{h3} = 2.2$ . Use a 90 percent confidence coefficient. Interpret your prediction interval.

6.18. **Mathematicians' salaries.** A researcher in a scientific foundation wished to evaluate the relation between intermediate and senior level annual salaries of bachelor's and master's level mathematicians ( $Y$ , in thousand dollars) and an index of work quality ( $X_1$ ), number of years of experience ( $X_2$ ), and an index of publication success ( $X_3$ ). The data for a sample of 24 bachelor's and master's level mathematicians follow:

| $i:$      | 1    | 2    | 3    | . . . | 22   | 23   | 24   |
|-----------|------|------|------|-------|------|------|------|
| $X_{i1}:$ | 3.5  | 5.3  | 5.1  | . . . | 5.6  | 4.8  | 3.9  |
| $X_{i2}:$ | 9    | 20   | 18   | . . . | 27   | 34   | 15   |
| $X_{i3}:$ | 6.1  | 6.4  | 7.4  | . . . | 4.3  | 8.0  | 5.0  |
| $Y_i:$    | 33.2 | 40.3 | 38.7 | . . . | 36.8 | 45.2 | 35.1 |

- Prepare a stem-and-leaf plot for each predictor variable. What information do these plots provide?
  - Obtain the scatter plot matrix and the correlation matrix. Interpret these and state your principal findings.
  - Fit regression model (6.5) for three predictor variables to the data. State the estimated regression function.
  - Obtain the residuals and prepare a box plot of the residuals. Does the distribution appear to be fairly symmetrical?
  - Plot the residuals against  $\hat{Y}$ , each predictor variable, and each two-factor interaction term on separate graphs. Also prepare a normal probability plot. Analyze your plots and summarize your findings.
  - Can you conduct a formal test for lack of fit here?
  - Divide the 24 cases into two groups, placing the 12 cases with the smallest fitted values  $\hat{Y}_i$  into group 1 and the remaining cases into group 2. Conduct the modified Levene test for constancy of the error variance, using  $\alpha = .05$ . State the decision rule and conclusion.
- 6.19. Refer to **Mathematicians' salaries** Problem 6.18. Assume that regression model (6.5) for three predictor variables with independent normal error terms is appropriate.
- Test whether there is a regression relation; use  $\alpha = .05$ . State the alternatives, decision rule, and conclusion. What does your test imply about  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ ? What is the  $P$ -value of the test?
  - Estimate  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  jointly by the Bonferroni procedure, using a 95 percent family confidence coefficient. Interpret your results.
  - Calculate  $R^2$  and interpret this measure.
- 6.20. Refer to **Mathematicians' salaries** Problem 6.18. Assume that regression model (6.5) for three predictor variables with independent normal error terms is appropriate. The researcher wishes to obtain simultaneous interval estimates of the mean salary level for four typical mathematicians specified as follows:

|        | 1   | 2   | 3   | 4   |
|--------|-----|-----|-----|-----|
| $X_1:$ | 5.0 | 6.0 | 4.0 | 7.0 |
| $X_2:$ | 20  | 30  | 10  | 50  |
| $X_3:$ | 5.0 | 6.0 | 4.0 | 7.0 |

Obtain the family of estimates using a 95 percent family confidence coefficient. Employ the most efficient procedure.

- 6.21. Refer to **Mathematicians' salaries** Problem 6.18. Assume that regression model (6.5) for three predictor variables with independent normal error terms is appropriate. Three mathematicians with the following characteristics did not provide any salary information in the study.



|         | 1   | 2   | 3   |
|---------|-----|-----|-----|
| $X_1$ : | 5.4 | 6.2 | 6.4 |
| $X_2$ : | 17  | 12  | 21  |
| $X_3$ : | 6.0 | 5.8 | 6.1 |

Develop separate prediction intervals for the annual salaries of these mathematicians, using a 95 percent statement confidence coefficient in each case. Can the salaries of these three mathematicians be predicted fairly precisely? What is the family confidence level for the set of three predictions?

## Exercises

- 6.22. For each of the following regression models, indicate whether it is a general linear regression model. If it is not, state whether it can be expressed in the form of (6.7) by a suitable transformation:

- $Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 \log_{10} X_{i2} + \beta_3 X_{i1}^2 + \varepsilon_i$
- $Y_i = \varepsilon_i \exp(\beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2}^2)$
- $Y_i = \beta_0 + \log_{10}(\beta_1 X_{i1}) + \beta_2 X_{i2} + \varepsilon_i$
- $Y_i = \beta_0 \exp(\beta_1 X_{i1}) + \varepsilon_i$
- $Y_i = [1 + \exp(\beta_0 + \beta_1 X_{i1} + \varepsilon_i)]^{-1}$

- 6.23. (Calculus needed.) Consider the multiple regression model:

$$Y_i = \beta_1 X_{i1} + \beta_2 X_{i2} + \varepsilon_i \quad i = 1, \dots, n$$

where the  $\varepsilon_i$  are uncorrelated, with  $E\{\varepsilon_i\} = 0$  and  $\sigma^2\{\varepsilon_i\} = \sigma^2$ .

- State the least squares criterion and derive the least squares estimators of  $\beta_1$  and  $\beta_2$ .
- Assuming that the  $\varepsilon_i$  are independent normal random variables, state the likelihood function and obtain the maximum likelihood estimators of  $\beta_1$  and  $\beta_2$ . Are these the same as the least squares estimators?

- 6.24. (Calculus needed.) Consider the multiple regression model:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i1}^2 + \beta_3 X_{i2} + \varepsilon_i \quad i = 1, \dots, n$$

where the  $\varepsilon_i$  are independent  $N(0, \sigma^2)$ .

- State the least squares criterion and derive the least squares normal equations.
  - State the likelihood function and explain why the maximum likelihood estimators will be the same as the least squares estimators.
- 6.25. An analyst wanted to fit the regression model  $Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i$ ,  $i = 1, \dots, n$ , by the method of least squares when it is known that  $\beta_2 = 4$ . How can the analyst obtain the desired fit by using a multiple regression computer program?
- 6.26. For regression model (6.1), show that the coefficient of simple determination  $r^2$  between  $Y_i$  and  $\hat{Y}_i$  equals the coefficient of multiple determination  $R^2$ .
- 6.27. In a small-scale regression study, the following data were obtained:

| $i:$      | 1  | 2  | 3  | 4  | 5  | 6  |
|-----------|----|----|----|----|----|----|
| $X_{i1}:$ | 7  | 4  | 16 | 3  | 21 | 8  |
| $X_{i2}:$ | 33 | 41 | 7  | 49 | 5  | 31 |
| $Y_i:$    | 42 | 33 | 75 | 28 | 91 | 55 |

Assume that regression model (6.1) with independent normal error terms is appropriate. Using matrix methods, obtain (a)  $\mathbf{b}$ ; (b)  $\mathbf{e}$ ; (c)  $\mathbf{H}$ ; (d)  $SSR$ ; (e)  $s^2\{\mathbf{b}\}$ ; (f)  $\hat{Y}_h$  when  $X_{h1} = 10$ ,  $X_{h2} = 30$ ; (g)  $s^2\{\hat{Y}_h\}$  when  $X_{h1} = 10$ ,  $X_{h2} = 30$ .

## Projects

- 6.28. Refer to the **SMSA** data set. You have been asked to evaluate two alternative models for predicting the number of active physicians ( $Y$ ) in an SMSA. Proposed model I includes as predictor variables total population ( $X_1$ ), land area ( $X_2$ ), and total personal income ( $X_3$ ). Proposed model II includes as predictor variables population density ( $X_1$ , total population divided by land area), percent of population in central cities ( $X_2$ ), and total personal income ( $X_3$ ).
- Prepare a stem-and-leaf plot for each of the predictor variables. What noteworthy information is provided by your plots?
  - Obtain the scatter plot matrix and the correlation matrix for each proposed model. Summarize the information provided.
  - For each proposed model, fit the first-order regression model (6.5) with three predictor variables.
  - Calculate  $R^2$  for each model. Is one model clearly preferable in terms of this measure?
  - For each model, obtain the residuals and plot them against  $\hat{Y}$ , each of the three predictor variables, and each of the two-factor interaction terms. Also prepare a normal probability plot for each of the two fitted models. Interpret your plots and state your findings. Is one model clearly preferable in terms of appropriateness?
- 6.29. Refer to the **SMSA** data set.
- For each geographic region, regress the number of serious crimes in an SMSA ( $Y$ ) against population density ( $X_1$ , total population divided by land area), total personal income ( $X_2$ ), and percent high school graduates ( $X_3$ ). Use first-order regression model (6.5) with three predictor variables. State the estimated regression functions.
  - Are the estimated regression functions similar for the four regions? Discuss.
  - Calculate  $MSE$  and  $R^2$  for each region. Are these measures similar for the four regions? Discuss.
  - Obtain the residuals for each fitted model and prepare a box plot of the residuals for each fitted model. Interpret your plots and state your findings.
- 6.30. Refer to the **SENIC** data set. Two models have been proposed for predicting the average length of patient stay in a hospital ( $Y$ ). Model I utilizes as predictor variables age ( $X_1$ ), infection risk ( $X_2$ ), and available facilities and services ( $X_3$ ). Model II uses as predictor variables number of beds ( $X_1$ ), infection risk ( $X_2$ ), and available facilities and services ( $X_3$ ).
- Prepare a stem-and-leaf plot for each of the predictor variables. What information do these plots provide?