

Terminal Descent: The Manufacturing Delay and Disruption Cycle

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Brent M. Johnstone, LM Fellow



Introduction



-The New York Times

FBI Files Go Digital, After Years of Delays
Computer System 12 Years in the Making Is Aimed at Better Sharing of Information; Effort Cost More Than \$600 Million

- The Wall Street Journal

Pentagon Struggles With Cost Overruns and Delays

-The New York Times

Budgeting gaffes led to \$15 million technology cost overrun at UT

- Austin American-Statesman

NASA inspector general issues a scathing report on moon effort
The cost of the SLS rocket's mobile launch tower is expected to be at least \$1 billion and be delivered years late

- The Washington Post

Cost overruns and schedule delays are a constant in news headlines...

How Bad Is It?

- **Bent Flyvbjerg, Professor Emeritus at Oxford University, has studied cost and schedule impacts of so-called “megaprojects”**
 - **Defined as large-scale commercial or government projects with investment > \$1B**
 - **Think high-speed rail lines, airports, seaports, the Olympics, high-energy particle accelerators, logistics for large supply chains, etc.**
- **Flyvbjerg’s Iron Law of Megaprojects: “Over budget, over time, under benefits, over and over again.”**
 - **47.9% are delivered on budget**
 - **8.5% are delivered on budget and on time**
 - **0.5% are delivered on budget, on time and with the projected benefits**
- **Other researchers (Smart, 2021) have confirmed:**
 - **Aerospace & Defense (A&D): 80% of projects overrun cost, 90% experience schedule delays**
 - **Average A&D development program exceeds budget by 50%**
 - **One in six A&D development programs exceed budget by 2x or greater**
 - **Smart saw similar results in software/IT, infrastructure, and Olympic Games**

Who's to Blame?

Typical reasons provided for cost/schedule issues:

- Poor program management
- Unrealistic cost & schedule estimates
- Technical challenges
- “Strategic misrepresentations”

Managers Get Blame for NASA Cost Overruns : Hearing: U.S. agency and private contractors both at fault, House panel is told

- Los Angeles Times

The most unsuccessful four years in the education of a cost estimator is fifth grade arithmetic.

- Augustine's Law VIII

Senior Official Responsible for Big Dig Project Resigns

- The New York Times

Study identifies reasons for soaring nuclear plant cost overruns in the U.S.

- Massachusetts Institute of Technology

But these reasons are ultimately unsatisfying...Is it true we never learn from our mistakes?

“Terminal Descent”

- If we dismiss incompetent program managers, estimators who can’t add, and advocates who can’t tell the truth as reasons why programs run into cost & schedule difficulties, what is the reason?
- Broadleaf Capital study of project schedule overruns suggests systemic relationship between unanticipated events & “firefighting” efforts made to recover schedule



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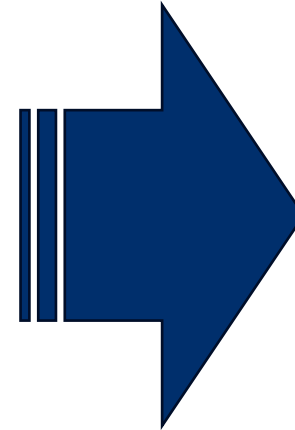
- “Expedient measures” include starting tasks out of sequence, making serial tasks become parallel, increasing resource levels or using different personnel, etc.
- These less-efficient measures degrade productivity and increase labor hours to finish tasks
- Program falls further behind, and the cycle continues....

Good-faith efforts made to recover schedule can make cost and schedule worse, not better

Change & Disruption

- What “unanticipated events” begin the cycle?

- Late-to-need engineering
- Late-to-need tooling
- Changes in customer requirements or work scope
- Changes in customer funding
- Part shortages or late delivery of materials
- Engineering changes
- And the list goes on.....



The common denominator is:

Change

- What is disruption?

- “Change-induced impact on the cost of performing work that is not directly charged (so, productivity loss and increased rework)” -- Cooper, 2022
- Disruption is not the direct cost of the change, it’s the follow-on impacts – loss of learning, diminished productivity, staffing fluctuations, late deliveries

How Do We Estimate Cost of Disruption?

...Not easily

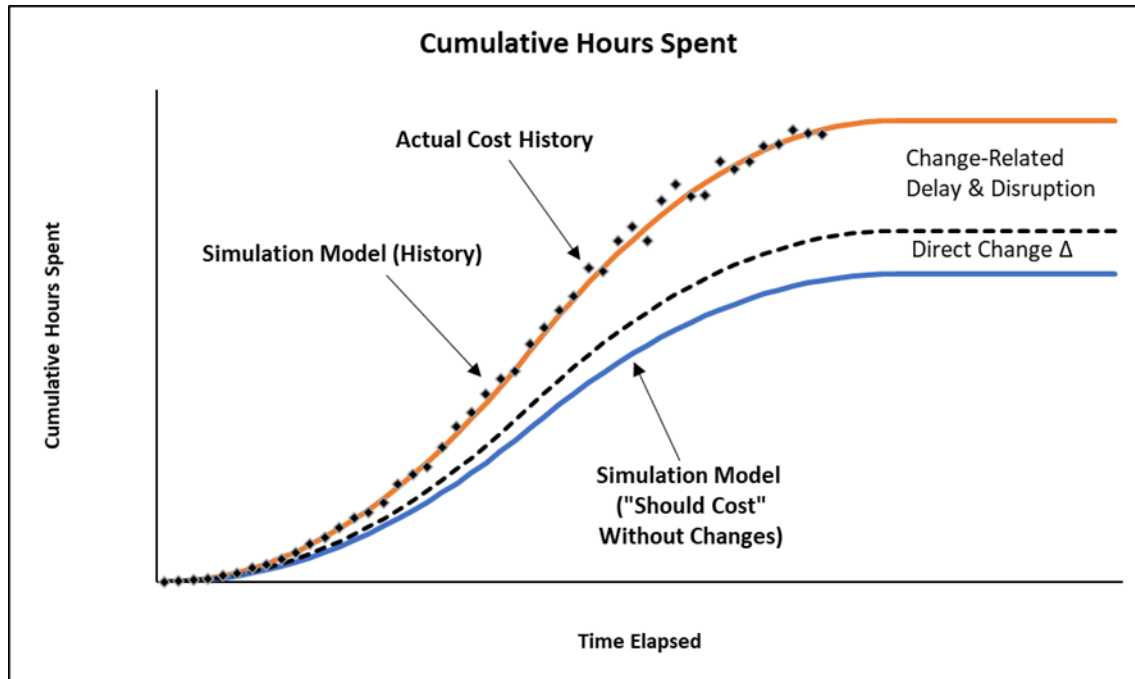
- **Often unable to separate disruption charges from baseline work**
 - **An operator drilling holes in an aircraft bulkhead doesn't separately charge the extra time it took him because of an engineering change that required relearning**
 - **And the additional time attributable to relearning his task may be commingled with other impacts which are completely unrelated to the disruption**
- **Even if we can separately see rework & repair charges, that is only part of the picture**
- **We rarely have “similar-to” situations that mirror the disruption situation we are being asked to estimate**

So where can we turn?

Disruption & The Law

- **Estimating cost of disruption is important in litigation over responsibility for schedule delays**
- **Some legally-accepted methods:**
 - **Measured Mile – Compare period of good efficiency to a bad period**
 - **Earned Value – Compare planned performance to actual performance**
 - **Total Cost – All cost overrun is attributed to delay**
 - **Modified Total Cost – Total cost overrun is reduced for claimant’s recognized inefficiencies**
- **Each of these has issues...One legal authority: “Disruption is most misunderstood, most debated, most abused, and hence least well-recovered aspect of cost damages.”**
- **Another legal approach pioneered in 1970s is Systems Dynamics method**
 - **Pioneered by Pugh-Roberts Associates team led by Kenneth Cooper**
 - **Initially employed in Ingalls Shipbuilding’s \$500M claim against US Navy for responsibility for delays on LHA amphibious assault ship and DD-963 destroyer programs**
 - **Navy settled out of court for \$447M**

Systems Dynamics Modeling

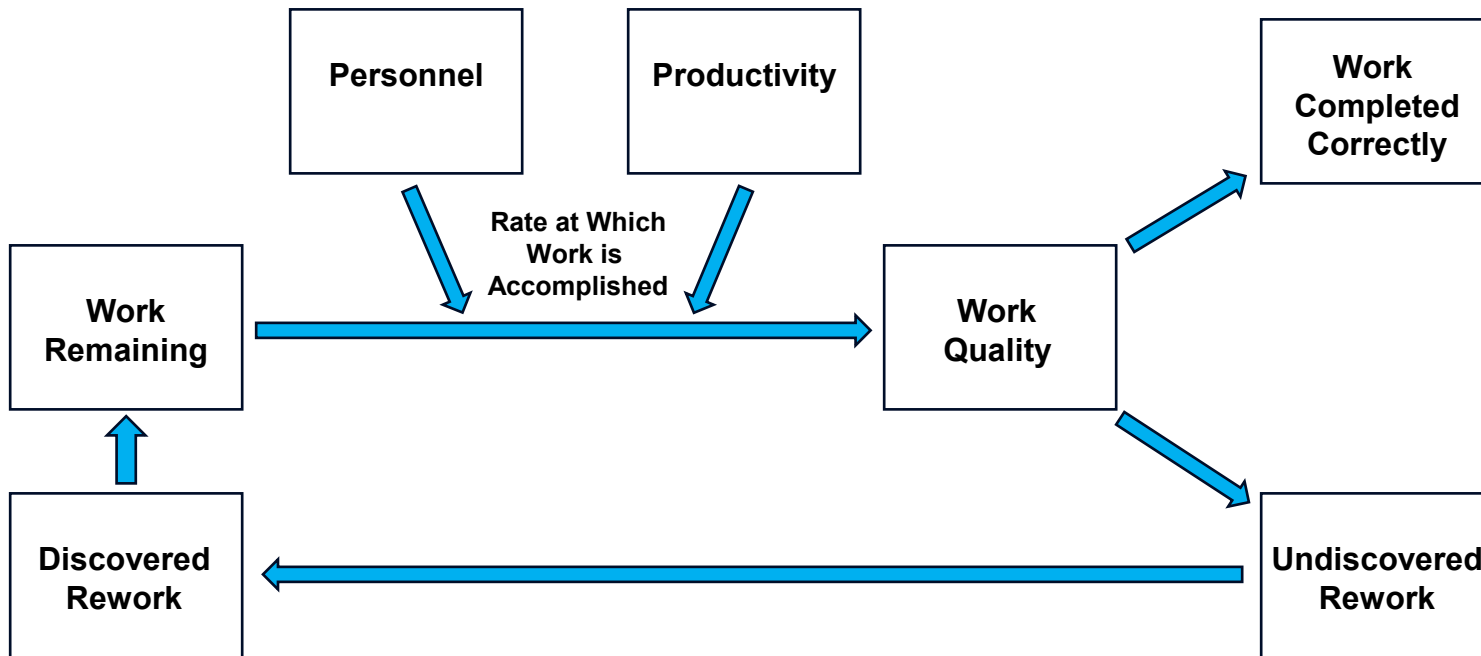


Systems Dynamics Modeling Approach to Delay & Disruption Estimates (Cooper, 2022)

- **Systems Dynamics models the build process with feedback cycles that imitate delay and disruption cycles**
- **Model is built and calibrated to actual cost history (including delay & disruption)**
- **Model is then rerun to determine what the program should have cost if the changes had not occurred**
- **Since direct change delta is typically known, the remainder is the change-related delay and disruption**

The Change Cycle

- Key feedback cycle in Systems Dynamics modeling



- Work is accomplished correctly, or it must be reworked.
- *The need to rework is not discovered immediately.*
- When rework is discovered, it adds to the work remaining.
- To maintain schedule, contractor may need to staff up using less skilled labor...impacting productivity and quality.
- Rework leads to more rework.

- Quality is the “fraction of work that will *not* require rework.” (Cooper, 1980)

Proof of Concept Model

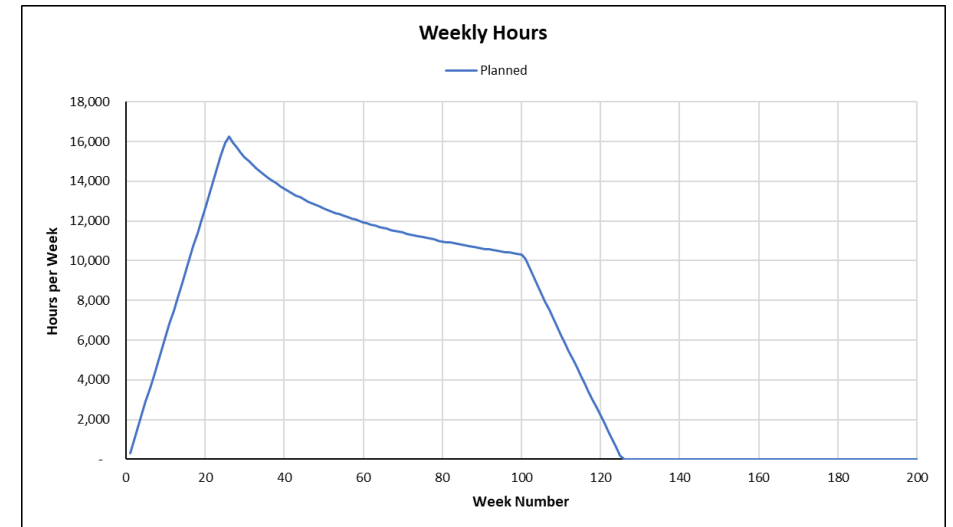
- **Wanted to create a proof-of-concept disruption model for a notional aircraft development program**
- **Parameters:**
 - **Demonstrate potential disruption on a notional aircraft development program**
 - **Should be high-level & modeled at the major task area (fabrication, assembly, etc.)**
 - **Not built at the component level (i.e., forward fuselage, center fuselage, wing, etc.) or at the workstation level**
 - **Not be based on company-proprietary data nor be based on any current or planned aircraft program**
 - **Should be Microsoft Excel-based and not require commercial simulation software**
 - **Output should be directional only, intended to instruct and not suitable for proposal or litigation purposes**
- **No existing aircraft model, but McCue's shipbuilding model (McCue, 1997) provided a structure and many valuable insights & relationships**

Baseline Model

- Shows the planned cost & schedule and represents “success”

Product Week	Phase Week	Planned Performance										
		Planned Standards Remaining at Week Begin	Planned Weeks Remaining	Planned Work (stds per week)	Planned Productivity (stds per man per week)	Planned Overtime	Planned Heads	Weekly Planned Manhours	Cum Planned Manhours	Gross Completion Rate (stds per week)	Reported Work Complete (stds)	Normal Quality
26	1	144,800	124	33	4.00	1.00	8	325	325	33	33	85%
27	2	144,839	123	98	4.00	1.00	24	975	1,300	98	98	85%
28	3	144,814	122	163	4.00	1.00	41	1,625	2,925	163	163	85%
29	4	144,724	121	228	4.00	1.00	57	2,275	5,200	228	228	85%
30	5	144,570	120	293	4.00	1.00	73	2,925	8,125	293	293	85%
31	6	144,350	119	358	4.00	1.00	89	3,575	11,701	358	358	85%
32	7	144,105	118	423	4.00	1.00	106	4,225	15,926	423	423	85%
33	8	143,798	117	488	4.00	1.00	122	4,875	20,801	488	488	85%
34	9	143,430	116	553	4.00	1.00	138	5,525	26,327	553	553	85%
35	10	143,003	115	618	4.00	1.00	154	6,175	32,502	618	618	85%
36	11	142,537	114	683	4.00	1.00	171	6,825	39,327	683	683	85%
37	12	142,007	113	748	4.00	1.00	187	7,475	46,803	748	748	85%
38	13	141,417	112	813	4.00	1.00	203	8,125	54,928	813	813	85%
39	14	140,766	111	878	4.00	1.00	219	8,776	63,704	878	878	85%
40	15	140,139	110	943	4.00	1.00	236	9,426	73,129	943	943	85%
41	16	139,411	109	1,008	4.00	1.00	252	10,076	83,205	1,008	1,008	85%
42	17	138,605	108	1,073	4.00	1.00	268	10,726	93,931	1,073	1,073	85%
43	18	137,731	107	1,138	4.00	1.00	284	11,376	105,306	1,138	1,138	85%
44	19	136,797	106	1,203	4.00	1.00	301	12,026	117,332	1,203	1,203	85%
45	20	135,801	105	1,268	4.00	1.00	317	12,676	130,008	1,268	1,268	85%
46	21	134,742	104	1,333	4.00	1.00	333	13,326	143,334	1,333	1,333	85%
47	22	133,682	103	1,398	4.00	1.00	349	13,976	157,310	1,398	1,398	85%
48	23	132,492	102	1,463	4.00	1.00	366	14,626	171,936	1,463	1,463	85%
49	24	131,240	101	1,528	4.00	1.00	382	15,276	187,211	1,528	1,528	85%
50	25	129,925	100	1,593	4.00	1.00	398	15,926	203,137	1,593	1,593	85%
				1,625	4.00	1.00	406	16,251	219,388	1,625	1,625	85%
				1,625	4.07	1.00	399	15,960	235,349	1,625	1,625	85%

Partial snapshot

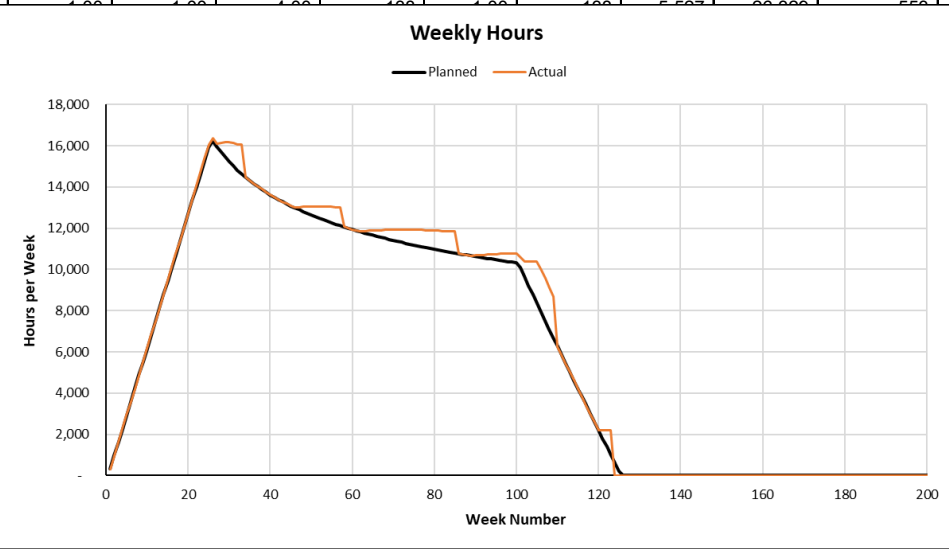


Alternate Model

- Shows alternate cost / schedule with disrupted conditions

Actual Performance																		
Product Week	Phase Week	Reported Work Remaining at Work Begin (stds)	Released Work (stds per week)	Normal Productivity (stds per man per week)	Impact of New Workers	Impact of Morale	Impact of Fatigue	Impact of Schedule Pressure	Actual Productivity (stds per week per man)	Desired Labor Heads	Actual Overtime	Actual Heads Available	Weekly Actual Manhours	Cum Actual Manhours	Gross Completion Rate (stds per week)	Reported Work Complete (stds)	Normal Quality	
26	1	144,800	33	4.00	1.00	1.00	1.00	1.00	4.00	8	1.00	8	325	325	33	33	80%	
27	2	144,839	98	4.00	1.00	1.00	1.00	1.00	4.00	24	1.00	24	975	1,300	98	98	80%	
28	3	144,814	163	4.00	1.00	1.00	1.00	1.00	4.00	41	1.00	41	1,625	2,925	163	163	80%	
29	4	144,724	228	4.00	1.00	1.00	1.00	1.00	4.00	57	1.00	57	2,275	5,200	228	228	80%	
30	5	144,570	293	4.00	1.00	1.00	1.00	1.00	4.00	73	1.00	73	2,925	8,125	293	293	80%	
31	6	144,350	358	4.00	1.00	1.00	1.00	1.00	4.00	89	1.00	89	3,575	11,701	358	358	80%	
32	7	144,113	423	4.00	1.00	1.00	1.00	1.00	4.00	106	1.00	106	4,225	15,926	423	423	80%	
33	8	143,816	488	4.00	1.00	1.00	1.00	1.00	4.00	122	1.00	122	4,876	20,802	488	488	80%	
34	9	143,460	553	4.00	1.00	1.00	1.00	1.00	4.00	138	1.00	138	5,527	26,329	553	553	80%	
35	10	143,048	618	4.00	1.00	1.00	1.00	1.00	4.00	154	1.00	154	6,178	32,507	618	618	80%	
36	11	142,599	683	4.00	1.00	1.00	1.00	1.00	4.00	170	1.00	170	6,829	39,336	683	683	80%	
37	12	142,090	748	4.00	1.00	1.00	1.00	1.00	4.00	186	1.00	186	7,480	46,816	748	748	80%	
38	13	141,522	813	4.00	1.00	1.00	1.00	1.00	4.00	202	1.00	202	8,131	54,947	813	813	80%	
39	14	140,897	878	4.00	1.00	1.00	1.00	1.00	4.00	218	1.00	218	8,782	63,729	878	878	80%	
40	15	140,299	943	4.00	1.00	1.00	1.00	1.00	4.00	234	1.00	234	9,433	73,162	943	943	80%	
41	16	139,603	1,008	4.00	1.00	1.00	1.00	1.00	4.00	250	1.00	250	10,084	83,246	1,008	1,008	80%	
42	17	138,831	1,073	4.00	1.00	1.00	1.00	1.00	4.00	266	1.00	266	10,735	93,981	1,073	1,073	80%	
43	18	137,996	1,138	4.00	1.00	1.00	1.00	1.00	4.00	282	1.00	282	11,386	105,367	1,138	1,138	80%	
44	19	137,102	1,203	4.00	1.00	1.00	1.00	1.00	4.00	298	1.00	298	12,037	117,404	1,203	1,203	80%	
45	20	136,150	1,268	4.00	1.00	1.00	1.00	1.00	4.00	314	1.00	314	12,688	130,092	1,268	1,268	80%	
46	21	135,139	1,333	4.00	1.00	1.00	1.00	1.00	4.00	330	1.00	330	13,339	143,431	1,333	1,333	80%	
47	22	134,130	1,398	4.00	1.00	1.00	1.00	1.00	4.00	346	1.00	346	13,990	157,421	1,398	1,398	80%	
48	23	132,994	1,463	4.00	1.00	1.00	1.00	1.00	4.00	362	1.00	362	14,641	172,062	1,463	1,463	80%	
49	24	131,799	1,528	4.00	1.00	1.00	1.00	1.00	4.00	378	1.00	378	15,292	187,354	1,528	1,528	80%	
50	25	130,544	1,593	4.00	1.00	1.00	1.00	1.00	4.00	394	1.00	394	15,943	203,297	1,593	1,593	80%	
51	26	129,230	1,625	4.00	1.00	1.00	1.00	1.00	4.00	400	1.00	400	16,250	219,547	1,625	1,625	80%	
52	27	127,857	1,625	4.07	1.00	1.00	1.00	1.00	4.07	407	1.00	407	16,250	236,000	1,625	1,625	80%	

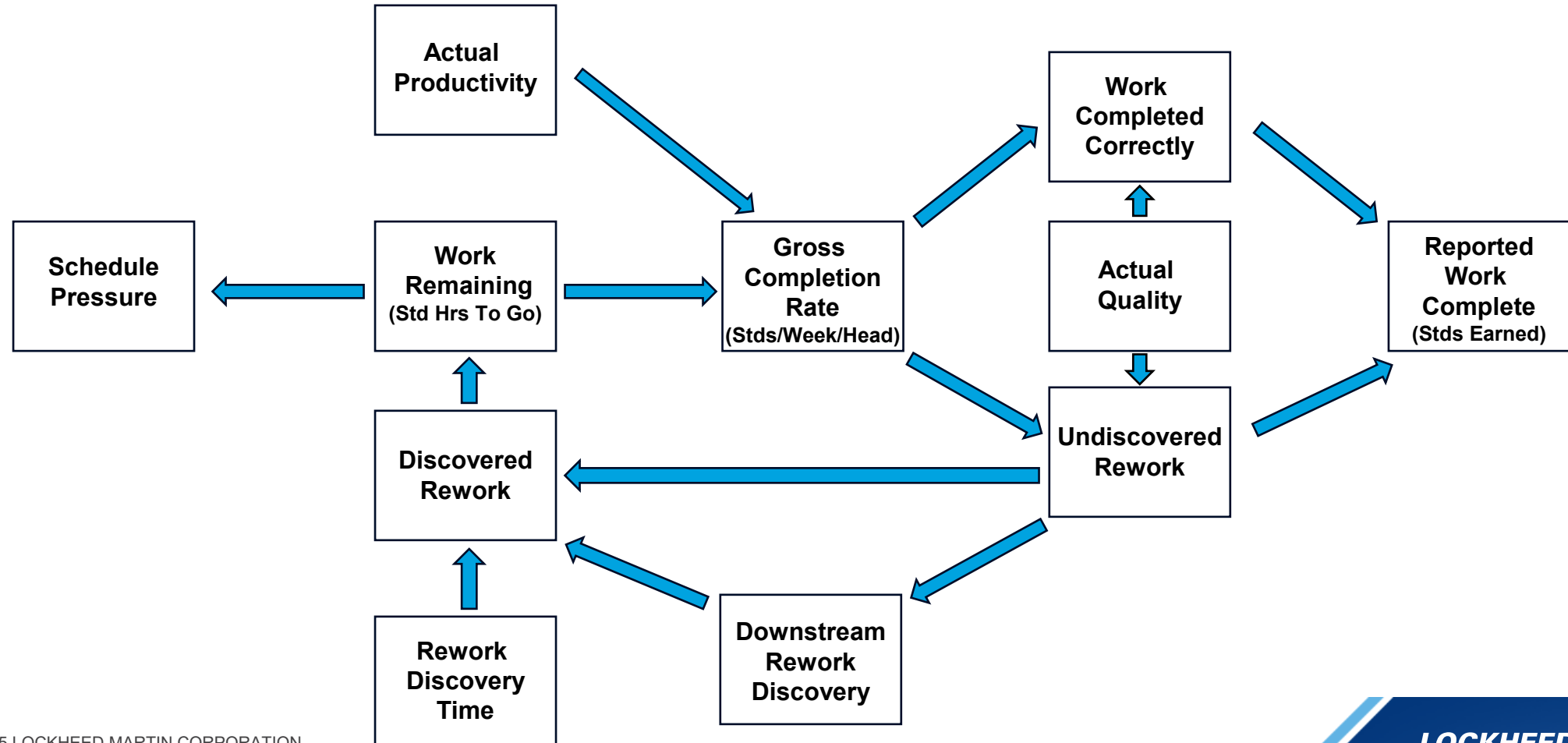
In this case, we assume 20% of effort will have to be reworked... Baseline was 15%



Partial snapshot

Work Accomplishment Cycle

- Workflow based on McCue (1997)
- Standard hours are used as the measurement of work accomplished
 - Allows us to measure work completion without considering learning curve impacts, etc.

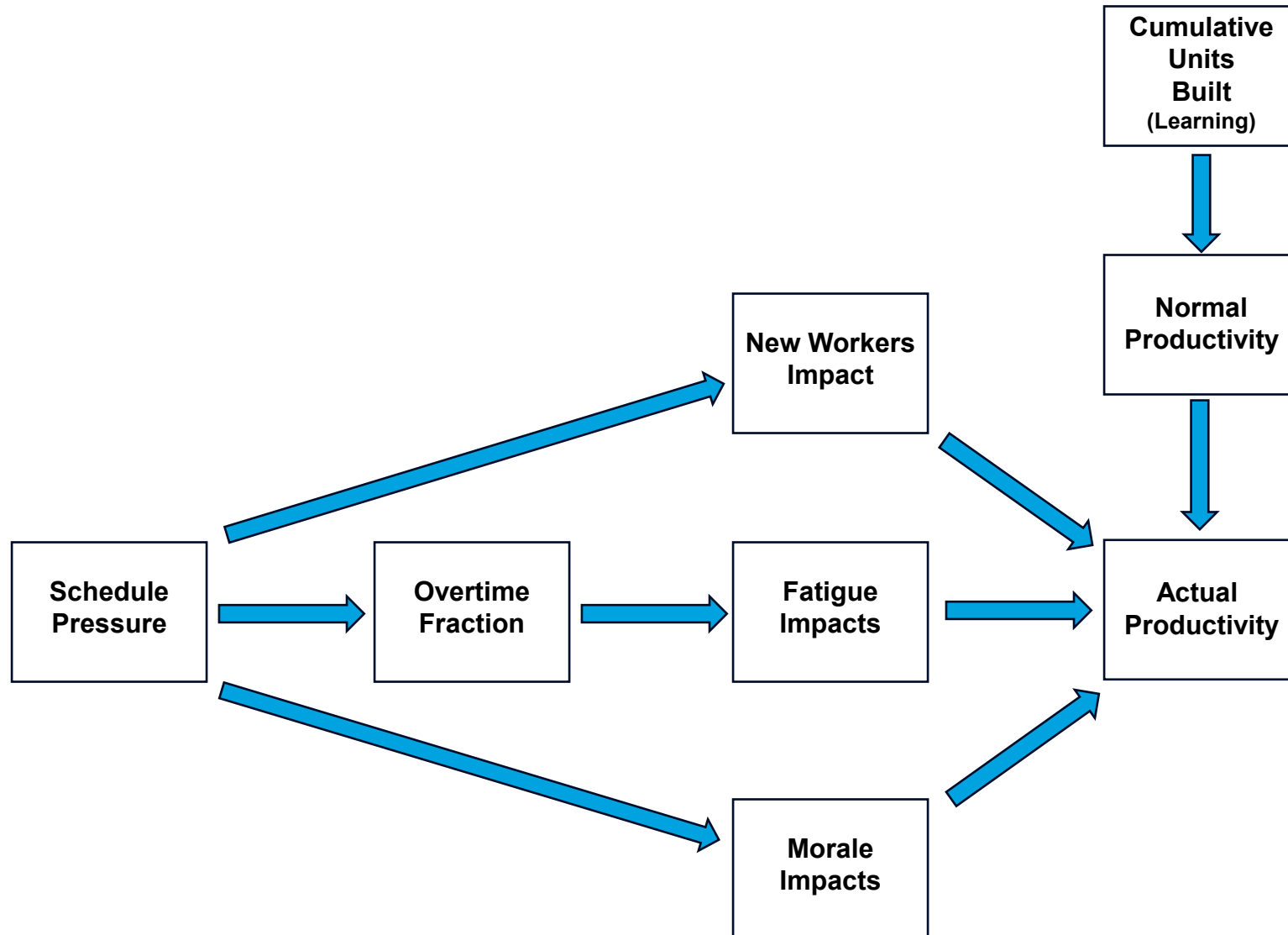


Downstream Discovery Cycle

- Important to recognize that rework is not discovered immediately....
- When it is discovered, it may happen in a downstream build area

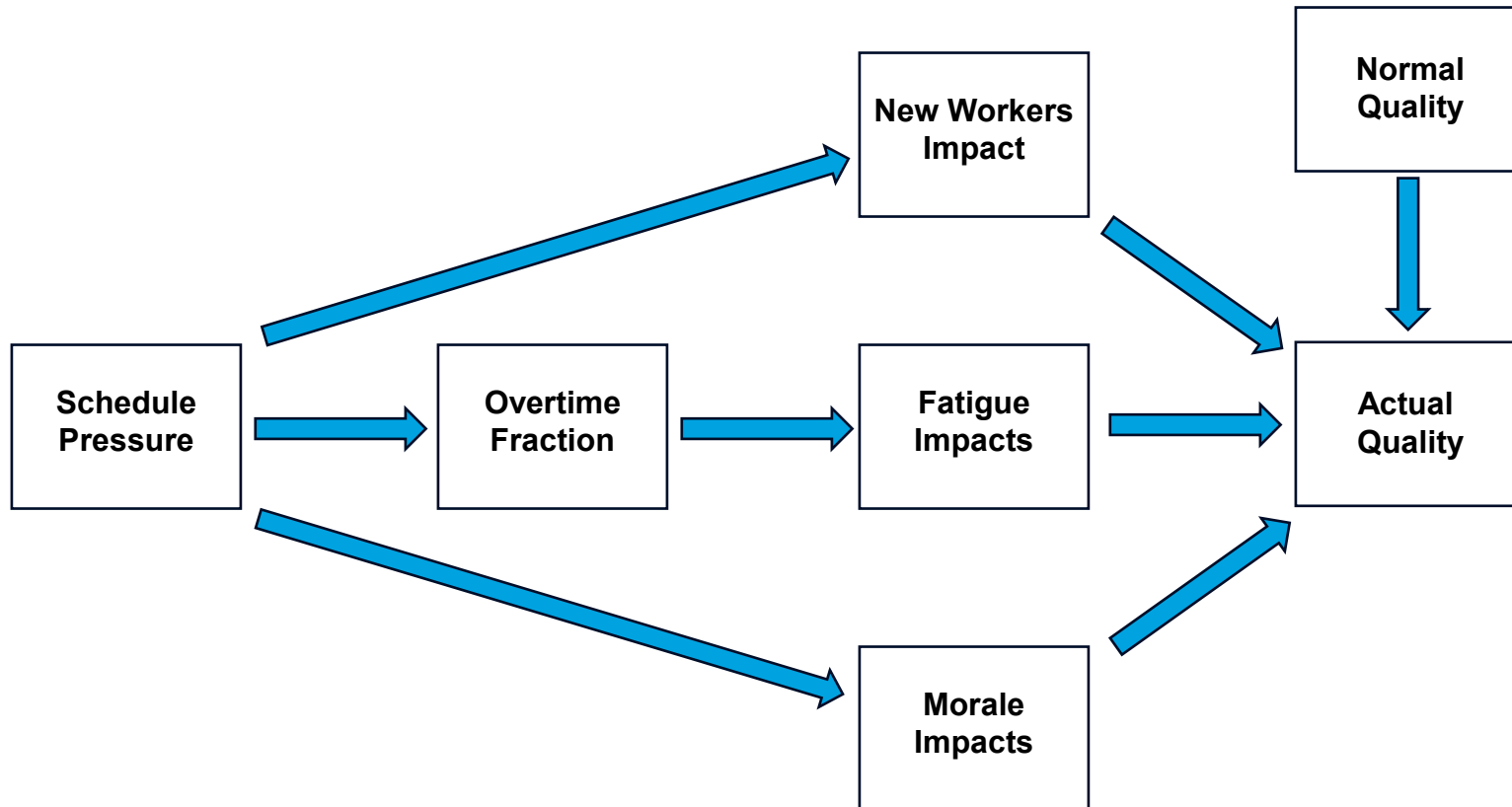
		Rework Discovered In:				
		Design Release	Fabrication	Component Assembly	Mate/Final	Flight Line
Rework Generated By:	Design Release					
	Fabrication					
	Component Assembly					
	Mate/Final					
	Flight Line					

Productivity Impact Cycle



- **Workflow based on McCue (1997)**
- **In response to schedule pressures, we can add new workers and/or work additional overtime**
- **Impact of additional workers + fatigue (from add'l overtime) degrade productivity**
- **Schedule pressure often negatively impacts morale, which also degrades productivity**

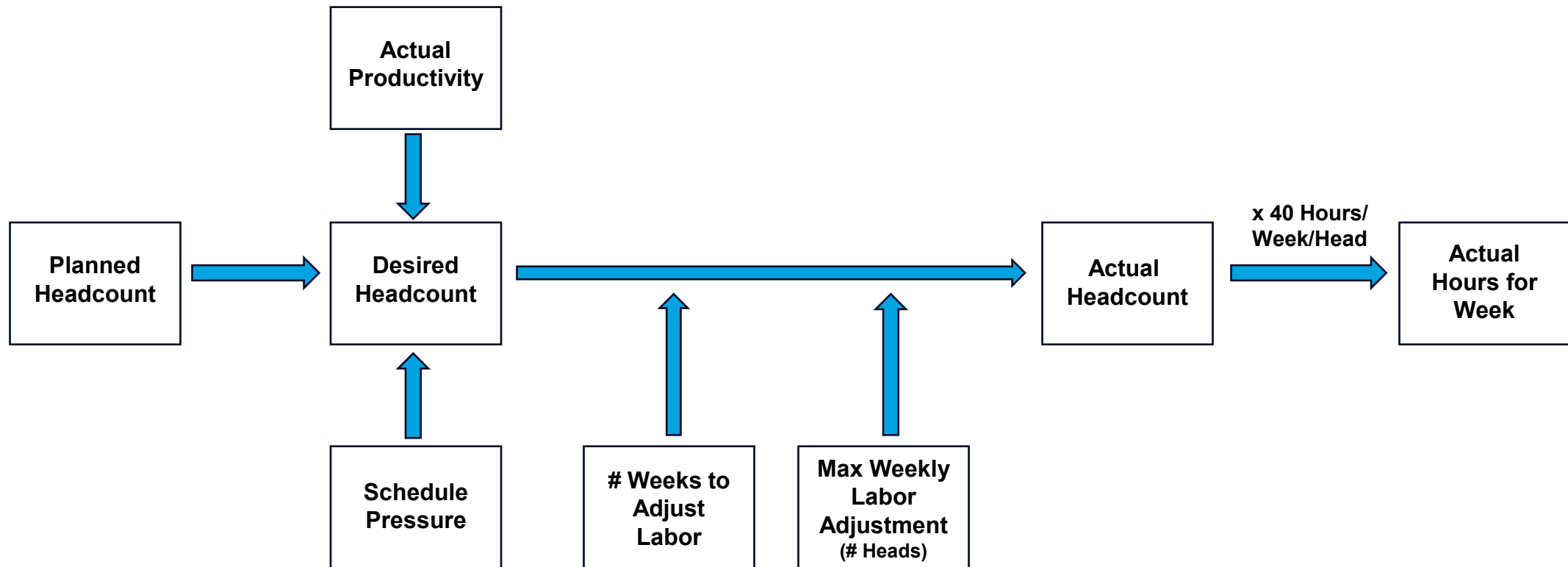
Quality Impact Cycle



- **Workflow based on McCue (1997)**
- **Quality is impacted similarly to productivity**
- **Adding new workers + + fatigue degrade quality**
- **Poor morale also degrades quality**
- **Degraded quality in turn puts more work into the rework cycle**

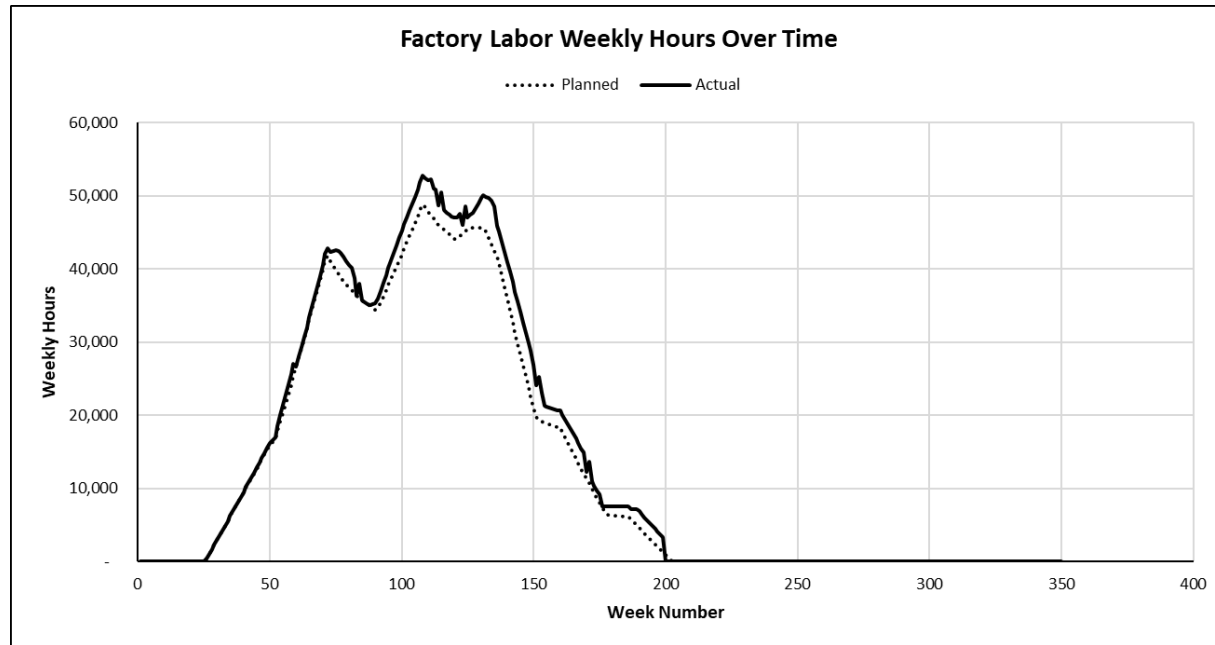
Labor Adjustment Cycle

- Workflow based on McCue (1997)
- Actual headcount is a function of productivity and schedule pressure
- Delay to bring new people on & a limit on how many can be brought on at a given time.



Case Study #1

- Can we put these cycles together and run a test case?
- Baseline assumes 85% quality, alternate assumes 80% quality

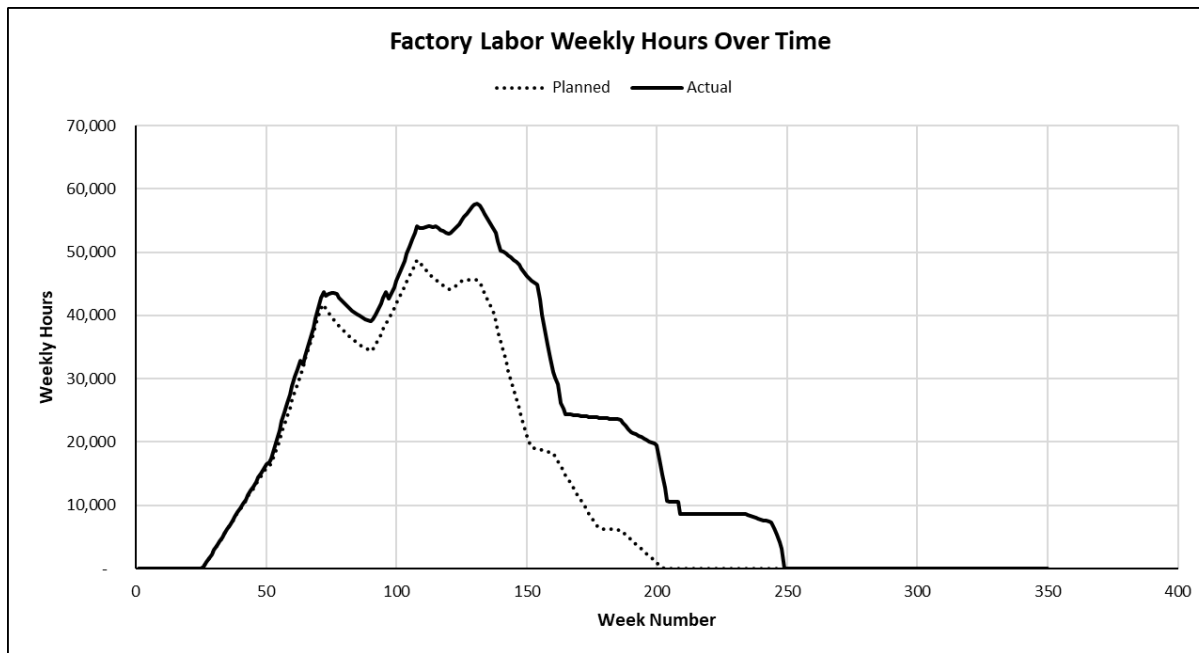


Area	Hours		
	Planned	Actual	Variance
Fabrication	1.00	1.04	4.4%
Component Assembly	1.00	1.08	7.5%
Mate/Final	1.00	1.12	11.7%
Flight Line	1.00	1.16	15.9%
Total Factory	1.00	1.08	8.5%

- Schedule is maintained with a slight cost overrun

Case Study #2

- Now assume a further degradation of quality
- Baseline assumes 85% quality, alternate assumes 75% quality

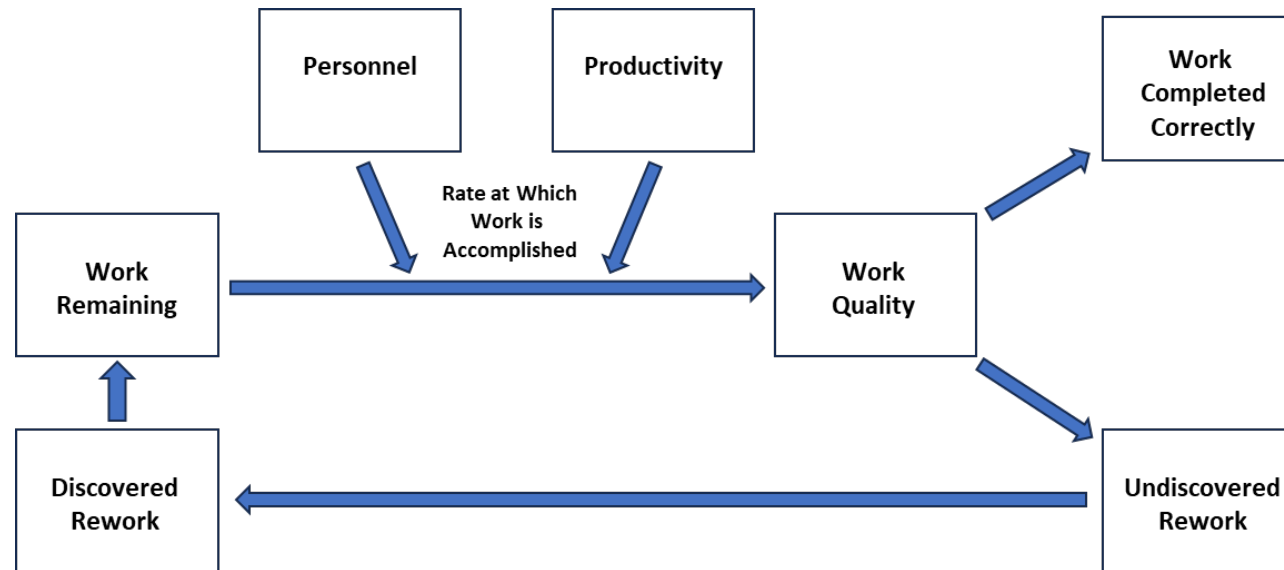


Area	Hours			Schedule (Weeks)		
	Planned	Actual	Variance	Planned	Actual	Variance
Fabrication	1.00	1.12	11.5%	1.000	1.03	3.2%
Component Assembly	1.00	1.24	23.7%	1.000	1.11	10.9%
Mate/Final	1.00	1.77	76.6%	1.000	1.35	35.2%
Flight Line	1.00	2.43	142.6%	1.000	1.55	55.4%
Total Factory	1.00	1.44	44.5%	1.000	1.23	22.8%

- Schedule slips by 23%, cost increases by 45%
- What happened?

Rework Cycle = Downward Spiral

- System is overwhelmed by rework with deteriorating impacts to personnel and productivity, starting the downward spiral
- Rework leads to more rework



- **Baseline: Rework = 20% of standard work content**
- **Case 1: Rework = 28% of standard work content (42% over baseline)**
- **Case 2: Rework = 46% of standard work content (134% over baseline)**

Lessons Learned/Improvements

- **Cost estimating relationships primarily drawn from shipyard experience (McCue, 1997)...These may not be appropriate for aircraft production. Additional research on rework, productivity and quality required.**
- **Calibration to historical cases of disruption is essential to test validity of cost and schedule relationships**
- **Current model has no tooling or facility constraints...introducing these constraints would yield more realistic answers**
- **Current model requires cumbersome manual reprofile of staffing if actual schedules exceed plan...automated profiling is desirable**
- **Current model does not consider part shortages or engineering changes, which are key sources of disruption**
- **Current model does not deal with delays in ramping up manpower, e.g. program funding limitations**
- ***Ad hoc* Microsoft Excel spreadsheet model is not optimal for simulation**
 - **Excel-based SimQuick simulation (freeware) might be more viable**
 - **Alternate is licensed simulation software**

Conclusions

- **Estimating delay & disruption impacts are difficult & typically based on judgment and rules of thumb**
- **Underestimate compounding impact of excessive rework and quality issues**
- **Modeling disruption appears to be a viable means to estimate cost impacts**
- **Further research & refinement is needed to create a usable estimating model**
- **Benefits:**
 - **More defensible estimates**
 - **Better understanding of program risk**
 - **Potentially assess alternate recovery strategies for known disruptions**

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