Cost and Energy Consumption Optimization of Product Manufacture in a Flexible Manufacturing System

Nancy Diaz and David Dornfeld

Laboratory for Manufacturing and Sustainability, University of California at Berkeley, USA

Abstract

A manufacturing system for discrete part production under flexible process routings is studied for the reduction of cost and energy. Focus is centered on the process planning stage for product manufacture, i.e. machine tool selection. Machine tool scheduling was implemented in a discrete-event simulation environment for the evaluation of several scenarios in which the number of machines tools in a manufacturing cell was varied. Cost was found to be dominated by labor rate and processing time, whereas the energy consumption for the best case scenario was reduced by 8.5% for the production of 1000 parts.

Keywords:

Process Planning; Machining; Cost; Energy; Flexible Manufacturing

1 INTRODUCTION

Process planners typically take into consideration customer satisfaction, worker safety, profit maximization, and machine tool availability when determining the optimal process plan for part manufacture. It is becoming increasingly important, though, for manufacturing facilities to account for the environmental impact of part production as concern for resource availability grows.

The research presented herein outlines a methodology for optimizing for cost and environmental impact of a flexible manufacturing system. Previous work in sustainable manufacturing at the facility level is limited, as the majority of facility-level optimization is focused on costing. Research accounting for the environmental impact at the facility-level include Fang, et al. who studied the energy consumption and peak power demanded by a two machine job shop [1], Heilala, et al. who developed a simulation tool for optimizing between production efficiency and environmental impact, using a toy manufacturing plant as a case study [2], and Johansson, et al. who showed how discrete-event simulation (DES) and life-cycle assessment can be combined to evaluate the performance of a manufacturing system with the exemplary case study of a paint shop [3].

These studies though either focused on the manufacture of one type of product, manufacturing with preset processing conditions and equipment, or both. Since products evolve over time and some facilities manufacture a high mix of products at a range of processing conditions, methods must be developed to assess the environmental impact of a facility to more accurately characterize operations by moving away from a deterministic approach to environmental impact assessments.

2 PROCESS PLANNING

Simple part features requiring milling can typically be produced by a wide array of Computer Numerical Control (CNC) machine tools. A job shop is an example of a facility that produces a high mix of specialty parts that can be produced by a variety of machine tools. In such a manufacturing environment operators require a high worker skill level and the facility is set up such that it has flexibility in production so a layout organized by manufacturing process is commonly utilized [4]. The production of parts undergoing routing flexibility is the focus of this research.

When routing flexibility exists within a facility, a process planner defines the optimal route for production. Process planning can be broken down into the following steps adapted from Scallan [5]:

1. interpret the engineering drawing,
2. select the appropriate workpiece material and manufacturing process(es),
3. select the machine tool(s) and processing condition(s),
4. select the workholding device(s),
5. develop quality assurance method(s),
6. estimate the cost to produce the product(s), and
7. document the process plan.

The customer provides an engineering drawing which is interpreted by the process planner in order to recommend the appropriate type of workpiece material, size, and shape to use and manufacturing process(es) to produce the part. These factors are typically dictated by part characteristics including the types of features and tolerance specifications. Once the manufacturing process(es) are selected, the optimal machine tool is selected; variables taken into consideration include machine tool availability and work volume, the precision necessary to meet the part tolerance, and the power of the spindle motor.

The process planner or a separate toolpath planner designs the toolpath and selects the tooling and optimal process conditions. If the planners are optimizing for say process time, they may first design the toolpath, recommend process conditions, then select the machine tool to manufacture the part, thus taking a bottom-up approach. Alternatively, they may take a top-down approach and first select a machine tool, then determine the optimal toolpath and process parameters if, for example, the spindle motor or work volume is a critical factor. This particular step of process planning can have interdependencies (see Figure 1, below).

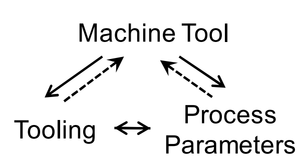

Figure 1: Dependencies of machine tool selection criteria.

Once the machine tool is selected and the toolpath and process conditions are defined, the workholding devices are selected. Thereafter, quality assurance methods are developed. Finally, the cost of production can be estimated and the final process plan is documented.

In a flexible manufacturing system the greatest flexibility in the process plan lies in step 3 - selecting the machine tool, tool path, and process conditions. The primary step in the optimization for cost and environmental impact will therefore be taken to be in choosing the appropriate machine tool.

3 METHODS

3.1 Costing of Machine Tool Operation

The components which comprise the life-cycle cost of machining were identified by Enparantza, et al. in [6] and summarized below in Table 1.

Life-Cycle Phase	Factor
Acquisition	*Purchase* Purchase Price Shipping *Install/Setup* Support Equipment Training
Use	*Operation* Direct Labor Utilities Consumables Jig Tools Waste *Maintenance* Preventative Corrective
End-of-Life	Resell Recycle Dispose

Table 1: Machine tool costing factors adapted from [6]

The cost to purchase and install a machine tool, $c_{acquisition}$, must be amortized over the functional life of the machine tool, t_{life}. The part processing time, $t_{process}$,(a parameter dictated by the toolpath) was assumed to be independent of the type of machine tool used to manufacture the part.

$$C_{acquisition} = c_{acquisition} * \frac{t_{process}}{t_{life}} \quad (1)$$

Throughout the ownership of the machine tool, the primary factors taken into consideration were direct labor and electricity costs. Labor costs are directly proportional to the processing time and the labor rate, c_{labor}, as seen below in Equation 2.

$$C_{labor} = c_{labor} * t_{process} \quad (2)$$

The cost of the electricity to power the machine tool is a function of the electricity rate, c_{elec}, idle power, P_{idle}, idle time of the machine tool, t_{idle}, process power, $P_{process}$, and the process time, $t_{process}$.

$$C_{elec} = c_{elec} * (P_{idle} * t_{idle} + P_{process} * t_{process}) \quad (3)$$

The cost of shared consumables such as cutting tools, maintenance oil, coolant, and water were neglected since these resources would be amortized over the parts produced by the facility. Facility overhead and holding costs were also neglected since they are independent of the type of machine tool used.

Maintenance cost depends on the type of machine tool and how it is used throughout its life-time. A comprehensive life-cycle cost analysis of machining which includes maintenance cost is presented in [7], but the ownership cost presented herein focuses solely on labor and electricity since historical data is not available for the machine tools under study.

Pertaining to the end-of-life of a machine tool, manufacturing facilities that must maintain flexibility in the capability of their production equipment typically choose to resell their used machine tools when they seek a replacement [8]. Upgrading or remanufacturing the same machine tool is generally not a cost-effective solution because of the significant advances in machine tool technology, specifically the controller, achieved over its useful life as is the case with many products requiring electrical power [9]. Since the end-of-life costs or profits are amortized over the functional life of the machine tool, the end-of-life impact remains negligible and the total cost will be represented by Equation 4.

$$C_{total} = C_{acquisition} + C_{labor} + C_{elec} \quad (4)$$

The cost of acquiring the machine tools was assumed to range between \$100,000 and \$200,000, each with an assumed functional life of 15 years. A labor rate of \$40/hour and an electricity rate of \$0.12/kW-hr were used.

Though the acquisition cost of the machine tool is sizable, since the acquisition cost was amortized over the functional life it had a negligible impact. Even when a low utilization of the machine tool is assumed, i.e. if the machine tool was only utilized for part processing 30% of the time throughout its functional life, the acquisition cost would still be negligible relative to the cost of ownership. Reducing the functional life from 15 to 10 years also showed a negligible change in specific cost of machining.

During the use phase, the cost of electricity relative to the cost of labor was extremely low, so the labor rate naturally overshadowed electrical energy costs. The overall cost was therefore dominated by processing time and the labor rate. In strategizing for cost reduction, since labor rate is fixed one should target a reduction in processing time, which can be achieved with proper tooling so as to maintain optimal cutting conditions. If this approach were taken though the cutting tool price should be accounted for as well.

3.2 Environmental Impact

The use phase of a machine tool has been shown to have the greatest environmental impact, even in facilities with a low utilization of the machine tools [8]. The principal resources consumed during machine tool operation include electrical energy, water, cutting fluid, cutting tools, and workpiece material [10]. This research focuses on the use of electrical energy to power machine tools. The energy consumption associated with the manufacture of cutting fluids was found to be negligible by [11] and the environmental impact concerning the raw material extraction is typically sizable, but since the material type is generally dictated by the product designer it is outside of the scope of decisions that can be made by the manufacturer.

It was previously shown by Diaz that the energy consumed by a machine tool could be characterized with the following model:

$$E_{process} = (K * \frac{1}{MRR} + b) * V \quad (5)$$

where K and b are the specific energy constants, MRR is the material removal rate and V the volume of material removed [12].

The energy consumed by CNC machine tools has an inverse relationship with the material removal rate (MRR) because these machine tools have a high tare power demand [13], [14]. That is, even in standby mode when the machine tool is not processing parts the machine tool still demands a significant amount of power. Thus, the electrical energy consumption for any given machine tool is dominated by the time required to process the part when optimal cutting conditions are used as shown by Diaz, et al. [14].

3.3 Characterization of Part Processing

Discrete-event simulation was used to model the processing of three types of parts in a flexible manufacturing facility, labeled generically types A, B, and C and produced in proportions of 45%, 30%, and 25%, respectively. Parts were modeled as having exponentially distributed interarrival times with a mean interarrival time of 10 minutes. They were processed using a first-in-first-out (FIFO) queuing discipline in a multi-server queuing model as shown below in Figure 2.

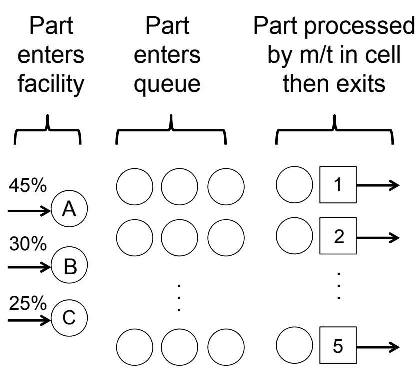

Figure 2: Part queuing in model of facility operations.

The machine tools capable of producing the different part types were limited to the cell constraints in Table 2. That is, part type A could be produced with a machine tool from cell in M1, M2, M3, or M4 while part type C could only be produced by a machine tool in cell M5 (i.e. a micromachining center).

Type	Cell Constraints	MRR (mm^3/s)	$t_{process}$ (min)
A	M1, M2, M3, or M4	500 to 600	45 to 50
B	M2, M4, or M5	305 to 350	95 to 105
C	M5	0.75 to 1.75	120 to 135

Table 2: Uniformly distributed part processing parameters.

The MRR's followed the cell constraints and machine tool capabilities. The MRR and the processing time remained constant throughout the production of any given part. However, these parameters were uniformly distributed over the ranges outlined in Table 2 for each part type. Therefore, the facility produced a highly diverse mix of products.

3.4 Machine Tool Selection Criteria

Since the parts could be produced by a range of machine tools, the machine tool selection criteria will be based on the cost and energy optimization strategy. The machine tool cost was found to be dominated by labor and therefore proportional to process time. Given that the process time is currently independent of the type of machine tool being used, the cost was assumed to remain constant for the production of a part. Thus, the type of machine tool used to produce the part was chosen such that the energy consumed during machining was reduced.

The machine tool cells provided in Table 3 assumed to be available at the facility. Distinctions were made as to whether or not the cell operated under dry or wet cutting conditions since the processing energy consumption is affected by such conditions. The cells were preferred in the following order based on lowest processing energy consumption: M1, M3, M2, M5, and M4, i.e. a machine tool in cell M1 consumed the lowest energy while processing parts at a particular MRR and one in cell M4 consumed the highest energy at the same MRR.

	Machining Center	K [J/s]	b [J/mm^3]	P_{idle} [W]
M1	Fadal VMC 4020 (Dry)	1330	2.845	740
M2	Fadal VMC 4020 (Wet)	1396	3.082	740
M3	Mori Seiki DV 5500 (Dry)	1344	2.830	1020
M4	Mori Seiki DV 5500 (Wet)	2019	2.953	1020
M5	Mori Seiki NVD 1500 (Wet)	1481	3.678	924

Table 3: Parameters for process energy and idle power demand [14]-[15] for machine tool cells M1-M5.

The strategy utilized for machine tool scheduling was based on the cell constraints outlined in Table 2 and the cell ranking based on lowest process energy consumption. The DES model tracked the number of available machine tools within a cell rather than the availability of each individual machine tool. If no machine tool was readily available to start production then the part entered the shortest queue (see Figure 3 where *MaxG* is the number of cells in the facility, and i and j iterate through the number of machine tool (m/t) cells).

This machine tool selection strategy gives preference to high machine tool utilization so as to avoid the consumption of energy for non-value added time during idling. Alternative strategies can be studied such as reducing the overall time spent in the facility (processing and wait time) or prioritizing parts in queues based on expected processing energy consumption or lead time. Since flexible manufacturing facilities such as job shops underutilize machine tools, it is also important to consider if it would be more beneficial for a part to wait for a less energy intensive machine tool to become available rather than immediately start production at an available machine tool, especially if the part has a long processing time. Such a part scheduling strategy will be studied in future work.

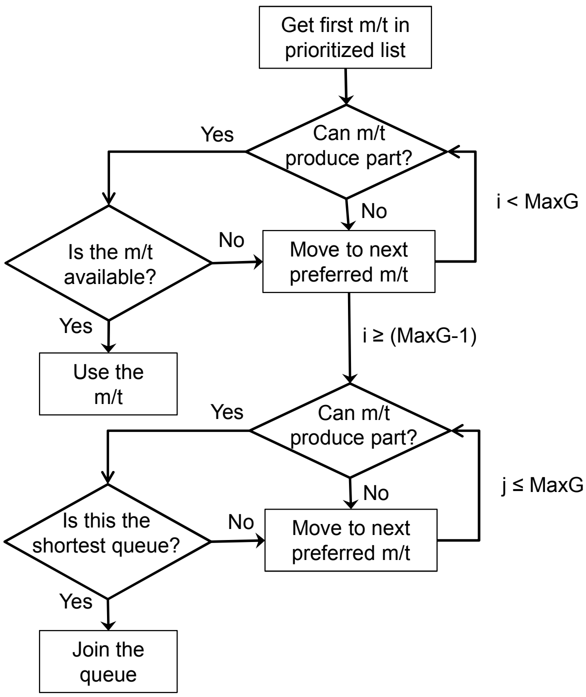

Figure 3: Machine tool selection decision tree.

4 RESULTS AND DISCUSSION

4.1 Machine Tool Cost and Energy Consumption

The production of 1000 parts was first simulated for a facility with 11 machine tools (see case 1 in Table 4). The DES model allowed for cost and energy accounting at the part, cell, and facility level, information that was used to make informed decisions about cell modification by considering underutilized and energy-intensive machine tools.

Machine tool operation cost the manufacturing facility a total of $52,801 with the process planning strategy outlined in Figure 3. The total energy consumed by the five manufacturing cells amounted to 11.85 GJ, 92.8% of which was used for process energy and the remaining 7.2% for idle energy (see Figure 4). Details regarding the further breakdown of the idle energy consumption are included; note that cells M1, M2, and M5 consumed the greatest proportions of idle energy consumption - information that was used in planning the alternative cell designs.

The energy consumption for a total of seven scenarios (each with a different number of machine tools in each cell) was estimated. Table 4 shows the number of machine tools in each cell for each case. The baseline, case 1, had 11 machine tools in total and the

	Case 1*	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
M1	3	2	3	3	2	2	1
M2	2	2	2	1	2	2	2
M3	1	1	1	1	1	1	1
M4	1	1	0	0	0	0	0
M5	4	4	4	4	4	3	3

Table 4: Number of machine tools in each manufacturing cell for cases 1-7 where (*) represents the base case.

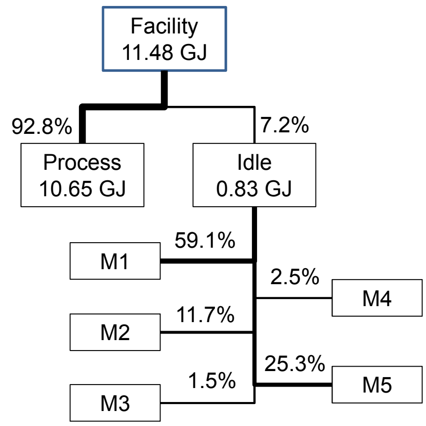

Figure 4: Breakdown of machine tool energy consumption.

cases thereafter had between one and four fewer machine tools. The cells that were altered in this study relative to the base case are highlighted in gray.

The Fadal VMC 4020 under dry cutting conditions (cell M1) had the largest fraction of idle energy consumption. Therefore, one machine tool was first removed from cell M1 in case 2. One or more machine tools from cell M1 were also removed in cases 5, 6, and 7. The Mori Seiki DV 5500 from cell M4 was also removed in cases 3-7 since this machine tool consumed the greatest electrical energy during processing under wet cutting conditions. Lastly, the number of machine tools in cells M2 and M5 were varied since these cells had the second largest fraction of idle energy consumption in the baseline scenario.

The cost of machine tool operation changed only slightly in the evaluation of cases 1-7, ranging from $52,769 to $52,814 for the production of 1000 parts. This is so because the labor rate and process time dominated the cost, rather than the type of machine tool used. The greatest cost savings relative to the original configuration of the manufacturing cells was only 0.06% in case 7.

The energy saved for the scenarios presented are shown in Figures 5 and 6, below. Case 4 is the only scenario that consumes more energy than the baseline. 11.1% of the total energy consumed by the machine tools (11.88 GJ) was spent on idling machine tools. The idle energy consumption increased relative to the baseline case when a machine tool from cells M2 and M4 were removed in case 4 due to part queuing.

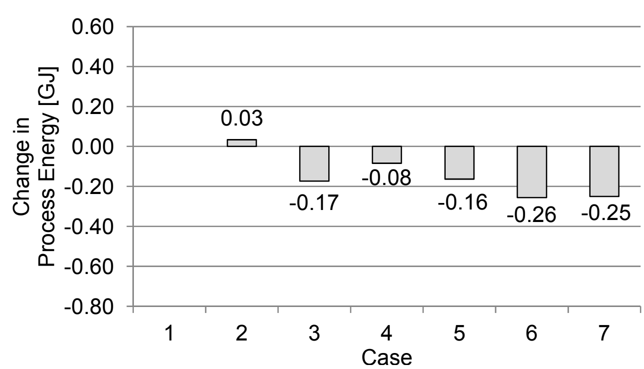

Figure 5: Change in process energy consumed relative to case 1.

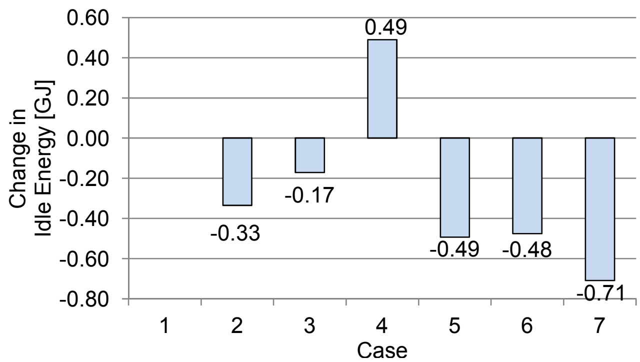

Figure 6: Change in idle energy consumed relative to case 1.

4.2 Part Queuing

Wait time, the time that a part spends waiting in a queue, was calculated for the seven cases and is depicted below in Figure 7. The first-quartile, median, third-quartile, maximum, and average wait times are shown. Since setup time was ignored in this analysis, the minimum wait time in all cases is zero because a fraction of the parts begin the processing stage immediately if a machine tool is available.

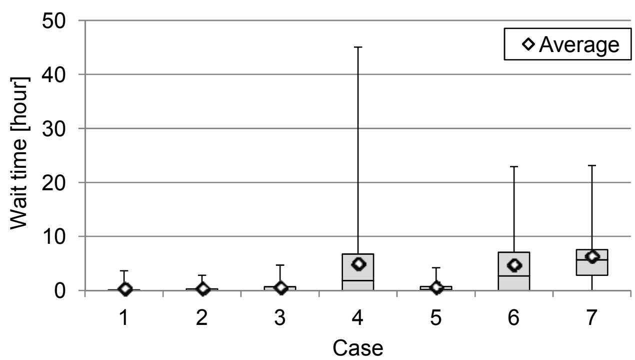

Figure 7: Variation of part wait time by case.

The greatest variability in wait times occurred in cases 4, 6, and 7. These cases also have the highest overall wait times. The variability is caused by the constraints on part production, i.e. parts are restricted to a set of machine tools for production. So when a machine tool is removed from a cell that is highly utilized the queue length grows, at times, at an unstable rate.

For example, in case 4 the removal of a machine tool in cells M2 and M4 caused a sharp increase in wait time since part types A and B are both processed by this cell and they comprise 75% of the total parts. The cause for the variability in wait time in cases 6 and 7 is similar. Cell M5 processes many parts so when a machine tool is removed from this cell, the wait time grows and the rest of the cells are spent in idle mode as the cell finishes its queue. So although cases 6 and 7, in particular, had lower overall machine tool energy consumption when accounting for processing and idle electrical energy consumed, the parts spend a longer period of time in the facility. Thus, if overhead and holding costs were incorporated to determine the facility-wide energy consumption these cases may not in fact be ideal scenarios.

In order to determine the ideal resources for the facility, aside from concentrating on lowest energy consumed the stability of queues should be accounted for as well. In this example, cases 1, 2, 3, and 5 had stable queues. Of these scenarios, case 5 had the lowest overall energy consumption and would therefore be the recommended option for the design of the facility.

5 CONCLUSIONS AND FUTURE WORK

A methodology was presented for modeling the operation of a flexible manufacturing system for seven cases. While the difference in cost for the scenarios was negligible, the energy consumption for processing parts and idling machine tools varied significantly with savings of up to 8.53% relative to the baseline, case 1, for the cell organization of case 7. Taking into consideration the stability of the cell queues, case 5 was the most promising with energy reductions of 6.37% as well as stable queues.

Future research should focus on varying machine tool selection strategies and accounting for the machine tool's performance and other capabilities. Some machine tools may be able to produce a given part at an improved (lower) processing time. This would prove to be important not only for reducing the energy consumption, but for cost reductions as well. Additional work will also focus on the variability of MRR during part production caused by the inherent complexity of toolpaths.

The methodology for cost and energy consumption optimization utilizing DES modeling was presented for a manufacturing facility with high product variability and a relatively low volume of production. However, the simulation of a facility with a low mix, high volume of parts can be accomplished as well by increasing the interarrival rate and reducing the number of part types produced.

6 ACKNOWLEDGMENTS

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