TABLE 7.2

Approximate Costs in Dollars per Pound for Various Metals

	Density						
	lb/in.^{3}	mg/m^3	Bar	Rod	Sheet <0.5 in.	Plate >0.5 in.	Tube
Ferrous							
Carbon steel	0.283	7.83	0.51	0.51	0.36	0.42	0.92
Alloy steel	0.31	8.58	0.75	0.75	1.20	—	—
Stainless steel	0.283	7.83	1.50	1.50	2.50	2.50	—
Tool steel	0.283	7.83	6.44	6.44	—	6.44	—
Nonferrous							
Aluminum alloys	0.10	2.77	1.93	1.93	1.95	2.50	4.60
Brass	0.31	8.58	0.90	1.22	1.90	1.90	1.90
Nickel alloys	0.30	8.30	5.70	5.70	5.70	5.70	—
Magnesium alloys	0.066	1.83	3.35	3.35	6.06	6.06	3.35
Zinc alloys	0.23	6.37	1.50	1.50	1.50	1.50	—
Titanium alloys	0.163	4.51	15.40	15.40	25.00	25.00	—

Note: To convert to dollars per kilogram multiply by 2.2.

conditions so the values given in Table 7.2 are included for the purposes of calculations in this Chapter.

7.12.2 Machine Loading and Unloading

Nonproductive costs are incurred everytime the workpiece is loaded into (and subsequently unloaded from) a machine tool. An exhaustive study of loading and unloading times has been made by Fridriksson [1]; he found that these times can be estimated quite accurately for a particular machine tool and work-holding device if the weight of the workpiece is known. Some of Fridriksson's results are presented in Table 7.3, which can be used to estimate machine loading and unloading times. To these figures must be added the times for turning coolant on and off, cleaning the work-holding or clamping device, and so on.

7.12.3 Other Nonproductive Costs

For every pass, cut, or operation carried out on one machine tool, further nonproductive costs are incurred. In each case, the tool must be positioned, perhaps the feed and speed settings changed, the feed engaged, and then, when the operation is completed, the tool must be withdrawn. If different tools are employed, then the times for tool engagement or indexing must also be taken into account. Some time elements for these tasks for different types of machine tools are presented in Table 7.4.

Also included in Table 7.4 are estimates of the basic setup time and additional setup time per cutting tool. The total set-up time must be divided by the size of the batch in order to obtain the setup time per component.

7.12.4 Handling between Machines

One of the costs to be considered is that incurred in moving batches of partially machined workpieces between machines. Fridriksson [1] made a study of this by assuming that

TABLE 7.3

Loading and Unloading Times (s) versus Workpiece Weight

	Workpiece Weight				
	0–0.2	0.2–4.5	4.5–14	14–27 (kg)	
Holding Device	**0–0.4**	**0.4–10**	**10–30**	**30–60 (lb)**	**Crane**
Angle plate (2 U-clamps)	27.6	34.9	43.5	71.2	276.5
Between centers, no dog	13.5	18.6	24.1	35.3	73.1
Between centers, with dog	25.6	40.2	57.4	97.8	247.8
Chuck, universal	16.0	23.3	31.9	52.9	—
Chuck, independent (4 jaws)	34.0	41.3	49.9	70.9	—
Clamp on table (3 clamps)	28.8	33.9	39.4	58.7	264.6
Collet	10.3	15.4	20.9	—	—
Faceplate (3 clamps)	31.9	43.3	58.0	82.1	196.2
Fixture, horizontal (3 screws)	25.8	33.1	41.7	69.4	274.7
Fixture, vertical (3 screws)	27.2	38.6	53.3	—	—
Hand-held	1.4	6.5	12.0	—	—
Jig	25.8	33.1	41.7	—	—
Magnet table	2.6	5.2	8.4	—	—
Parallels	14.2	19.3	24.8	67.0	354.3
Rotary table or index plate (3 clamps)	28.8	36.1	44.7	72.4	277.7
"V" Blocks	25.0	30.1	35.6	77.8	365.1
Vise	13.5	18.6	24.1	39.6	174.2

Source: Adapted from Fridriksson, L. Nonproductive Time in Conventional Metal Cutting. Report No. 3, *Design for Manufacturability Program*, University of Massachusetts, Amherst, February 1979.

TABLE 7.4

Some Nonproductive Times for Common Machine Tools

Machine Tool	Time to Engage Tool; etc.[a] (s)	Basic Setup Time (h)	Additional Setup per Tool (h)
Horizontal band saw	—	0.17	—
Manual turret lathe	9	1.2	0.2
CNC turret lathe	1.5	0.5	0.15
Milling machine	30	1.5	—
Drilling machine	9	1.0	—
Horizontal-boring machine	30	1.3	—
Broaching machine	13	0.6	—
Gear hobbing machine	39	0.9	—
Grinding machine	19	0.6	—
Internal grinding machine	24	0.6	—
Machining center	8	0.7	0.05

[a] Average times to engage tool, engage and disengage feed, change speed or feed. (Includes change tool for machining center.)

stacks of pallets of workpieces were moved around the factory using forklift trucks. He developed the following expression for t_f, the transportation time for a round trip by a forklift truck

$$t_f = 25.53 + 0.29(l_p + l_{rd})\, s \tag{7.39}$$

where l_p is the length of the pathway between machines and l_{rd} is the distance the truck must travel to respond to a request—both lengths are measured in feet.

Assuming that $(l_p + l_{rd})$ is 450 ft (137 m) on average and that for every trip with a load of full pallets, a trip must be made with empty pallets, the total time is

$$t_f = 315\,\text{s} \tag{7.40}$$

If a full load of pallets and workpieces is 2000 lb, the number of workpieces of weight W transported would be $2000/W$ and the time per workpiece t_{tr} is given by

$$t_{tr} = \frac{315}{(2000/W)} = 0.156W\ \text{s} \tag{7.41}$$

Thus, for a workpiece weighing 10 lb, the effective transportation time is only 1.6 s, which is small compared to typical loading and unloading times for that size workpiece (Table 7.3). However, allowances for transportation time can be added to the loading and unloading times, and these become significant for large workpieces.

7.12.5 Material Type

The so-called machinability of a work material has been one of the most difficult factors to define and quantify. In fact, it is impossible to predict the difficulty of machining a material from knowledge of its composition or its mechanical properties, without performing a machining test. Nevertheless, it is necessary for the purposes of cost estimating to employ published data on machinability. Perhaps the best source of such data, presented in the form of recommended cutting conditions, is the *Machining Data Handbook* [2].

7.12.6 Machining Costs

The machining cost for each cut, pass, or operation is incurred during the period between when the feed is engaged and, finally, disengaged. It should be noted that the tool would not be cutting for the whole of this time, because allowances for tool engagement and disengagement must be made—particularly for milling operations. However, typical values for these allowances can be found and are presented for various operations in Table 7.5 as correction factors to be applied to the actual machining time.

For an accurate estimation of actual machining time, it is necessary to know the cutting conditions, namely, cutting speed, feed, and depth of cut in single-point tool operations, and the feed speed, depth of cut, and width of cut in multipoint tool operations. Tables giving recommended values for these parameters for different work materials can fill large volumes, such as the Metcut *Machining Data Handbook* [2].

Analysis of the selection of optimum machining conditions shows that the optimum feed (or feed per tooth) is the largest that the machine tool and cutting tool can withstand.

TABLE 7.5

Allowances for Tool Approach

Operations	Allowances
Turn, face, cut-off bore,	$t'_m = t_m + 5.4 \quad d_m > 2$
groove, thread	$t'_m = t_m + \left(1.35\, d_m^2\right) \quad d_m \le 2$
Drill (twist) (approach)	$t'_m = t_m\left(1 + 0.5d_m/l_w\right)$
Drill (twist) (start)	$t'_m = t_m + \left(88.5/\upsilon f\right)\big) d_m^{1.67}$
Helical, side, saw, and key slot milling	$l'_w = l_w + 2\left(a_e\left(d_t - a_c\right)^{0.5} + 0.066 + 0.011d_t\right)$
Face and end milling	$l'_w = l_w + d_t + 0.066 + 0.011d_t$
Surface grinding	$l'_w = l_w + d_t/4$
Cyl. and int. grinding	$l'_w = l_w + w_t$
All grinding operations	$a'_r = a_r + 0.004 \quad a_r \le 0.01$
	$a'_r = a_r + 0.29\left(a_r - 0.01\right) \quad \begin{cases} a_r > 0.01 \\ a_r \le 0.024 \end{cases}$
	$a'_r = a_r + 0.008 \quad a_r > 0.024$
Spline broaching	$l_t = -5 + 15d_m + 8l_w$
Internal keyway broaching	$l_t = 20 + 40w_k + 85d_k$
Hole broaching	$l_t = 6 + 6d_m + 6l_w$

Source: Adapted from Ostwald, P.F. *AM Cost Estimator*, McGraw-Hill, New York, 1985/1986.

Note: t_m = machining time, s; d_m = diameter of the machined surface, in.; l_w = length of the machined surface in the direction of cutting, in.; υ_f = speed × feed, in.^{2}/min (Table 7.6); a_e = depth of cut or depth of the groove in milling, in.; d_t = diameter of the cutting tool, in.; w_t = width of the grinding wheel, in.; a_r = depth of the material removed in rough grinding, in.; l_t, = length of the tool, in.; w_k = width of the machined keyway, in.; d_k = depth of the machine keyway, in.

Then, selection of the optimum cutting speed can be made by minimizing machining costs (see Equation 7.33). The product of cutting speed and feed in a single-point operation gives a rate for the generation of the machined surface that can be measured in in.^{2}/min, for example. The inverse of such rates is presented by Ostwald [3] for a variety of workpiece and tool materials and for different roughing and finishing operations. Problem arises, however, when applying the figures for roughing operations. For example, Ostwald recommends a cutting speed of 500 ft/mm (2.54 m/s) and a feed of 0.02 in. (0.51 mm) for the rough machining of low carbon steel (170 Bhn) with a carbide tool. For a depth of cut of 0.3 in. (7.6 mm) this would mean a metal removal rate of 36 in.^{3}/min (9.82 μm^3/s). The *Machining Data Handbook* [2] quotes a figure of 1.35 hp min/in.^{3} (3.69 GJ/m^3) (unit power) for this work material. Thus, the removal rate obtained in this example would require almost 50 hp (36 kW). Since a typical medium-sized machine tool would have a 5 to 10 hp motor (3.7 to 7.5 kW) and an efficiency of around 70%, it can be seen that the recommended conditions could not be achieved except for small depths of cut. Under normal rough-machining circumstances, therefore, a better estimate of machining time would be obtained from the unit horsepower (specific cutting energy) for the material, the volume of material to be removed, and the typical power available for machining, as described earlier in this chapter.

For multipoint tools such as milling cutters, the chip load (feed per tooth) and the cutting speed are usually recommended for given tool materials. However, in these cases the machining time is not directly affected by the cutting speed but by the feed speed, which is controlled independent of the cutter speed. Thus, assuming that the optimum cutting speed is employed, the feed speed that gives the recommended feed per tooth can be used to estimate the machining time. Again, a check must be made that the power requirements for the machine tool are not excessive.

7.12.7 Tool Replacement Costs

Everytime a tool needs replacement because of wear, two costs are incurred:

1. The cost of machine idle time while the operator replaces the worn tool, and
2. The cost of providing a new cutting edge or tool. The choice of the best cutting speed for particular conditions is usually made by minimizing the sum of the tool replacement costs and the machining costs, since both of these are affected by changes in the cutting speed.

The minimum cost of machining a feature in one component on one machine tool is given by Equation 7.35. If the expressions for machining time t_m (Equation 7.31) and cutting speed υ_c (Equation 7.33) are substituted, the minimum cost of production can be expressed by

$$C_{min} = Mt_l + \frac{Mt_{mc}}{(1-n)} \tag{7.42}$$

where t_{mc} is the machining time when the optimum cutting speed for minimum cost is used.

It can be seen that the factor $1/(1 - n)$ applied to the machining time allows tool replacement costs provided that the cutting speed for minimum cost is always employed. The factor would be 1.14 for high-speed steel tooling and 1.33 for carbides.

Under those circumstances where the use of optimum cutting conditions would not be possible because of power limitations, it is usually recommended that the cutting speed be reduced. This is because greater savings in tool costs result than if the feed were reduced. When the cutting speed has been reduced, with a corresponding increase in the machining time, the correction factor given by Equation 7.42 overestimates tool costs. If t_{mp} is the machining time where the cutting speed υ_{po} giving maximum power is used, then the production cost C_{po} for maximum power is given by

$$C_{po} = Mt_l + Mt_{mp} + \frac{(Mt_{ct} + C_t)t_{mp}}{t_{po}} \tag{7.43}$$

where t_{po} is the tool life obtained under maximum power conditions, which, from Taylor's tool life equation, is

$$t_{po} = t_c\left(\frac{\upsilon_c}{\upsilon_{po}}\right)^{1/n} \tag{7.44}$$

The tool life t_c under minimum cost conditions is given by Equation 7.34, and substituting Equations 7.44 and 7.34 into Equation 7.43 and using the relation in Equation 7.31 gives

$$C_{po} = Mt_l + Mt_{mp}\left\{1 + \left[\frac{n}{(1-n)}\right]\left(\frac{t_{mc}}{t_{mp}}\right)^{1/n}\right\} \tag{7.45}$$

Thus, Equation 7.45 can be used instead of Equation 7.42 when the cutting speed is limited by the power available on the machine tool and, therefore, when $t_{mp} > t_{mc}$.

7.12.8 Machining Data

In order to employ the approach described above, it is necessary to be able to estimate, for each operation, the machining time t_{mc} for minimum cost conditions and the machining time t_{mp} where the cutting speed is limited by power availability. It was shown earlier that machining data for minimum cost for single-point tools, presented in handbooks, can be expressed as speed × feed (υf), or the rate at which the machined surface can be generated. Table 7.6 gives typical values of υf for several material classifications selected and for lathe operations using high-speed tools or brazed carbide tools. These values were adapted from the data in the *Machining Data Handbook* [2], Analysis of the handbook data shows that if disposable insert carbide tools are to be used, then the data for brazed carbide tools can be multiplied by an average factor of 1.17.

When turning a surface of diameter d_m for a length l_w, the figures for υf given in Table 7.6 would be divided into the surface area ($A_m = \pi/_w d_m$) to give the machining time t_{mc}.

Thus

$$t_{mc} = \frac{60A_m}{(\upsilon f)}\ \text{s} \tag{7.46}$$

For an estimate of the machining time t_{mp} for maximum power it is necessary to know the power available for machining and the unit power p_s (specific cutting energy) for the work material. Table 7.6 gives average values of p_s for the selection of work materials employed here.

When estimating the power available for machining P_m, it should be realized that small components are generally machined on small machines with lower power available, whereas larger components are machined on large higher-powered machines. For example, a small lathe may have less than 2 hp available for machining, whereas an average-sized lathe may have 5–10 hp available. A larger vertical lathe perhaps has 10–30 hp available. Typical power values for a selection of machines are presented in Figure 7.47, where the horsepower available for machining P_m is plotted against the typical weight capacity of the machine.

The machining time for maximum power is given by

$$t_{mp} = 60\, V_m p_s / P_m\ \text{s} \tag{7.47}$$

where V_m is the volume of material to be removed in the machining operation. If a_p is the depth of cut, then V_m is given approximately by $\pi d_m l_w a_p$. However, for a facing or cut-off

TABLE 7.6

Machining Data

		Turning, Facing and Boring			Drilling and Reaming (1 in.)	
		vf (in²/min)[a]				
Material	**Hardness**	**HSS**	**Brazed Carbide**	p_s (hp/in.³/min)[b]	*vf*(in.²/min)[a] HSS	p_s (hp/in.³/min)[b]
Low carbon steel (free machining)	150–200	25.6	100	1.1	33.0	0.95
Low carbon steel	150–200	22.4	92	1.35	13.4	1.2
Medium and high carbon steel	200–250	18.2	78	1.45	15.1	1.4
Alloy steel (free machining)	150–200	23.7	96	1.3	16.4	1.15
Stainless, ferritic (annealed)	135–185	12.6	48	1.55	9.4	1.35
Tool steels	200–250	12.8	54	1.45	6.2	1.4
Nickel alloys	80–360	9	42	2.25	14.3	2.0
Titanium alloys	200–275	12.6	24	1.35	7.9	1.25
Copper alloys (soft) (free machining)	40–150	76.8	196	0.72	38.4	0.54
Zinc alloys (die cast)	80–100	58.5	113	0.3	51.1	0.2
Magnesium and alloys	49–90	162	360	0.18	75.2	0.18
Aluminum and alloys	30–80	176	352	0.28	79.8	0.18

Factor	**For**	**Turning, Facing Boring**	**Milling**
k_f	Finishing	0.60	0.89
k_i	Disposable Insert	1.17	1.13

Factor	**For**	**Tool Diameter (in.) (mm)**							
		1/16	1/8	1/4	1/2	3/4	1	1.5	2 in.
k_h		1.59	3.18	6.35	12.7	19.7	25.4	38.1	50.8 mm
	Drilling and reaming	0.08	0.19	0.35	0.60	0.83	1.00	1.23	1.47

Factor	**For**	**Length/Diameter Ratio**					
		< 2	3	4	5	6	8
k_d	Deep holes	1.00	0.81	0.72	0.56	0.52	0.48

Source: Adapted from *Machining Data Handbook*. Vols. 1 and 2, 3rd ed. Metcut Research Association Inc., 1980.

[a] To convert in.²/min to m²/min, multiply by 6.45×10^{-4}.

[b] To convert hp min/in.³ to GJ/m³ multiply by 2.73.

All data are for rough machining. For finish machining multiply by k_f.

For cut-off or form tool operations, multiply by 0.2.

The term *carbide* refers to tools with brazed carbide inserts. For tools with disposable carbide inserts, multiple by k_i.

Data for drilling are for 1.0 in. diameter tools with hole depth/diameter less than 2.

For sawing, multiply the data for turning with HSS tools by 0.33.

For tap or die threading, multiply data for turning with HSS tools by 10 and divide by TPI (threads per inch); for standard threads $TPI = 2.66 + 4.28/d_m$.

For single-point threading, multiply result for die threading by number of passes, approximately 100/TPI, and add tool engagement time for each pass.

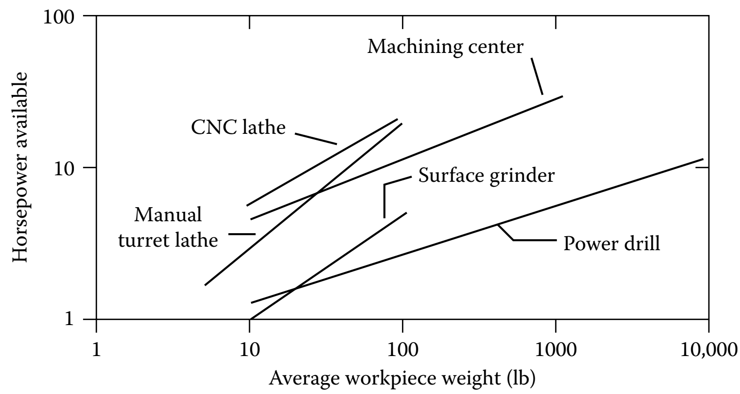

FIGURE 7.47
Relation between horsepower and workpiece weight for some machine tools.

operation carried out at constant rotational speed, the power limitations apply only at the beginning of the cut and the machining time is longer than that given by Equation 7.47.

It was pointed out earlier that for milling operations, it is convenient to estimate machining time from knowledge of the feed speed υ_f that gives the recommended feed per tooth. Data for milling selected materials are presented in Table 7.7.

The machining time t_m for recommended conditions is thus given by

$$t_{mc} = 60l_w/\upsilon_f \text{ s} \tag{7.48}$$

where l_w is the length of the feature to be milled. However, it is important to note that this result must be corrected for the approach and overtravel distances, which are often as large as the cutter diameter.

The machining time for maximum power is given by Equation 7.47, but, again, corrections must be made for cutter approach and overtravel.

7.12.9 Rough Grinding

Limitations on the rate at which grinding operations can be carried out depend on many interrelated factors, including the work material, the wheel grain type and size, the wheel bond and hardness, the wheel and work speeds, downfeed, infeed, the type of operation, the rigidity of the machine tool, and power available. It appears that, assuming adequate power, these limitations can be summarized in terms of the maximum metal removal rate per unit width of the grinding wheel Z_w/w_t. For example, the *Machining Data Handbook* [2] gives the following recommendations for the rough grinding of annealed free-machining low carbon steel on a horizontal-spindle reciprocating surface grinder:

Wheel speed: 5500–6500 ft/min

Table speed: 50–150 ft/min

Downfeed: 0.003 in./pass

Crossfeed: 0.05–0.5 in./pass (1/4 wheel width maximum)

Wheel: A46JV (aluminum oxide grain, size 46, grade J, vitrified bond)

TABLE 7.7

Machining Data for Milling Operations

Material	Hardness (Bhn)	Milling v_f (in./min)[a] Side and Face HSS	Brazed Carb.	End (1.5 in.) HSS	Brazed Carb.	p_s (hp/in.^{3}/min)[b]
Low carbon steel (free machining)	150–200	19.2	52.9	4.5	15.7	1.1
Low carbon steel	150–200	13.5	43.3	2.2	9.9	1.4
Medium and high carbon steel	200–250	10.8	37.3	1.8	8.9	1.6
Alloy steel (free machining)	150–200	13.7	40.2	2.7	10.5	1.3
Stainless, ferretic (annealed)	135–185	14.0	41.0	2.4	6.0	1.7
Tool steels	200–250	6.7	23.7	0.9	4.5	1.5
Nickel alloys	80–360	4.1	7.7	1.0	—	2.15
Titanium alloys	200–275	3.9	13.2	1.5	7.1	1.25
Copper alloys (soft) (free machining)	40–150	50.5	108.3	9.9	20.7	0.72
Zinc alloys (die cast)	80–100	28.0	60.1	9.8	16.0	0.4
Magnesium and alloys	40–90	77.0	240.6	27.5	55.0	0.18
Aluminum and alloys	30–80	96.2	216.5	20.4	36.7	0.36

Source: Adapted from *Machining Data Handbook*. Vols. 1 and 2, 3rd ed. Metcut Research Association Inc., 1980.

[a] To convert in/min to mm/s multiple by 0.423.

[b] To convert hp/min/in3 to GJ/m3 multiply by 2.73.

If the wheel width w_t were 1 in. and an average table speed (work speed) of 75 ft/min were employed, then a downfeed of 0.003 in. and a maximum crossfeed of 0.25 in. would give a metal removal rate Z_w of 0.68 in.^{3}/min. In a plunge-grinding operation, the wheel width would be equal to the width of the groove to be machined and the rough grinding time t_{gc} for recommended conditions would be given by

$$t_{gc} = 60\,V_m/Z_w \tag{7.49}$$

where V_m is the volume of metal to be removed and Z_w is the metal removal rate (in.^{3}/min). If the groove depth a_d were 0.25 in. and the groove length l_w were 4 in., the grinding time would be

$$t_{gc} = 60 a_d w_t l_w/Z_w = 60(1)(0.25)(4)/0.68 = 88.2\text{ s}$$