Session 2457

Toward Complete, Coherent Production System Design Experiences

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Abstract

A need existed for students to have access to complete, coherent system design experiences that helped them better understand basic system design ideas and better integrate tools and techniques in the design process. Students were first introduced to basic concepts and relationships of production system dynamics. They were then given a series of four related design problems in which they could change system variables to achieve desired cycle time, throughput, or work in process levels. Each change carried with it a different cost and limit. The challenge was to stay within budget and maximize performance against objectives. Along with the design itself, students submitted a management report and an academic report.

Introduction

This paper describes a set of computer-based design experiences in the area of production system design and improvement. A need existed for students to have access to complete, coherent system design experiences that helped them better understand basic system design ideas and better integrate tools and techniques in the design process. The effort described in this paper was a first attempt to create those experiences in a senior-level course, Production Systems Design.

The paper begins with a brief description of the course and its objectives. Next, the learning context is described, followed by the general framework used for each design experience. Individual design experiences are then described. The paper concludes with lessons learned and future improvements planned.

Production Systems Design and Manufacturing Systems Engineering

The course, Production Systems Design, is a four credit hour course (two design credits) that focuses on planning the overall production process and designing the workplace in a discrete part production environment. Given a scenario that describes an organization's competitive goals, its products and process flows, and its available production technology, students are expected to:

- Apply a production systems design methodology, tools and techniques;
- Calculate product demand and determine resource requirements;
- Design the physical arrangement of a production system;
- Analyze and evaluate system design in terms of performance measures;
- Provide justification for proposed changes to baseline methods of operation; and
- Develop an implementation plan for the proposed production system design.

Topical coverage includes production system design methodologies, establishing competitive priorities, time-based manufacturing strategies, quantitative analysis of operational performance, facilities layout, and methods engineering. Also, key factors that influence the effectiveness, efficiency, and productivity of production systems are explored.

Students who take Production Systems Design are (typically) graduating seniors enrolled in the Manufacturing Systems Engineering degree program. This degree program focuses on the specification of manufacturing machines and their use. Core courses include those necessary to sufficiently understand, specify, implement, and evaluate operator-machine-workpiece interfaces. Besides Production Systems Design, students complete a variety of mechanical, chemical, and thermal materials processing courses, Ergonomics, Simulation, Design for Manufacturing and Assembly, and Computer Integrated Manufacturing. Supplementing these core courses are electives designed to further strengthen knowledge and skills in materials, manufacturing processes, quality, and manufacturing economics. Before enrolling in Production Systems Design most students have taken Ergonomics and Simulation, and all have taken Production Planning and Inventory Control, a course prerequisite. In addition, most students take Design for Manufacturing and Assembly and Computer Integrated Manufacturing during the same academic section as Production Systems Design.

For years Production System Design was taught as a combination facilities design-methods engineering course. Design problems were limited to those solved using paper, pencil, and a calculator. During the past two years, Professor Rod Johnson expanded topical coverage and incorporated computer-based design tools into the course, specifically FactoryCad, FactoryFlow, and FactoryPlan. These tools were used in a semester design project. Because the course had no official textbook, Professor Johnson also developed a set of lecture note handouts for student use. I followed Professor Johnson's approach when teaching the course this past summer. I then began to integrate into the course the design experiences described in this paper when teaching the course this fall.

The Learning Context

Students' academic workloads and learning attitudes led to and influenced the development of the student design experiences created for Production Systems Design. All students alternate between work and school in 12 week sections. At the classroom level this translates into an accelerated semester: the instructor and student must cover in eleven weeks what a traditional semester-based system covers in 15 (excluding final exam week). Most students take six courses each academic section; a few students take seven or eight courses. During the senior year, design credits comprise 30-50% of total credit hours. These design credits tend to be earned through semester projects, projects that aren't usually assigned until halfway through the academic section. Finding students who have four design projects due the tenth or eleventh week of each academic section is not unusual. Student burnout becomes noticeable to instructors by the sixth or seventh week; by tenth week, covering new material generally proves both inefficient and ineffective.

The workload described above creates a situation familiar to educators, but perhaps more severe here. First, students perceive themselves as having little if any time to think about underlying ideas, ponder the meaning of answers found at the end of equations, or prepare for class simply for its sake. Most students run from one graded deadline to the next, trying to maximize either their grade or their grade-to-effort ratio. As the academic section wears on, an instructor can feel as if she or he works in the fast food business. The above situation, however, works counter to the goal of integration.

Second, students look to be trained, not educated. In this regard the managerial ethos seems well ingrained in these students by their senior year. Like many managers, they apply short-sighted thinking under the philosophical banner of pragmatism. Both assigned work and material presented are judged against an application criterion that has a (seemingly) short time horizon attached to it: Can I apply this at work tommorrow? While the variety of co-op employers, employment experiences, and future career plans leads different students to different answers to this question, students press for realism in assignments.

In developing the design experiences for Production Systems Design, the above situation was taken as a given rather than as a variable to be manipulated and changed. Therefore, a decision was made to:

- Develop a series of shorter design experiences that require six to eight hours of effort each rather than one large, end-of-section experience.
- Cast each design experience in the context of a management decision.
- Place all theory and lecture material in the context of these design experiences and require students to apply textbook theory to each design experience.
- Put students in direct competition with one another for design grades and heavily weigh the design experiences (70% of the final course grade) so that students take each design experience seriously.
- Limit design teams to two students to minimize student coordination and group dynamic costs.
- Eliminate longer, comprehensive exams and use shorter quizzes after each design experience to test individual member's subject knowledge and skill.
- Complete all design experiences by the ninth week of the academic section.

General Design Experience Framework

Students were first introduced to basic concepts and relationships of production system dynamics (as opposed to the static case). They then developed a spreadsheet analysis of a simple production system (Figure 1). The basis for the spreadsheet calculations is found in Chapters 8 and 12 of Hopp and Spearman (1996). Students were then given a series of four design problems (discussed below) in which they could change system variables to achieve desired cycle times, throughputs, or work in process levels. Each change carried with it a different cost. The challenge was to maximize performance against certain objectives. These objectives changed from design problem to design problem as did the initial performance values and costs of change. In addition, sometimes a budget was provided; other times the students determined how much the desired change will cost. To make the experience simulate competitive markets, each design team's grade was given as a percentage of their design score relative to the best design score.

Along with the design itself, the students were required to submit a management report and an academic report. The management report was a typed, one page summary written for a management audience. It described the design objectives, the <u>three</u> (minimum) design alternatives considered, the recommended design alternative and its benefits and costs. If the desired design objective could not be achieved for the budgeted amount, or if other constraints needed to be relaxed to achieve it, the students had to describe this reality and demonstrate it as a fourth (or n+1) alternative.

The academic report was a typed, one page description that forced each design team to analyze their design process and thinking: Why should what you did be considered design? (Answers here had to include a definition of design and a breakdown of time spent on each phase of the design process.) What was learned or reinforced through this design experience? (Answers had to discuss specific relationships uncovered.) Would you approach this design problem differently if you had to do it again? What additional data, if any, should be considered? If appropriate, students were to include a discussion of how they dealt with spreadsheet calculation errors or unclear instructions. In addition, the academic report discussed the design score equation and whether it should be maximized or minimized.

A completed exploratory or sensitivity analysis worksheet or spreadsheet was attached to the academic report (Figure 2). The exploratory analysis formed the basis for the design alternatives considered by looking at the effect of a unit change in X on Y and the cost of that change. Students were to tie design alternative justifications directly to this exploratory analysis.

Product	Routing	Avg. Weekly Demand	Avg. Daily Demand	Daily Pieces Started @1	Daily Pieces Started @2	Process Batch Size	Avg. Daily # Process Batches	Move Batch Size	Avg. Daily # Move Batches
M	1-2	250	50	55	52	20	2.8	20	2.6
S	1-2	345	69	76	71	40	1.9	40	1.8

Station	Avg. Raw Process Time (minutes)	Avg. Raw Process Variance	Raw Process CV	Raw Process SCV	Probability of Defect	Process Time (minutes)	1st Adjusted Variance	1st Adjusted CV	1st Adjusted SCV
1	3.00	4.00	0.67	0.44	0.07	3.23	4.73	0.67	0.45
2	4.00	9.00	0.75	0.56	0.03	4.12	9.51	0.75	0.56

Station	MTTF (hours)	MTTR (hours)	Machine Availability	Process Time (minutes)	2nd Adjusted Variance	2nd Adjusted CV	2nd Adjusted SCV
1	160	13	0.92	3.49	414.40	5.84	34.06
2	240	20	0.92	4.47	835.90	6.47	41.88

Station	Average Process Batch Size	Avg. Setup Time (minutes)	Avg. Setup Variance	Process Time (minutes)	3rd Adjusted Variance	3rd Adjusted CV	3rd Adjusted SCV
1	28	40.0	10.0	4.91	469.54	4.41	19.49
2	28	30.0	10.0	5.53	867.08	5.32	28.33

Station	SCVa	Daily Load (jobs/day)	Total Time (hrs/day)	Operator PFD Allow	Available Prod. Time (hrs/day)	Arrival Rate (jobs/hr)
1	1.00	132	8	10%	7.2	18.3
2	8.34	123	8	10%	7.2	17.0

Station	# Machines	Prod. Rate (jobs/hr)	Utilization	SCVd
1	2	24.4	0.75	8.34
2	2	21.7	0.79	15.74

Station	Avg. Move Batch Size	Variability Term	Utilization Term	Capacity Term	CT in Queue (hours)	Wait for Batch (hours)	Process Time (hours)	Move Time (hours)	Avg. Total Cycle Time (hours)
1	28	4.67	2.63	0.041	0.50	2.22	0.08	0.50	3.31
2	28	12.04	3.29	0.046	1.82	2.50	0.09	0.25	4.67
				Totals	**2.33**	**4.73**	**0.17**	**0.75**	**8.0**

Station	Avg. WIP Queue (pcs)	Avg. WIP Machine (pcs)	Avg. WIP Station (pcs)	Avg. WIP Transit (pcs)	Avg. WIP Total (pcs)
1	9.2	42.2	51.4	9.2	60.6
2	31.1	44.3	75.3	4.3	79.6
Totals	**40.3**	**86.5**	**126.7**	**13.4**	**140.2**

Figure 1. Example Steady State Analysis Spreadsheet
(CV = Coefficient of Variation, SCV = Squared Coefficient of Variation)

		Add Machine	Decrease Move Batch	Reduce Raw Process Time	Reduce Set Up Time	Reduce Set Up Variance	Increase MTTF	Decrease MTTR	Improve Quality
	Unit Cost	$3,000	$50	$150	$75	$175	$200	$125	$100
	Unit Change	1.0	5.0	0.1	5.0	10%	10%	10%	0.01
	Limit	1.0	10.0	0.3	10.0	30%	20%	30%	0.03
Station									
1	CT New	7.0	7.2	7.9	7.8	8.0	7.9	7.8	7.9
	$/CT Reduct	$3,000	$63	$1,500	$375	---	$2,000	$625	$1,000
	Design Score*								
2	CT New	6.4	7.7	7.7	7.6	8	7.9	7.8	7.8
	$/CT Reduct	$1,875	$167	$500	$188	---	$2,000	$625	$500
	Design Score*								

* Starting with the 3rd design experience, students calculated design score as part of exploratory analysis.

Figure 2. Example Exploratory Analysis Spreadsheet

Design Experience #1

Design Experience #1 involved a four station, three product production system. Students were asked to reduce average cycle (response) time through all four stations to 16 hours or less (from 28 hours) and maintain daily production throughput requirements. In addition, they could spend no more than $75,000 to achieve the desired cycle time reduction. All three products were routed through all four stations with no backtracking or rework. Design scores were calculated using the following equation:

$$\frac{Budget}{Cost} + \frac{Cycle\ Time_{old}}{Cycle\ Time_{new}} + \frac{WIP_{old}}{WIP_{new}}$$

where WIP represents total, average work-in-process level. The design score was constructed to reinforce Little's Law, the relationship that holds between throughput, work in process, and cycle time. Design grades comprised 50% of the total grade and equaled a design team's design score divided by the maximum design score scored.

In reducing cycle time, students could change any or all the following factors:

Factor	Unit	Per Unit Change Cost	Limit
Capacity (# of Machines)	machine	$12,500	5
Mean Raw Process Time	%/station	$5,000	15%
Mean Process Variance	%/station	$7,500	10%
Mean Setup Time	%/station	$2,500	15%
Mean Setup Variance	%/station	$5,000	5%
Availability (MTTF or R)	5 %/machine	$4,000	20% of F, R
Arrival SCV to Station 1*	% decrease	$750	50%
Process Batch Size	% increase	None	10%
Move Batch Size	# moves/day	$300 x (#Moves - 60)	None

* Squared coefficient of variation

While one could argue about the relative costs of these change options and their limits, my main concern here was forcing students to consider the costs and benefits of design alternatives. Neither quality improvement or improved material handling and layout played a role here. Quality improvement was the focus of the Design Experience #2; material handling and layout were the focus of Design Experience #3.

Design Experience #2

Design Experience #2 involved the same production system used in Design Experience #1, with the added dimensions of quality defects and rework. Students were asked to reduce average cycle time through all four stations to 6 hours or less (from 80.5 hours), meet throughput requirements, and spend no more than $100,000 in achieving the desired cycle time reduction. Design scores were calculated using the following equation:

$$\frac{Cost}{Budget} + \frac{Cycle\ Time_{old}}{Cycle\ Time_{new}} + \frac{Scrap_{old}}{Scrap_{new}}$$

As before, design grades comprised 50% of the total grade and equaled a design team's design score divided by the maximum design score scored.

In reducing cycle time, students could change any or all the following factors:

Change Factor	Unit	Per Unit Change Cost	Limit
Process Mean (Quality)	%/machine	$75	20%
Process Variance (Quality)	%/machine	$150	20%
Capacity (Machines)	machine	$10,000	3
Mean Raw Process Time	%/machine	$300	15%
Mean Process Time Var.	%/machine	$600	30%
Mean Setup Time	%/machine	$150	15%
Mean Setup Time Var.	%/machine	$150	40%
Availability	% F or R/machine	$50	30% of F, R
Arrival SCV to Station 1*	% decrease	$500	50%
Process Batch Size	% increase	None	10%
Move Batch Size	# moves/day	$500 x (#Moves - 75)	None

* Squared coefficient of variation

The effects of process mean and variance changes on quality were accomplished using a spreadsheet. Process performance data were generated using Excel and then compared to specification limits to determine percentage defective and if a part could be reworked.

Design Experience #3

Design Experience #3 required students to investigate the benefits and costs of changing the layout of the above four stations, three product production system to manufacturing cells. Students were provided a FactoryCad drawing and FactoryFlow analysis of the existing layout, time study data (generated in Excel), and current operator-machine assignments. In addition, activity based costing data was provided.

Design scores were based on an expected daily productivity index. Because daily output and material usage remained unchanged with the new design, the productivity index equation used here considered current labor and equipment inputs divided by proposed labor and equipment inputs (note current labor and floor space costs used in both the numerator and denominator):

$$\frac{\text{(22 Total Operators Per Day) x (\$25/hour) x (8 hours/day) + (4,450 sq. ft.) x (\$120/sq. ft) / (250 days)}}{\text{(X Total Operators Per Day) x (\$25/hour) x (8 hours/day) + (Y sq. ft.) x (\$120/sq. ft) / (250 days)}}$$

Improved operator machine assignments, improved layout, and reduced work in process levels worked to increase productivity. Students could change the layout, wire basket size (for WIP), number of cells, number of and type of machines per cell, number and type or operators per cell, and whether operators took part in preventive maintenance activities. Assigning preventive maintenance duties to operators required an additional 15 minutes per day per operator, but machine MTTF increased 30% and MTTR decreased 15%. Additional machines were $15,000 each. Operator layoffs cost $25,000 per laid-off operator and resulted in a 10% productivity drop for three months (480 hours). Training on teamwork, quality improvement, and maintenance costs $1,000 per operator. On the job cross training results in a 10% productivity drop for two weeks (80 hours). Each machine moved costs $4,000 to move and the facility is shut down for two weeks (80 hours, 100% productivity drop) to make layout changes. Cell operator pay increased to $28 per hour from $25 per hour due to cross training. Walk time associated with material handling had to be incorporated into operator-machine assignments and shown on revised operator machine charts. In addition, reductions in cycle time resulted in additional sales; increases in cycle time resulted in lost sales.

Design Experience #4

Design Experience #4 incorporated assembly operations to the above production system. Students were asked to design a minimum cost, capacity feasible production system comprised of manufacturing and assembly operations to produce three new products, N1, N2, and N3. A precedence diagram was provided for these products as well as time data for work elements. Each product was comprised of 11 major component parts: one part produced by the four station production system used in the previous three design experiences and ten parts purchased from outside suppliers. Supplier delivery performance varied and management desired a purchased component availability of 99%.

Design scores were calculated using the following equation:

$$(\%Over\ Capacity\ +\ 1.5\ x\ \%Under\ Capacity)\left(\frac{Prod\ Cycle\ Time}{Equipment\ Cost}+\frac{Assembly\ Cycle\ Time}{Assembly\ Station\ Cost}\right)10{,}000$$

Percentage over or under capacity was determined by randomly selecting the average daily demand for a random 20 day period. This required that students perform an analysis of expected daily product demand that was provided to them in an Excel file.

Lessons Learned Along the Way

The lessons that follow are based on my experience, evaluation of student performance, and discussions with students.

- Design experiences need to begin the second week of the academic section to complete the last design experience by the ninth or tenth week of the section. Design Experience #1 was not assigned until the fourth week of the academic section, Design Experience #4 was not assigned until the tenth week. As a result, Design Experience #4 was modified and limited to a production capacity decision and an assembly line design based on that decision.

- Each design experience, students should submit a plan of attack, complete with deliverables and due dates. This may prove helpful in two ways. First, students struggled with describing their design process in their academic report . Second, students procrastinated. Some procrastination was due to students having trouble in deciding where to begin attacking the problem.

- Design scores need to be better explained. Students did not fully understand what was meant by the design score and, in the beginning, ignored it in developing their design.

- I assumed too much at first concerning the exploratory analysis. Students did not know how to approach it or interpret its results. For example, one design team conducted an exploratory analysis that showed a unit change in MTTR produced an overall design score of 12. After spending an additional ten hours or so on the design experience, they achieved a design score of 13. None of their design alternatives reflected the MTTR change.

- Because students did not properly conduct or fully understand the exploratory analysis, they did not have a feel for the maximum design score possible. Because their design grade was some percentage of the maximum design score achieved, most design teams did not know when to quit concerning improving their design.

- For some design experiences it may be better to identify specific changes that could be made and their expected results rather than class of changes and a range of possible outcomes.

- To better integrate lecture material with the design experiences, some class sessions should be taught in a room with computers.

- Overall, students found the design experiences to be challenging and practical.

Future Plans

In the upcoming year I plan to edit the spreadsheets used in the course to make them more consistent from one design experience to the next. I then plan to acquire the initial, multimedia hardware and software and develop competence in the technology by developing a learning module on production system dynamics. The learning module will introduce basic ideas and relationships of production system dynamics and then use the simple production system spreadsheet example to demonstrate those ideas and relationships. Students will be led through what-if, steady state analyses using a spreadsheet to help them gain insight to basic relationships. The production system example will be built in such a way that the instructor can readily make changes to process parameters, product routings, and product names (to accommodate both manufacturing and service production systems).

The following year I plan to build on the initial learning module and add simulation modeling to complement the steady state, spreadsheet analysis. The simulation model would allow students to view system behavior over time and help them to better understand the meaning and use of both steady state analysis and simulation in system design. I then plan to add additional learning modules that evaluate alternative process technologies, product flows and facility layouts given the above production system. Again, students will be led through what-if analyses to help them gain insight to basic ideas and relationships.

Finally, I plan to develop a learning module that focuses on individual workstation design. Students would make workstation changes and then evaluate the effects of workstation changes on overall production system performance. By year's end, I plan on having a complete, coherent production system design learning experience that begins with basic production system dynamics and performance and considers the effects of process technology, product flow, facility layout, and workstation design on that performance (and vice versa).

Reference

Hopp, Wallace J. and Mark L. Spearman (1996) *Factory Physics: Foundations of Manufacturing Management*, Irwin.

Biographical Notes

Paul E. Rossler is an assistant professor of Industrial Engineering at GMI Engineering & Management Institute. His interests include organizational performance improvement philosophies and methods, management history, and industrial engineering design processes. He earned his BSIE from GMI, and his MSIE and PhD from Virginia Tech.