Measuring Process Performance: Rate, Cost, Quality, and Flexibility

John Hart, September 2016
based on a previous document by Prof. Tim Gutowski

In 2.008, we study a spectrum of manufacturing processes including machining, injection molding, casting, sheet forming, and additive manufacturing. Moreover, many parts and finished products are manufactured using multiple processes. To enable the best selection of individual processes as well as their integration into a manufacturing system, it is important to define attributes by which we can compare performance.

The goal of this document is to introduce the "big four" attributes of process performance that we discuss in 2.008: **Rate (R), Cost (C), Quality (Q), and Flexibility (F)**. Undoubtedly, other attributes such as environmental impact are important, and some decisions are constrained by specific needs (e.g. materials, existing infrastructure). However, we will keep it straightforward for now, and provide more detail as we learn about each process. The basic **R/C/Q/F** framework will prove to be very useful (and hopefully will become intuitive) when evaluating the quantitative and qualitative performance of any manufacturing process.

1. Rate

The rate metric provides a measure of how quickly a process takes place. At the machine level, rate can be reported as the number of parts or unit operations that can be completed in a given unit of time. Alternatively, rate may be reported as the cycle time, or the time it takes to complete one part or process a unit volume of material (e.g., the material removal rate in milling). A faster rate is typically more attractive when comparing processes, notwithstanding attributes that may suffer if rate is increased (e.g., tool life, dimensional quality). The rate for a given process depends on the process physics as well as on the specific part design and equipment capabilities.

For example, in 2.008, we will find that a typical cycle time for injection molding of a thermoplastic yo-yo body part is approximately 30 seconds; specifically, this is for a polypropylene shell roughly 1 in^3 (16 cm^3) in volume or 0.5 ounces (0.14 N) by weight. Conversely, machining your paperweight will take approximately 15 minutes and produce an aluminum part that is less than 4.5 cubic inches (74 cm^3) and 7 ounces (1.94 N). The actual machining time will depend on the amount of material removed and the desired precision. Additionally, injection molding produces a near net-shape part by melting and forming the plastic, whereas machining may require significant material removal to obtain the desired product. Machining is, by its nature, a serial process, and therefore is a slower process than a forming operation that forms the shape in one operation.

Looking more closely at what determines the rate of injection molding, we find that each step in the process cycle contributes measurably to the cycle time, as depicted in Fig. 1. That said, the cooling time is often the largest contributor to the total cycle time. This is because the process must wait for the plastic inside the mold to cool to below its glass transition temperature in order for it to retain its shape after ejection from the mold.

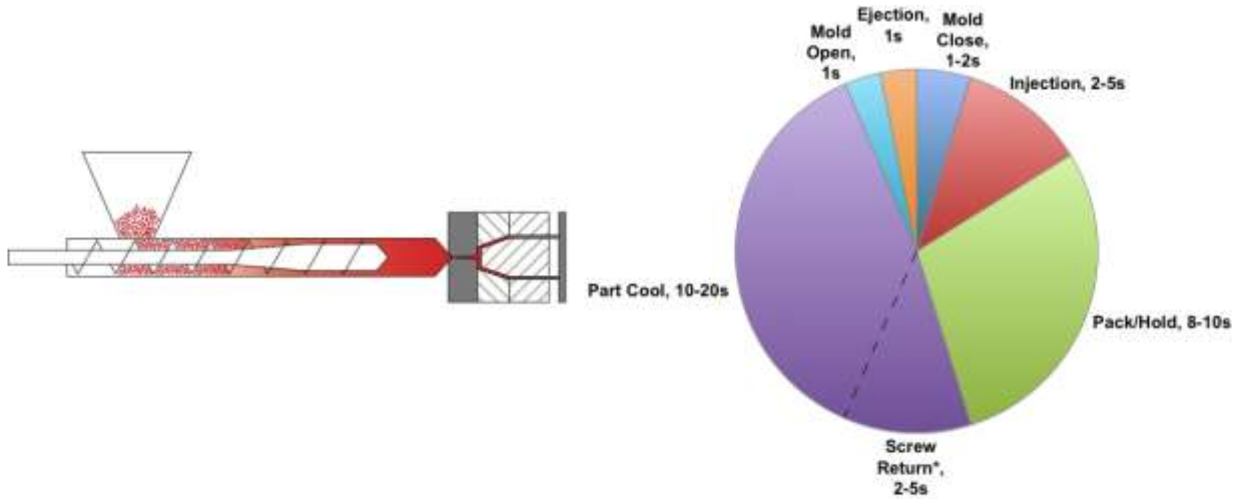

Figure 1: Typical injection molding cycle, note that the screw return which prepares the next shot occurs during mold cooling and does not add to the total time.

2. Cost

The cost of manufacturing a product is often a major component of its sales price; as a result, understanding the cost drivers of each process is essential to understanding the influence of design on manufacturability. To assess the cost associated with a particular process, expenses incurred can be classified into two categories: fixed costs and variables costs. Fixed costs, F, are defined as one-time expenditures typically consisting of the price of the equipment, tooling costs, and set-up or installation costs. Variable costs, V, are those recurring expenses required for making each part. These encompass the raw materials (including any scrap and associated disposal costs), labor costs tied to direct worker interaction with the process, as well as somewhat less tangible 'overhead' costs including energy consumption, rent, and other fees tied to running a company. Total manufacturing expenses (C) for production of N parts may then be approximated by the simple equation

$$C = F + V \cdot N \tag{1}$$

$$C/N = F/N + V \tag{2}$$

By this definition, the unit cost for each part decreases as production increases (Fig. 2). In fact, as the number of units, N, tends toward infinity, the cost tends asymptotically to V, the variable cost. Large fixed or start-up costs are major barriers to starting a manufacturing-based business. For example, the cost of a high-quality injection mold tool along with the machine can be \$10's to \$100's of thousands. As a result, except for large companies it is typical to seek 'contract' manufacturing; however, the high cost of tooling requires that a large production volume be guaranteed in order to place an order and eventually make a profit from sales of the product. As we will discuss later, the flexibility of additive manufacturing allows low-volume manufacturing without such significant tooling costs, though at present additive manufacturing does not offer the quality of most traditional processes.

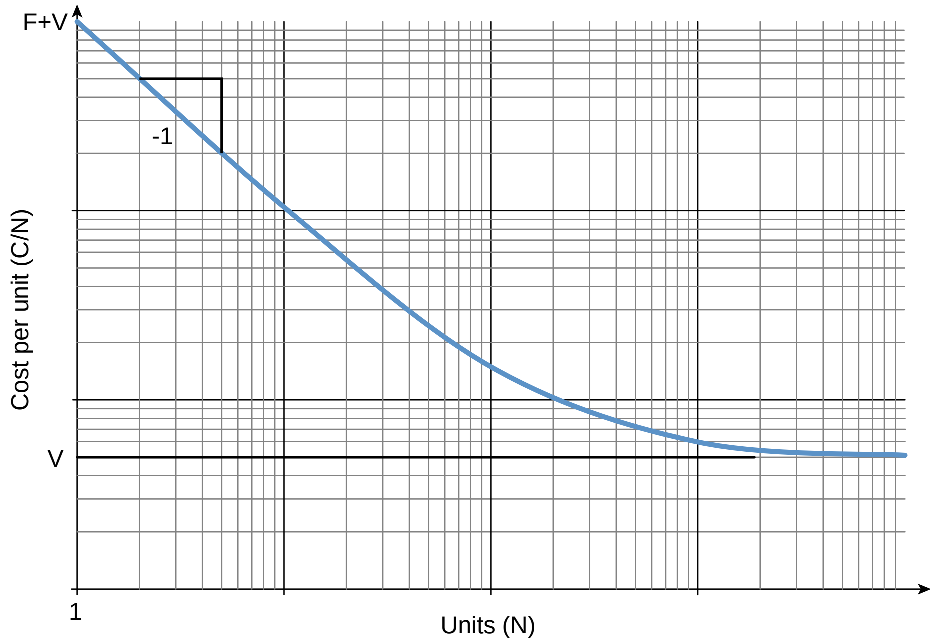

Figure 2: General relationship between manufacturing cost per part and production volume.

3. Quality

The quality a consumer perceives in a finished product may be influenced by many factors: durability, aesthetic appeal, etc. These attributes are often subjective, and as the saying goes, you can't please everyone (Fig. 3). From the process perspective, quality can be measured as the ability to hit a specific 'target', and this can be defined by technical metrics such as dimensional quality and surface finish, or end use functionality and durability.

In 2.008, our target for quality is typically given by a set of product characteristics along with tolerances or bounds on dimensions. In the lectures and projects, we will focus mostly on critical dimensions as measures of quality, because dimensions can be measured and their values can be related to the process physics that we study. We also learn that it is impossible to hit a target exactly every time due to inherent variability in a process such as the shrinkage of injection molded plastic and springback in sheetmetal forming. Variation in raw material can also influence process outcomes, such as a slight change in the melting temperature of plastic pellets or slight differences in the Young's modulus and yield stress of aluminum from one batch to the next.

With these sources of error beyond the reach of a manufacturing facility, it is important to understand and quantify process variation, which lets us monitor the quality of the output product and know when we exceed the acceptable bounds of variation. As will be seen later in 2.008, the most common way to measure process capability is by tracking of critical dimensions and applying statistical analysis to the data, assuming it is normally distributed (Fig. 4). One basic metric for process precision is the standard deviation (σ, sigma). If tolerances span three standard deviations on either side of a target, 99.73% of parts produced should fall within the specification limit. Pushing this further, some companies try and double the range, 'six-sigma,' aiming to reduce the number of defective parts to approximately two per billion (!) for products such as jet engine components that must have extremely high reliability.

Figure 3: Defects in m&m's (left) typical sample of plain m&m's; (center) defects in the placement of the 'm' including a misprint and off-center placement; (right) a misshapen m&m.

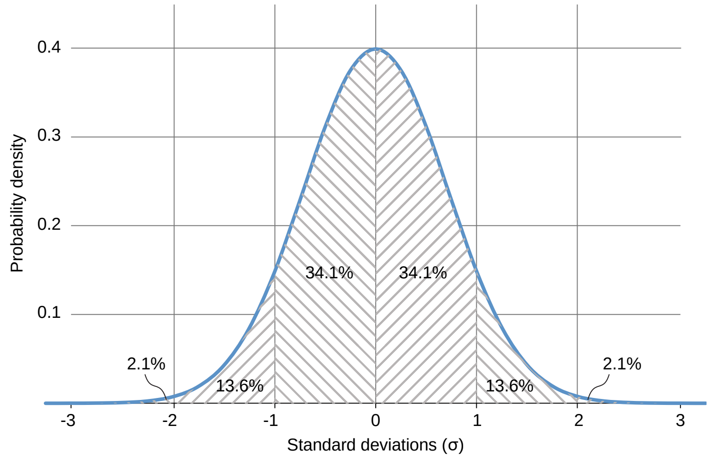

Figure 4: Normal distribution.

4. Flexibility

The final of the 'big four' attributes is flexibility. Flexibility in manufacturing is the ease with which a process can be adapted to produce a different part or design. There is not a convenient quantitative metric for flexibility, yet we can say that a more flexible process requires a lower cost and/or a shorter amount of time to adapt to a new part design than a less flexible process.

As an example of process flexibility, consider machining. With one machine, and the same tooling (e.g., a series of end mills), a variety of geometries may be manufactured from a variety of metals, simply by changing the CNC toolpath and workpiece size which may be done easily. In comparison, injection molding is less flexible than machining because a custom mold is needed to create a different part geometry. Additive manufacturing, ideally, provides the ultimate flexibility to make a single unique design or a large number of identical parts without requiring dedicate tooling or changes in the machine setup. An example is shown by the titanium aircraft brackets designed to leverage the capabilities of additive manufacturing (Fig. 5).

Figure 5: Titanium aircraft bracket produced using (left) conventional manufacturing and (right) additive manufacturing enabling the incorporation of internal cavities that reduce weight while meeting the load requirements (Image ©2016 General Electric Company).

5. Tradeoffs

As we learn about unit manufacturing processes along with system-level issues, we will realize that rate, quality, cost, and flexibility are typically coupled. As you might imagine, increasing the accuracy or precision of a process (i.e., the quality) often involves a decrease in rate or an increase in cost. Likewise, a more flexible process such as additive manufacturing or machining may have a higher cost than a less flexible process such as injection molding that is suited for high volume production. And this interrelation can be seen in many products. When we look at a product and wonder "how can this be so inexpensive?!" it is most likely because the processes and the operation of the manufacturing system is highly refined. Therefore, in 2.008 we wish to understand how the fundamentals of each process governs its performance in terms of the four attributes, and how we can select the best process for a given part in light of design requirements and performance tradeoffs (Fig. 6).

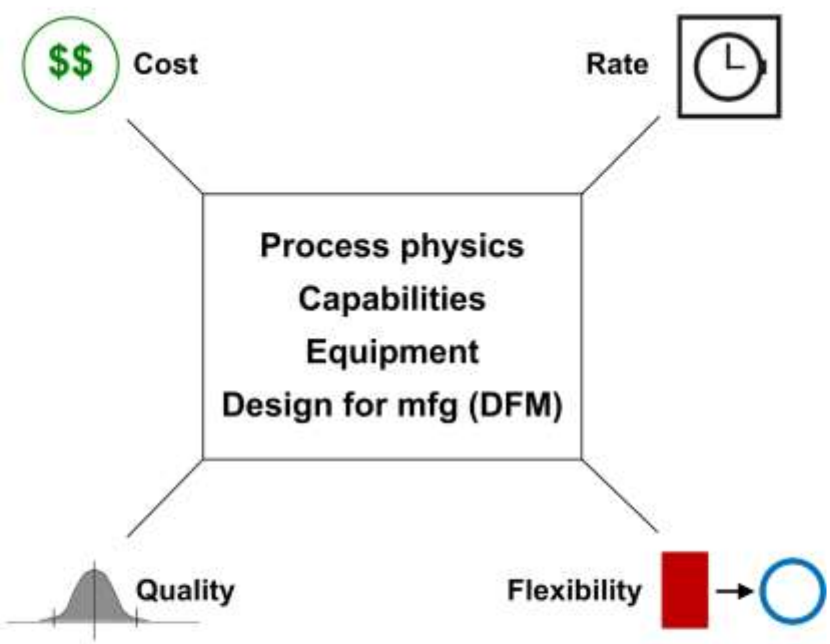

Figure 6: Summary of the four attributes and interrelated considerations that can be considered for any manufacturing process.