CHAPTER 6

Modeling Costs

As described in Chapter 1, one of the defining characteristics of WSCs is their emphasis on cost efficiency at scale. To better understand this, let us examine the total cost of ownership (TCO) of a data center. At the top level, costs split into capital expenses (Capex) and operational expenses (Opex). Capex refers to investments that must be made upfront and that are then depreciated over a certain timeframe. Examples are the construction cost of a data center or the purchase price of a server. Opex refers to the recurring monthly costs of actually running the equipment, excluding depreciation: electricity costs, repairs and maintenance, salaries of on-site personnel, and so on. Thus, we have:

TCO = data center depreciation + data center Opex + server depreciation + server Opex.

We focus on top-line estimates in this chapter, simplifying the models where appropriate. More detailed cost models can be found in the literature [Pat+05, Koo+07]. For academic purposes, our simplified model is accurate enough to model all major costs; the primary source of inaccuracy compared to real-world data centers will be the model input values, such as the cost of construction.

6.1 CAPITAL COSTS

Data center construction costs vary widely depending on design, size, location, and desired speed of construction. Not surprisingly, adding reliability and redundancy makes data centers more expensive, and very small or very large data centers tend to be more expensive (the former because fixed costs cannot be amortized over many watts, the latter because large data centers require additional infrastructure, such as electrical substations).

Table 6.1 shows a range of typical data center construction costs, expressed in dollars per watt of usable critical power, drawn from a variety of sources. In general, most large enterprise data centers cost around $9–13 per watt to build, and smaller ones cost more. The cost numbers in the table below shouldn't be directly compared since the scope of the projects may differ. For example, the amount quoted may or may not include land or the cost of a pre-existing building.

Table 6.1: Range of data center construction costs expressed in U.S. dollars per watt of critical power. Critical power is defined as the peak power level that can be provisioned to IT equipment

Cost/W	Source
\$12-25	Uptime Institute estimates for small- to medium-sized data centers; the lower value is for Tier I designs that are rarely built in practice [TS06].
\$9-13	Dupont Fabros 2011 Form 10K report [DuP11] contains financial information suggesting the following cost for its most recent facilities (built in 2010 and 2011; see page 39 for critical load and page 76 for cost): \$204M for 18.2 MW (NJ1 Phase I) => \$11.23/W \$116M for 13 MW (ACC6 Phase I) => \$8.94/W \$229M for 18.2 MW (SC1 Phase 1) => \$12.56/W
\$8-10	Microsoft's investment of \$130M for 13.2 MW (\$9.85/W) capacity expansion to its data center in Dublin, Ireland [Mic12]. Facebook is reported to have spent \$210M for 28 MW (\$7.50/W) at its Prineville data center [Mil12].

Historical costs of data center construction of Tier III facilities range from \$9–\$13 per watt. The recent growth of cloud computing is driving a data center construction boom. North American Data Center reports[5] nearly 300 MW under construction in 2017, a 5-year high. As data center construction projects continue to increase, costs are falling. The costs of most recent constructions range from \$7–\$9 per watt, as revealed in Form 10K reports from companies including Digital Realty Trust (DLR), CyrusOne (CONE), and QTS Realty Trust (QTS) [GDCC].

Characterizing cost in terms of dollars per watt makes sense for larger data centers (where size-independent fixed costs are a relatively small fraction of overall cost) because all of the data center's primary components—power, cooling, and space—roughly scale linearly with watts. Typically, approximately 60–80% of total construction cost goes toward power and cooling, and the remaining 20–40% toward the general building and site construction.

Cost varies with the degree of desired redundancy and availability, and thus we always express cost in terms of *dollars per critical watt*; that is, watts that can actually be used by IT equipment. For example, a data center with 20 MW of generators may have been built in a 2N configuration and provide only 6 MW of critical power (plus 4 MW to power chillers). Thus, if construction costs \$120 million, it costs \$20/W, not \$6/W. Industry reports often do not correctly use the term critical power, so our example data center might be described as a 20 MW data center or even a 30 MW data center if it is supplied by an electrical substation that can provide 30 MW.

Frequently, construction cost is quoted in dollars per square foot, but that metric is less useful because it cannot adequately compare projects and is used even more inconsistently than cost

[5] https://nadatacenters.com/wp-content/uploads/NADC-Newsletter-2018-R4.pdf

expressed in dollars per watt. In particular, there is no standard definition of what space to include or exclude in the computation, and the metric does not correlate well with the primary cost driver of data center construction, namely critical power. Thus, most industry experts avoid using dollars per square foot to express cost.

The monthly depreciation cost (or amortization cost) that results from the initial construction expense depends on the duration over which the investment is amortized (related to its expected lifetime) and the assumed interest rate. Typically, data centers are depreciated over periods of 15–20 years. Under U.S. accounting rules, it is common to use straight-line depreciation where the value of the asset declines by a fixed amount each month. For example, if we depreciate a $12/W data center over 12 years, the depreciation cost is $0.08/W per month. If we took out a loan to finance construction at an interest rate of 8%, the associated monthly interest payments add an additional $0.05/W, for a total of $0.13/W per month. Typical interest rates vary over time, but many companies use a cost of capital rate in the 7–12% range.

Server costs are computed similarly, except that servers have a shorter lifetime and thus are typically depreciated over 3–4 years. To normalize server and data center costs, it is useful to characterize server costs per watt as well, using the server's peak real-life power consumption as the denominator. For example, a $4,000 server with an actual peak power consumption of 500 W costs $8/W. Depreciated over 4 years, the server costs $0.17/W per month. Financing that server at 8% annual interest adds another $0.02/W per month, for a total of $0.19/W per month.

As discussed in earlier chapters, with the slowdown of Moore's law, WSCs are increasingly turning to hardware accelerators to improve performance per watt. The Capex of internally developed accelerators also includes non-recurring engineering (NRE), the cost of designing and fabricating the ASIC, as well the surrounding infrastructure. If developing and deploying 100,000 accelerators has a one time cost of $50M with each accelerator consuming 200 W, depreciated over 4 years, the NRE cost is $0.05/W per month.

6.2 OPERATIONAL COSTS

Data center operational expense (Opex) is harder to characterize because it depends heavily on operational standards (for example, how many security guards are on duty at the same time or how often generators are tested and serviced) as well as on the data center's size: larger data centers are cheaper because fixed costs are amortized better. Costs can also vary depending on geographic location (climate, taxes, salary levels, and so on) and on the data center's design and age. For simplicity, we will break operational cost into a monthly charge per watt that represents items like security guards and maintenance, and electricity. Typical operational costs for multi-megawatt data centers in the U.S. range from $0.02–$0.08/W per month, excluding the actual electricity costs.

Similarly, servers have an operational cost. Because we are focusing just on the cost of running the infrastructure itself, we will focus on just hardware maintenance and repairs as well as electricity costs. Server maintenance costs vary greatly depending on server type and maintenance standards (for example, response times for four hours vs. two business days).

Also, in traditional IT environments, the bulk of the operational cost lies in the applications; that is, software licenses and the cost of system administrators, database administrators, network engineers, and so on. We are excluding these costs here because we are focusing on the cost of running the physical infrastructure, but also because application costs vary greatly depending on the situation. In small corporate environments, it is not unusual to see one system administrator per a few tens of servers, resulting in a substantial per-machine annual cost [RFG02]. Many published studies attempt to quantify administration costs, but most of them are financed by vendors trying to prove the cost-effectiveness of their products, so that reliable unbiased information is scarce. However, it is commonly assumed that large-scale applications require less administration, scaling to perhaps 1,000 servers per administrator.

6.3 CASE STUDIES

Given the large number of variables involved, it is best to illustrate the range of cost factors by looking at a small number of case studies that represent different kinds of deployments.

First, we consider a typical new multi-megawatt data center in the U.S. (something closer to the Uptime Institute's Tier III classification), fully populated with servers at the high end of what can still be considered a volume rack-mountable server product. For this example we chose a Dell PowerEdge FC640, with 2 CPUs, 128 GB of RAM, and 960 GB SSD. This server draws 340 W at peak per Dell's configuration planning tool and costs approximately $5,000 as of 2018. The remaining base case parameters chosen are as follows.

- The cost of electricity is the 2018 average U.S. industrial rate of 6.7 cents/kWh.
- The interest rate a business must pay on loans is 8%, and we finance the servers with a 3-year interest-only loan.
- The cost of data center construction is $10/W, amortized over 20[6] years.
- Data center Opex is $0.04/W per month.
- The data center has a power usage effectiveness (PUE) of 1.5, the current industry average.

[6] We used 12 years in the first edition of the book, but 20 is more consistent with today's industry financial accounting practices.

- Server lifetime is 3 years, and server repair and maintenance is 5% of Capex per year.
- The server's average power draw is 75% of peak power.

Figure 6.1 shows a breakdown of the yearly TCO for case A among data center and server-related Opex and Capex components.

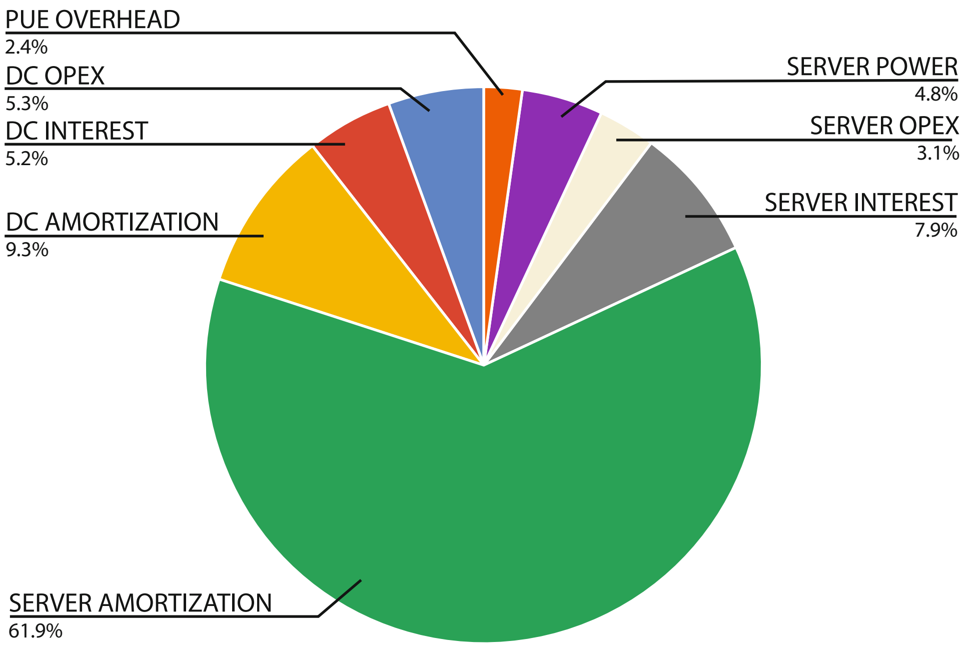

Figure 6.1: TCO cost breakdown for case study A.

In this example, typical of classic data centers, the high server capital costs dominate overall TCO, with 64% of the monthly cost related to server purchase and maintenance. However, commodity-based lower-cost (and perhaps lower-reliability) servers, or higher power prices, can change the picture quite dramatically.

For case B (Figure 6.2), we assume a cheaper, faster, higher-powered server consuming 600 W at peak and costing only $2,000 in a location where the electricity cost is $0.10/kWh. In this case, data center-related costs rise to 44% of the total, and energy costs rise to 19%, with server costs falling to 36%. In other words, the server's hosting cost (that is, the cost of all infrastructure and power to house it) is almost twice the cost of purchasing and maintaining the server in this scenario.

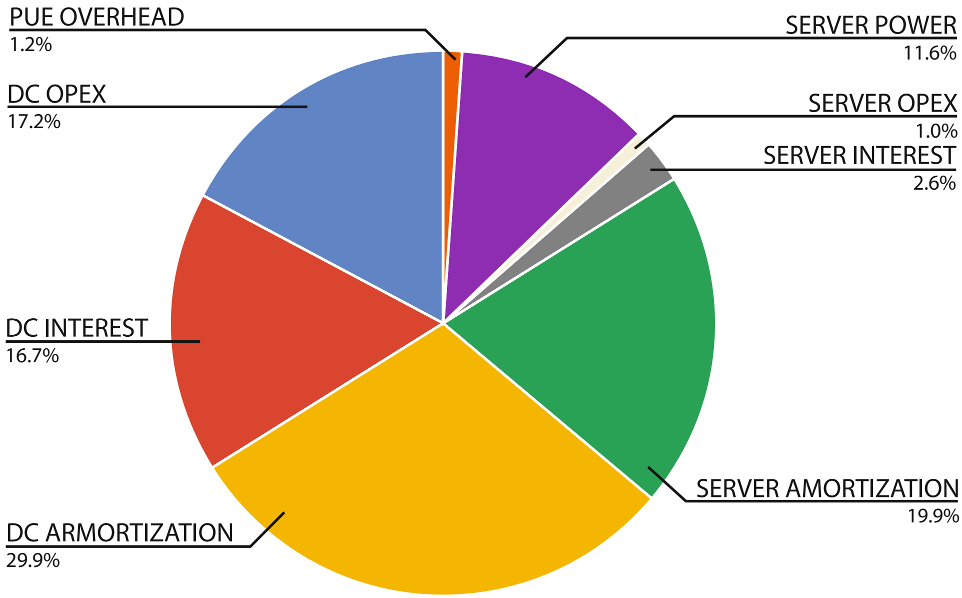

Figure 6.2: TCO cost breakdown for case study B (lower-cost, higher-power servers).

Note that even with the assumed higher power price and higher server power, the absolute 3-year TCO in case B is lower than in case A ($6,310 vs. $7,812) because the server is so much cheaper. The relative importance of power-related costs may increase, as shown in case B, because the power consumption (and performance) of CPUs has more than doubled between 2010 and 2018 (about 14% annually) [Techa], whereas the sale price of low-end servers has stayed relatively stable. As a result, the dollars per watt cost of server hardware is trending down, whereas electricity and construction costs are trending up. This indicates that over the long term, data center facility costs, which are proportional to power consumption, will become a larger fraction of total cost.

6.4 REAL-WORLD DATA CENTER COSTS

In fact, real-world data center costs are even higher than modeled so far. All of the models presented so far assume that the data center is 100% full and the servers are fairly busy (75% of peak power corresponds to a CPU utilization of approximately 50%; see Chapter 5). In reality, this is often not the case. For example, because data center space takes a while to build, we may want to keep a certain amount of empty space to accommodate future deployments. In addition, server layouts assume overly high (worst case) power consumption. For example, a server may consume *up to* 500 W with all options installed (maximum memory, disk, PCI cards, and so on), but the actual configuration deployed may only use 300 W. If the server layout assumes the nameplate rating of 500 W, we will reach a utilization factor of only 60% and thus the actual data center cost per server increases by 1.66x. Thus, in reality, the actual monthly cost per server is often considerably higher than shown above because the data center-related costs increase inversely proportional to data center power utilization.

As discussed in Chapter 5, reaching a high data center power utilization is not as simple as it may seem. Even if the vendor provides a power calculator to compute the actual maximum power draw for a particular configuration, that value will assume 100% CPU utilization. If we install servers based on that value and they run at only 30% CPU utilization on average (consuming 200 W instead of 300 W), we just stranded 30% of the data center capacity. However, if we install servers based on the average value of 200 W and at month's end the servers actually run at near full capacity for a while, our data center will overheat or trip a breaker. Similarly, we may choose to add additional RAM or disks to servers at a later time, which would require physical decompaction of server racks if we left no slack in our power consumption calculations. Thus, in practice, data center operators leave a fair amount of slack space to guard against these problems. Reserves of 20–50% are common, which means that real-world data centers rarely run at anywhere near their rated capacity. In other words, a data center with 10 MW of critical power will often consume a monthly average of just 4–6 MW of actual critical power (plus PUE overhead).

6.5 MODELING A PARTIALLY FILLED DATA CENTER

To model a partially filled data center, we simply scale the Capex and Opex costs (excluding power) by the inverse of the occupancy factor. For example, a data center that is only two-thirds full has a 50% higher Opex. Taking case B above but with a 50% occupancy factor, data center costs completely dominate the cost (Figure 6.3), with only 25% of total cost related to the server. Given the need for slack power just discussed, this case is not as far-fetched as it may sound. Thus, improving actual data center usage (using power capping, for example) can substantially reduce real-world data center costs. In absolute dollars, the server TCO in a completely full data center is $6,310 versus $8,981 in a half-full data center—all that for a server that we assumed cost just $2,000 to purchase!

Partially used servers also affect operational costs in a positive way because the servers use less power. Of course, the savings are questionable because the applications running on those servers are likely to produce less value. Our TCO model cannot capture this effect because it is based on the cost of the physical infrastructure only and excludes the application running on this hardware. To measure this end-to-end performance, we can measure a proxy for application value (for example, the number of bank transactions completed or the number of web searches) and divide the TCO by that number. For example, if we had a data center costing $1 million per month and completing 100 million transactions per month, the cost per transaction would be 1 cent. On the other hand, if traffic is lower at one month and we complete only 50 million transactions, the cost per transaction doubles to 2 cents. In this chapter, we have focused exclusively on hardware costs, but it is important to keep in mind that, ultimately, software performance and server utilization matter just as much. Such issues are also exacerbated in the context of accelerators that deliver higher value but also incur additional costs for the software ecosystem support.

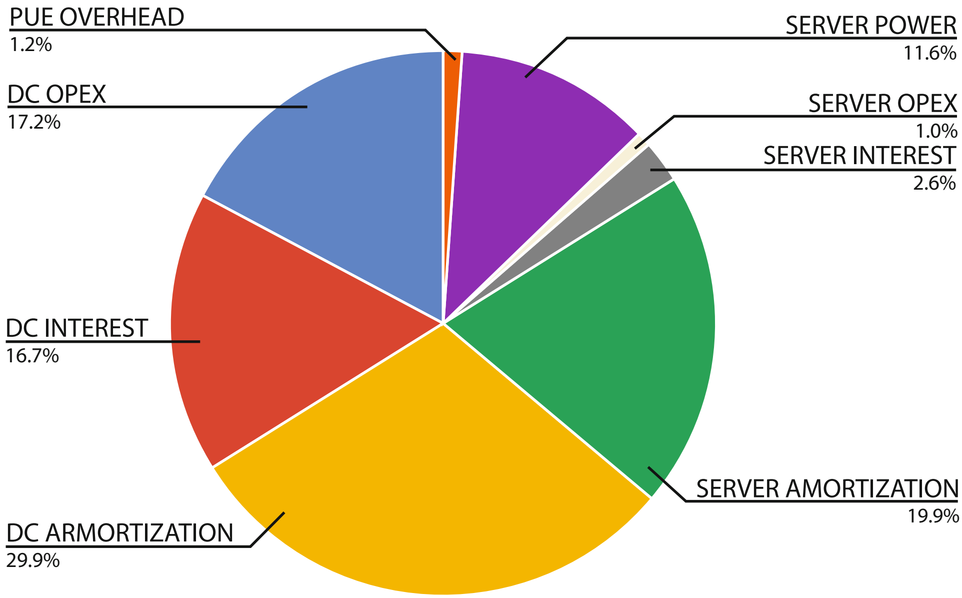

Figure 6.3: TCO case study C (partly filled facility).

6.6 THE COST OF PUBLIC CLOUDS

Instead of building your own data center and server, you can rent a VM from a public cloud provider such as Google's Compute Engine or Amazon's EC2. The Dell server used in our example is roughly comparable to a GCE n1-standard-16 instance, assumed at \$0.76/hr as an on-demand instance, or \$0.34/hr with a 3-year commitment.

Before we compare these with our cost model, consider the two very different pricing plans. Spot pricing is "pay-as-you-go." You can start and stop a VM at any time, so if you need one for only a few days a year, on-demand pricing will be vastly cheaper than other alternatives. For example, you may need two servers to handle your peak load for six hours per day on weekdays, and one server during the rest of the year. With a spot instance, you pay for only 30 hr per week vs. 168 hr if you owned the server. However, spot instances are fairly expensive: at \$0.76/hr, using one for three years at full price will cost \$19,972, vs. roughly \$8,000 for an owned server. (Note, however, that this does not burden the costs for other factors like utilization as discussed earlier.)

If you need a server for an extended period, public cloud providers will lower the hourly price in exchange for a long-term commitment and an upfront fee. Using the previous three-year contract as an example, a fully utilized instance would cost $8,987, about 45% of what you would pay for an on-demand instance for three years. This is competitive with the cost of an owned machine, possibly even cheaper since you could further reduce your cost in case you didn't need the server after year two.

How can a public cloud provider (who must make a profit on these prices) compete with your in-house costs? In one word: scale. As discussed in this chapter, many operational expenses are relatively independent of the size of the data center: if you want a security guard or a facilities technician on-site 24x7, the cost is the same whether your site is 1 MW or 5 MW. Furthermore, a cloud provider's capital expenses for servers and buildings likely are lower than yours, since they buy (and build) in volume. Google, for example, designs its own servers and data centers to reduce cost.

Why are on-demand instances so much more expensive? Since the cloud provider doesn't know whether you're going to need a server, it keeps additional servers ready in case someone wants them. Thus, the utilization of the server pool used for on-demand instances is substantially below 100% on average. For example, if the typical on-demand instance covers the six hours a day when traffic peaks, their utilization will be 25%, and thus their cost per hour is four times higher than that of a "baseload" instance that runs 24 hr a day.

Many cloud providers offer sustained use discounts to automatically lower the cost of a VM if it is used more continuously throughout a month. For example (GCE), the first 25% of hours in a given month are charged at the full rate, and afterwards the effective rate decreases successively so that a VM used for the entire month receives a 30% overall discount. Such automatic discounts can simplify planning since there is no need to commit to an annual contract ahead of time.