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DEFINING THE FUTURE

An Enterprise Model of Rising Ship Costs: Loss of Learning Due to Time between Ships and Labor Force Instability

The Advanced Learning Model (ALM 1-3)

Briefing to:

DoNCAS

Quantico, VA – 4 Sept 2008

Also briefed to:
ISPA/SCEA 2007, New Orleans, LA, 13 June 2007
NPS's 4th Acquisition Research symposium
Monterey, CA, 17 May 2007

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E. R. Druker, G. B. Rutledge, P. J. Braxton
Northrop Grumman Corporation

ALM "World Tour"

Date	Senior Attendee(s)	Variant	Organization	Position
Sept 21, 2004	Mr. Brian Cuccias	DDG Prelim	NGSS	DD(X) VP
Sept 22, 2004	Ms. Patti Tisone & NG Pricing Council	DDG	NG HQ	Corporate Director
Feb 14, 2005	Mr. Paul Robinson	DDG/LHD	NGSS	Sector VP
March 2, 2005	Capt. Goddard	DDG/LHD	Navy	DD(X) PM
March 2, 2005	Dr. Tze-Nan Lo; Dr. P. Bronson	DDG/LHD (abbr)	CAIG	DD(X) Analyst
April 4, 2005	Dr. Phil Dur & NGSS Management Council	DDG/LHD	NGSS	(Former) President NGSS
April 5, 2005	Mr. Richard Greco Jr., Capt. Sean Stackley	DDG/LHD	DoN Secretariat	ASN(FM&C), LPD PM
April 7, 2005	Capt. John D. Ingram	DDG/LHD	Navy	DDG PM
April 14, 2005	Capt. Rich Hooper	DDG/LHD	Navy	LHD PM
May 2, 2005	Ms. Allison Stiller	DDG/LHD	DoN Secretariat	DASN (Ships)
May 2, 2005	RADM Charlie Hamilton	DDG/LHD	Navy	PEO (Ships)
May 20, 2005	Bob Spiker, Bat Robinson, Mark Carroll	LPD	NGSS	Sector VP, Sector VP, VP
June 3, 2005	Mr. Tom MacKenzie, Mr. Creighton Greene	DDG/LHD	SASC	Senior staffers
June 29, 2005	VADM Crenshaw	DDG/LHD	OPNAV	N8
August 5, 2005	Mr. Tom Johnston	CVN	NGNN	Sector VP
Sept 7, 2005	Mr. Chris Deegan/ Capt. Rich Hooper	DDG/LHD	Navy	Dir. NAVSEA 017/ LHA 6 PM
Sept 27, 2005	LTC John Thurman, Fred Janicki, Capt. Hooper	DDG/LHD	OSD CAIG/NAVY	OSD CAIG, LHA 6 PM
Oct 7, 2005	Mr. Gary Bliss, Mr. Chris Deegan, Mr. Ed Foster, Mr. Brian Cuccias	DDG/abbr LHD	OSD CAIG/NAVY	Branch Head OSD CAIG
Nov 8, 2005	Mr. John Young & NG C&P Leadership Council	DDG/LHD	NG	VP, C&P
May 24, 2006	Capt. Rich Hooper	ALM 2	Navy	PMS 377
Jul 19, 2006	Management Council	ALM 2	NGSS	Pres, NGSS
May 17, 2007	NPS's 4th Acquisition Research Symposium	ALM 3	NPS	-
Jun 12, 2007	ISPA/SCEA 2007	ALM 3	SCEA	-
Sep 4, 2008	DoNCAS 2008	ALM 3	DoN	-

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Outline*

- **ALM 1 – Loss of learning for 2 classes (days between start Fab)**
  - The Base Case – the DDG Advanced Learning Model
    - DDG Learning Curve
  - The Validation Case – The LHD Advanced Learning Model
    - LHD Learning Curve
  - Meta-analysis and Mutual Confirmation
- **ALM 2 - The Enterprise Model – a predictive model for an entire shipyard complex**
- **ALM 3 – Percent overlap**
  - Shift of ALM 1 days-between-start-Fab to percent overlap
  - Prediction of the learning curve based upon the percent overlap alone
- **Conclusions**

* For logical flow, the order of the brief will be ALM 1,3,2

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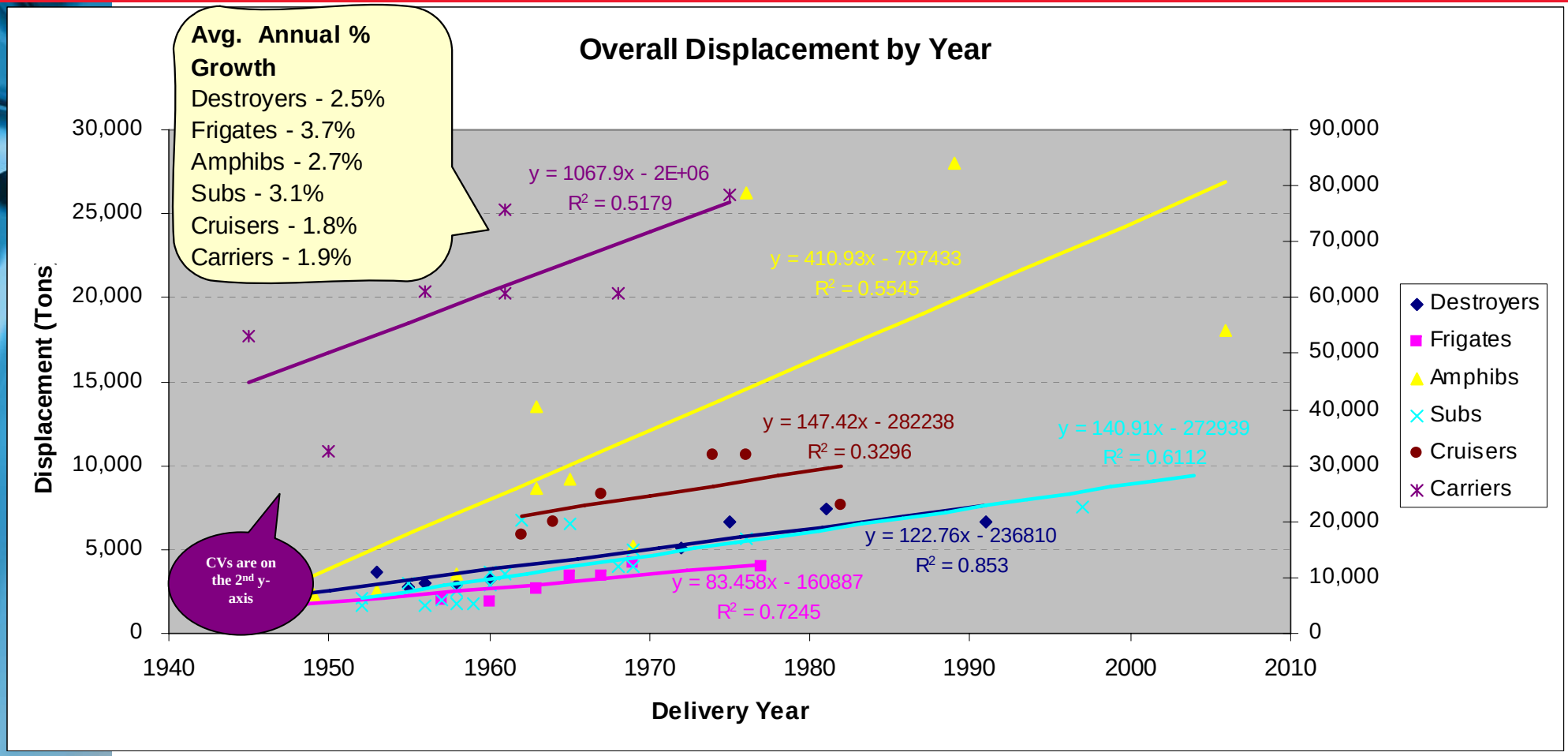
Historical Ship Growth by Weight

WWII to the Present



As an aside, we would like to mention that ship displacement (weight) has grown linearly since WWII, at a class-and-type-independent-rate of 2-3%, a fact often overlooked in discussions of rising ship costs

Note: Ship weight growth differed before WWII

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The DDG & LHD ALM 1
DDG 51 and LHD 1 Class Learning Curve Analyses

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Purpose

- **Describe analysis that demonstrates underlying learning in the DDG class**
  - This is the ALM 1 for DDGs
- **Show how the ALM 1 was applied to the LHD class which validated it**

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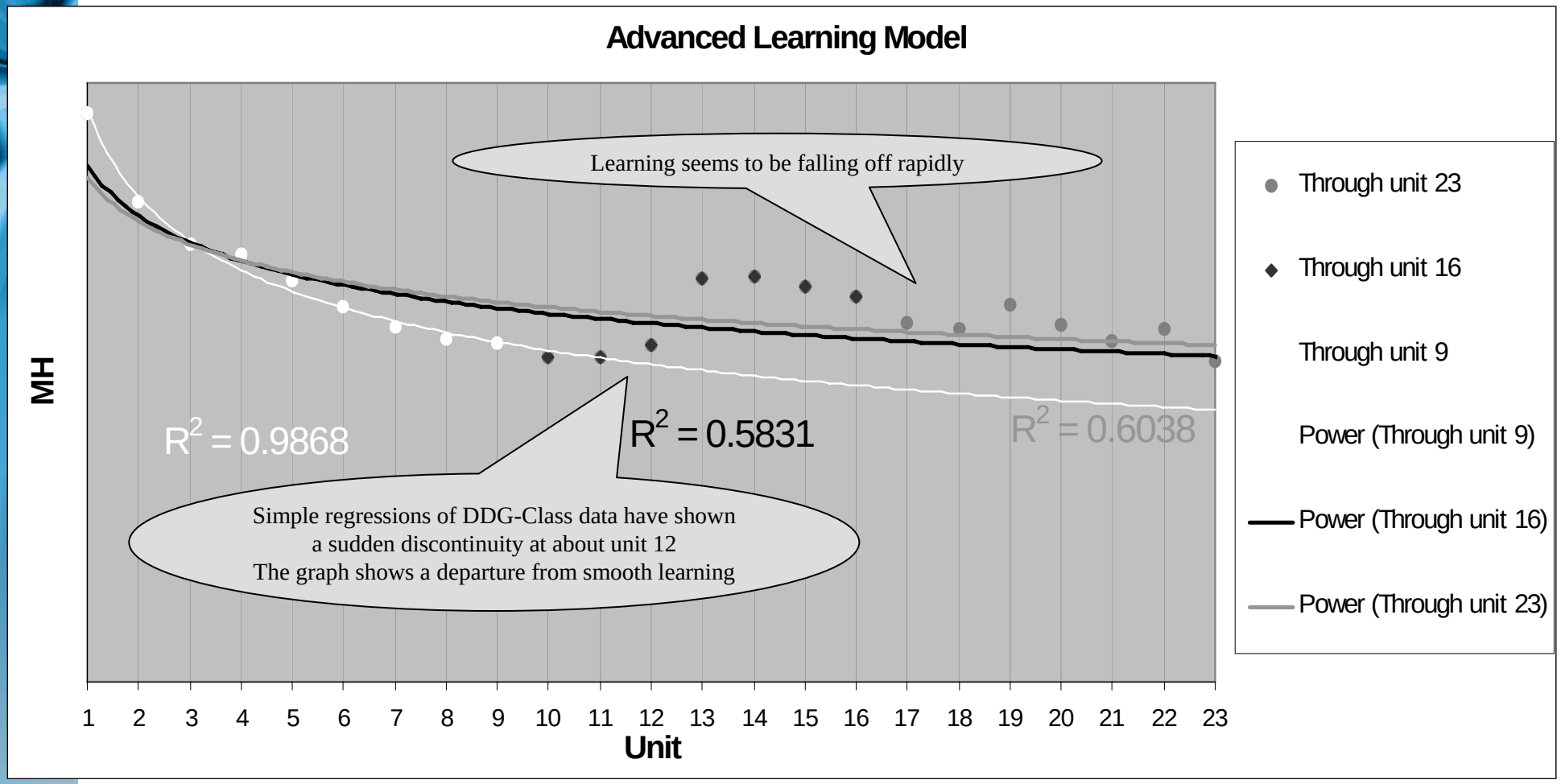
Original Work (w/ C/O)

Learning Curve Regressions through DDG 69 (9), DDG 86 (16) and DDG 95 (21)



Note: This is not a valid approach – it is a cautionary tale

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What is happening?

- **Learning curve theory requires:**
  - A steady work force
  - Building the same product multiple times
  - No significant interruptions or pauses
- **The DDG program wasn't like that, nor was the LHD program**
- **If these conditions are not fulfilled, there is <u>discussion</u> in the literature of loss of learning, but no <u>closed-form statistically based method</u> to predict how much learning is lost**
  - The Anderlohr Break-in-Production Model quantifies the effects of production breaks, but it requires expert opinion and so is not defensible – it is only useful when mutually agreed to
- **We will now look at the DDG case and show the ALM 1 approach by "peeling the onion"**

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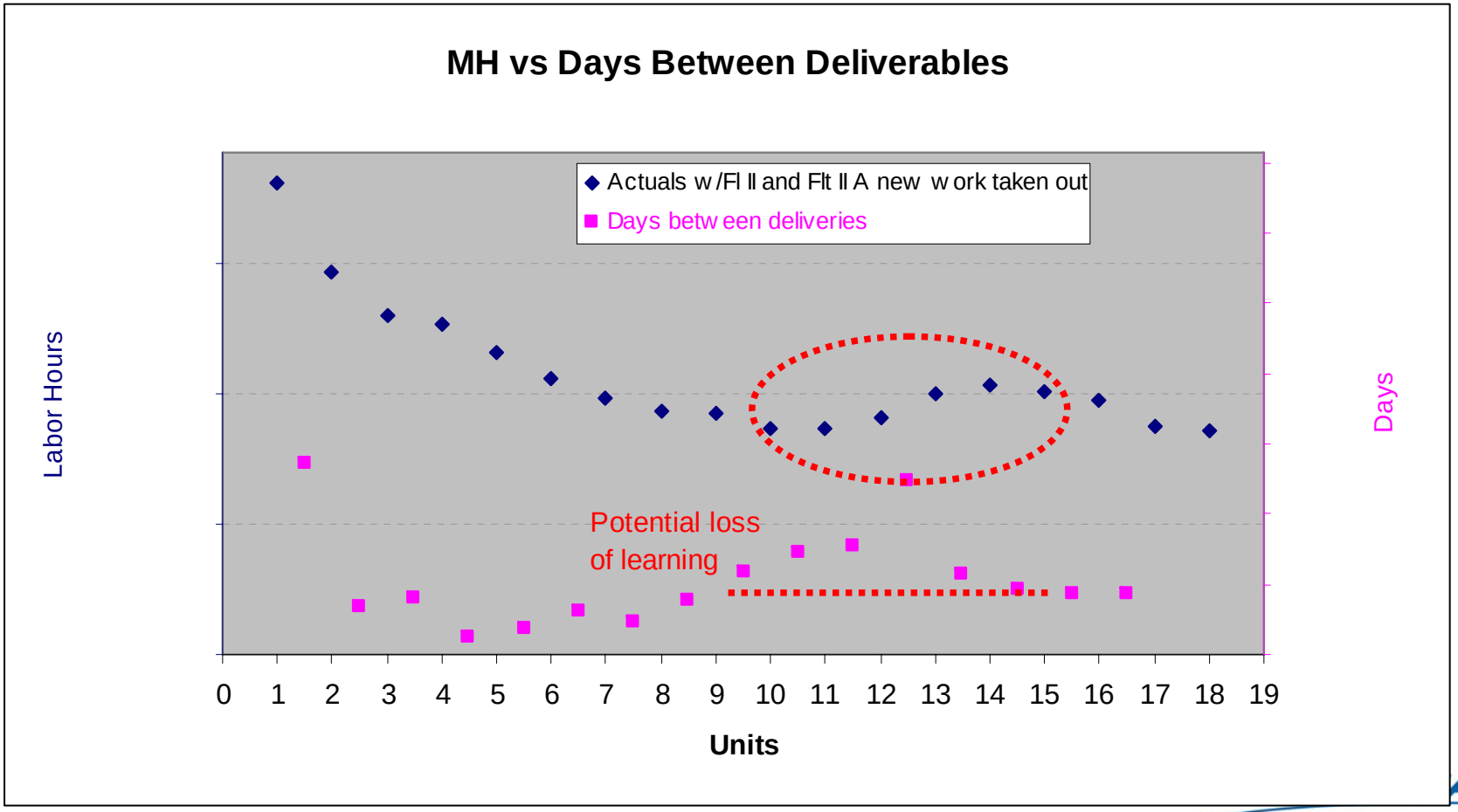
The Key Graphic
How One Graph Changed the Whole Approach

- **The below graphic, one of many scatter plots, proved to be the breakthrough**
- **Vessel Labor is plotted on the left axis, and interval between deliveries on the right**
  - The measure was later changed to Time Between Start Fab to avoid impacts of duration increases
  - The measure has again been changed to time between keel laying, a more dependable, and more widely available measure, but most of the analysis in this briefing is still in Start Fab terms



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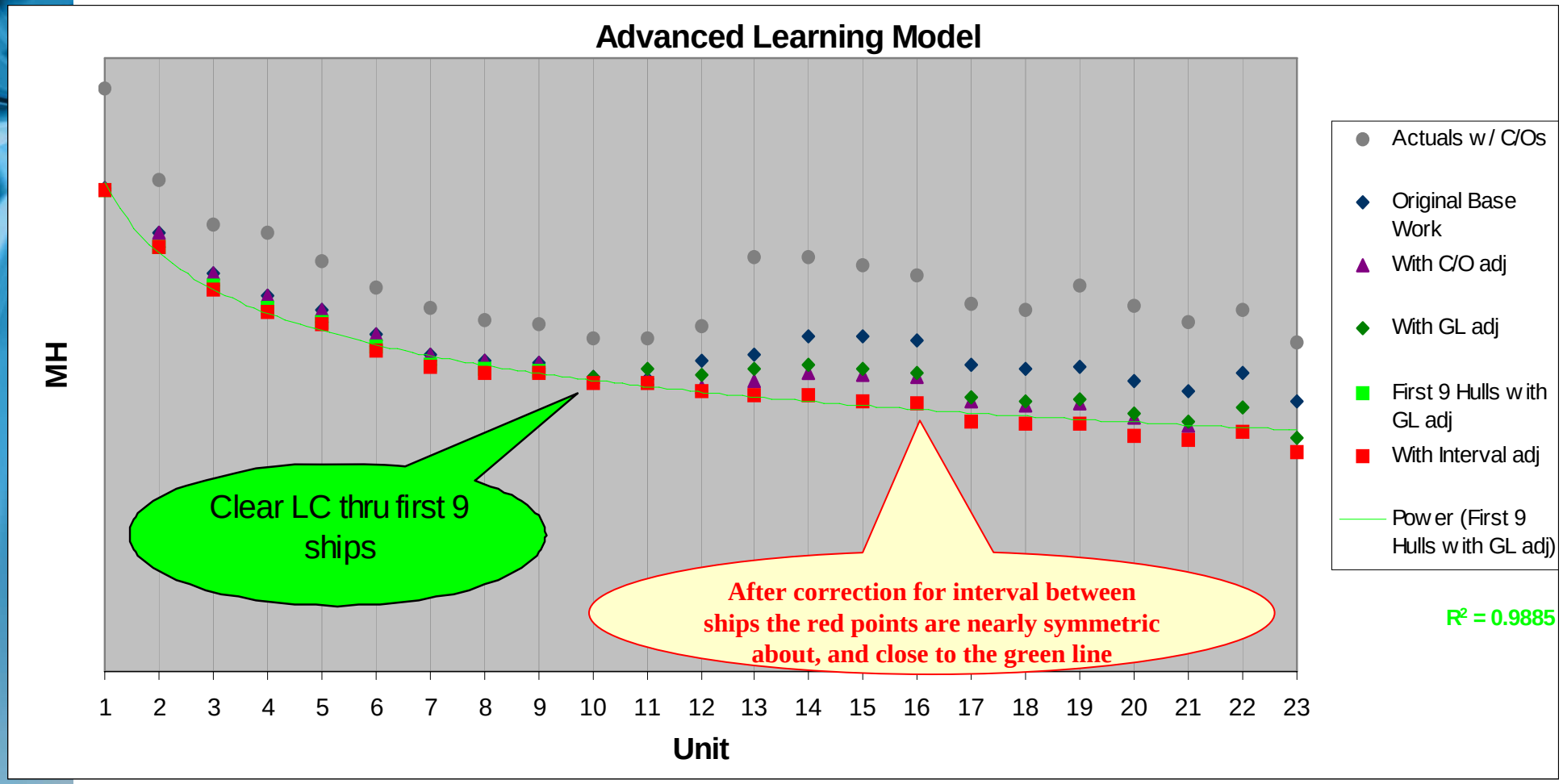
The Advanced Learning Model



- **We progressively applied adjustments to go from the original gray data points with "all effects in" to the final red data points with "all effects out"**

Supporting analysis to follow

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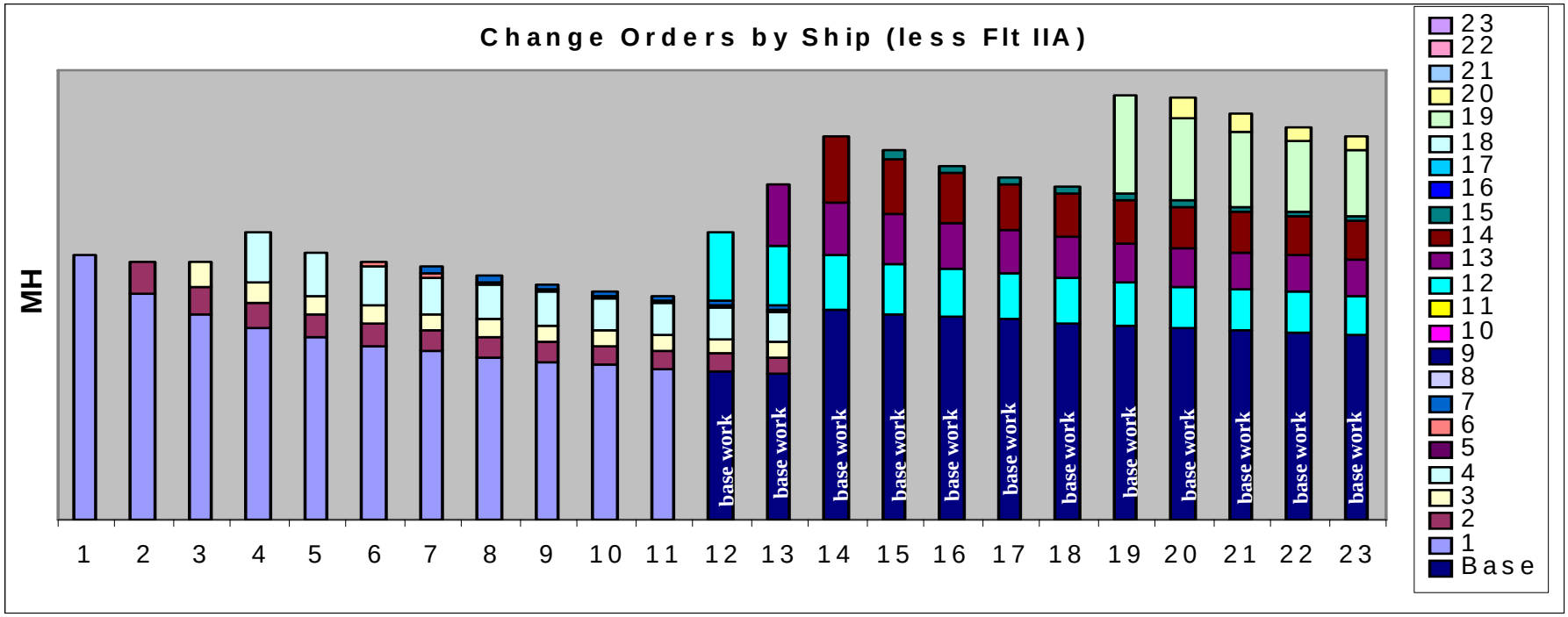
Change Order Model

Analysis for Step 2

- **Worked with Ingalls Change Order estimators to adjust total C/O values for Ripout, Disruption, and One-time changes, as well as absorption into base work**
- **Applied underlying % learning and used iterative process to determine "first-time changes" in work scope for each ship, these values were <u>not</u> recorded**
- **Interviewed senior engineers at Ingalls to determine where C/Os were absorbed into base work (reconciled with DDG RFPs)**
- **Results:**



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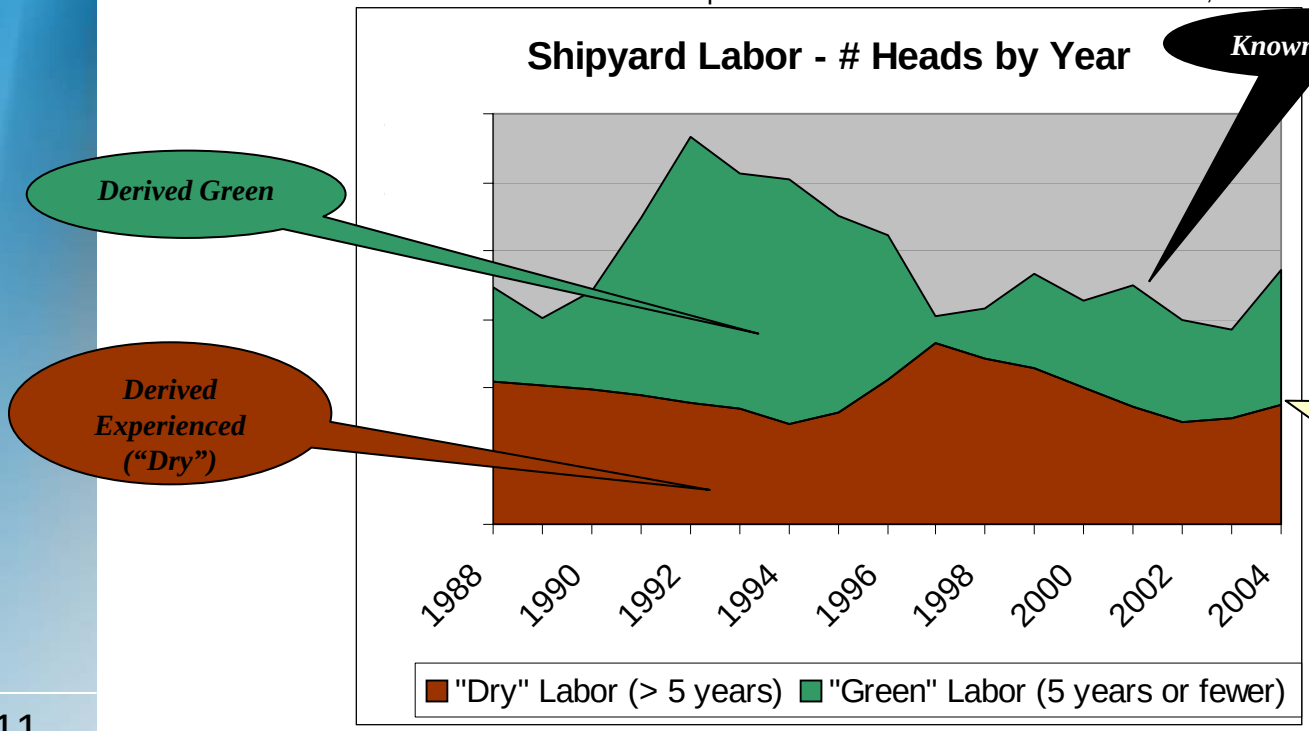
Green Labor Model

Analysis for Step 3

- **Assumptions:**
  - Green Labor is defined as a worker with <u>less than 5 years</u> experience; after 5 years, "Green Labor" becomes "Dry/seasoned Labor"
  - Green Labor is only partly as effective (% effectiveness = P) as Dry Labor (Ingalls study)
    - Newport News study shows a similar (lower) effect
    - Percentages probably differ with type of ship, yard, etc.
  - Green Labor is always hired and fired before Dry Labor
- **Using Ingalls Labor Data from 1988-2004 and third assumption above, derived average % Green Labor for each DDG**
  - Labor is split evenly throughout the shipyard with each class of ship receiving the same distribution of Green and Dry Labor
- **Adjusted all DDG hulls to notional Green Labor as follows:**
  - ((%DL + (P*%GL)) / (Notional%DL + (P*Notional%GL)) * MH
  - For example for a notional ship where average GL is 52.8% and initial manhours XXX the adjustment would be:
    - ((47.2% + (P*52.8%)) / (49.2% + (P*50.8%)) * XXX MH = YYY MH
    - Thus: If the notional ship had been built with notional Green Labor, it would have taken YYY MH



The Markov-chain model provides a result that is consistent with current green labor in the yard

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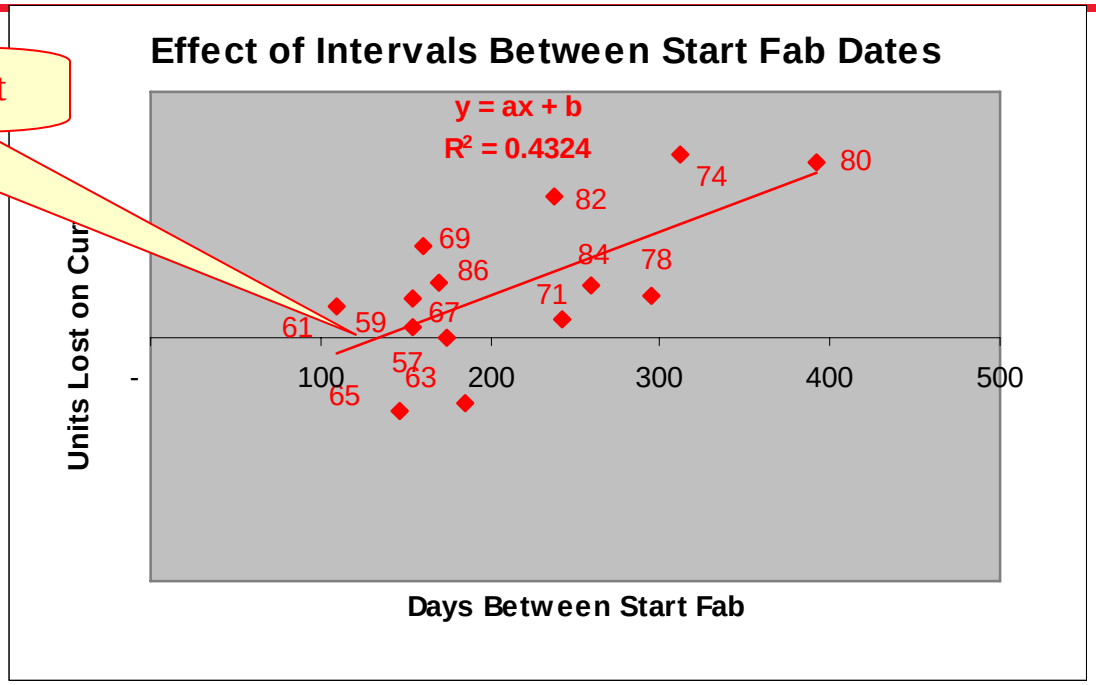
Interval Model

Analysis for Step 5

No-loss-of-learning point



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.6575657
R Square	0.4323927
Adjusted R	0.3850921
Standard Ei	0.6206015
Observatior	14

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	3.5207673	3.5207673	9.1413771	0.0105944
Residual	12	4.6217552	0.3851463		
Total	13	8.1425225			

	Coefficients	*tandard Erro*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.905235	0.4945857	-1.830289	0.0921419	-1.982844	0.1723748
X Variable		0.0021824	3.023471	0.0105944	0.0018434	0.0113535

Regression is significant at $\alpha = 0.05$ (p-value = 0.01)

Notes:

1) DDG 52 was omitted from the regression because DDG 52 has no interval by definition (there is no previous ship). DDG 55 was omitted because second ships have inordinately long gaps always, and do not seem to belong to the rest of the family. DDG 88-95 are omitted because the regression is meant to assess the impact of interval gaps and since DDG 88-95 are thought to have impacts due to facilities improvements, lean and six-sigma, etc in them, including them would have skewed the regression. In order to isolate the effect of the interval, we only regressed the "clean" points, 57-86.

2) R^2 and significance improve considerably with Keel Laying data

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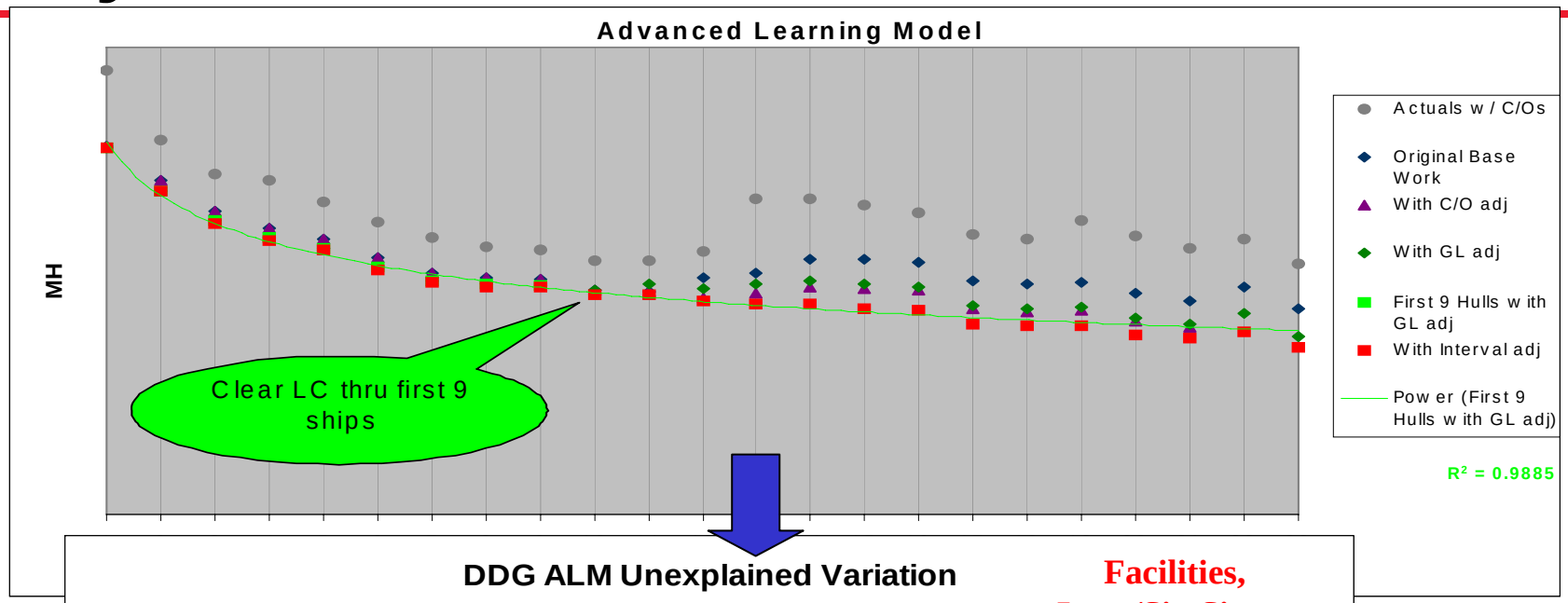
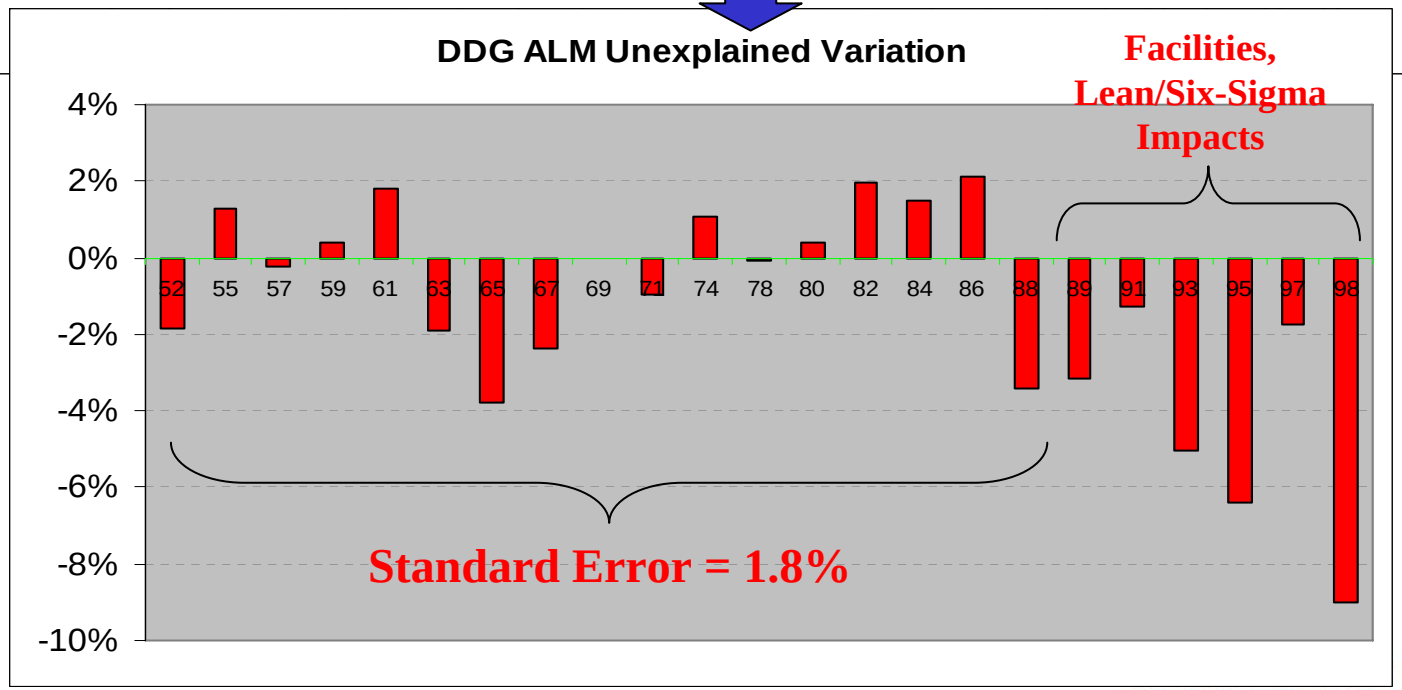
ALM 1 Unexplained Variation – DDG Analysis





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The LHD ALM: Validation of the DDG ALM LHD Class Learning Curve Analysis

- **The DDG ALM is complete and statistically valid**
- **We now turn to a second class of ship to ascertain whether the DDG ALM was an accident**
  - The science of statistics guards against this, but it is nevertheless customary to do a second independent trial to validate *important* studies

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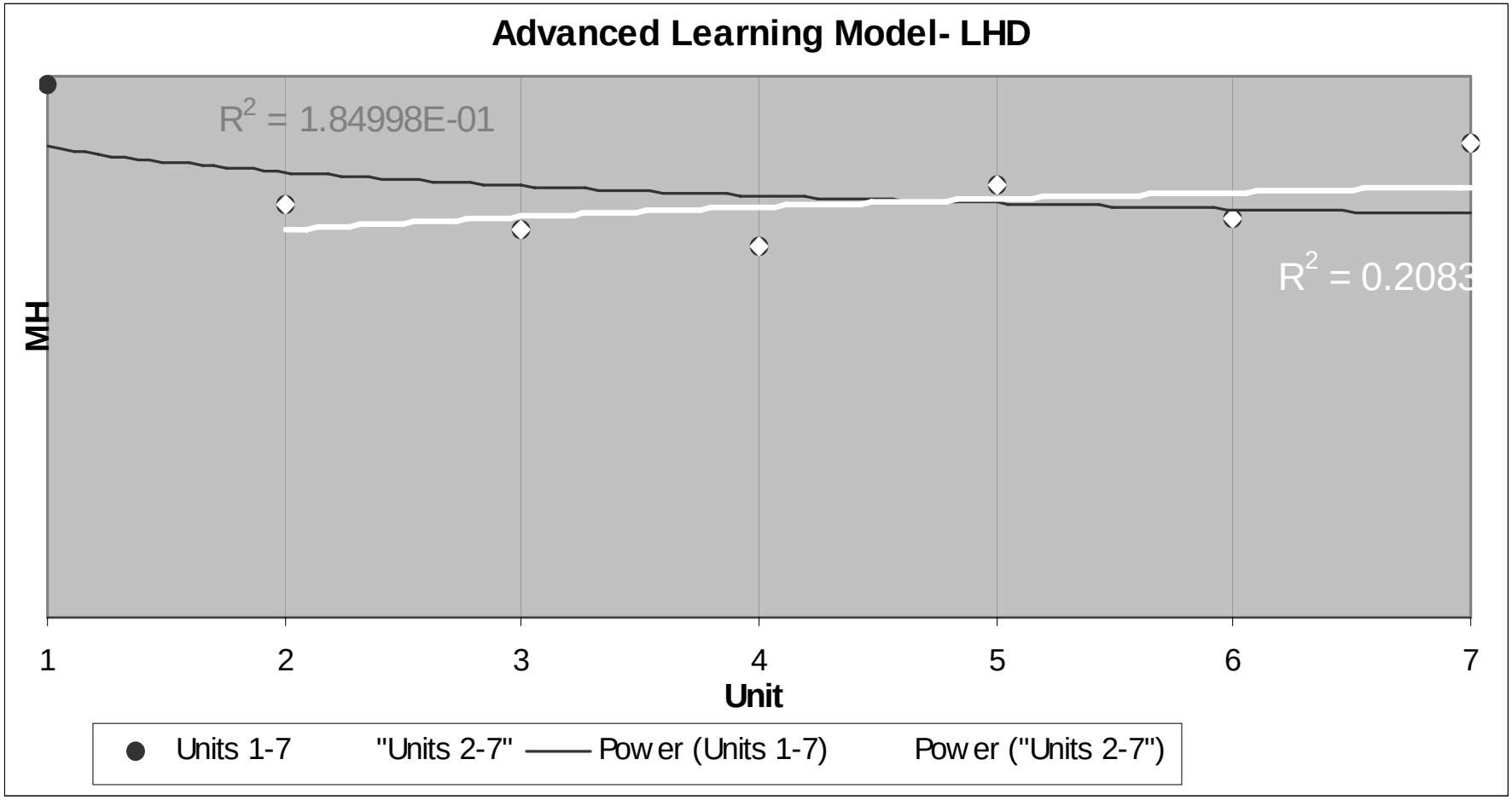
Original Work (w/o C/O)

Learning Curve Regressions through LHD 1-7 & LHD 2-7



Note: This is not a valid approach – it is a cautionary tale

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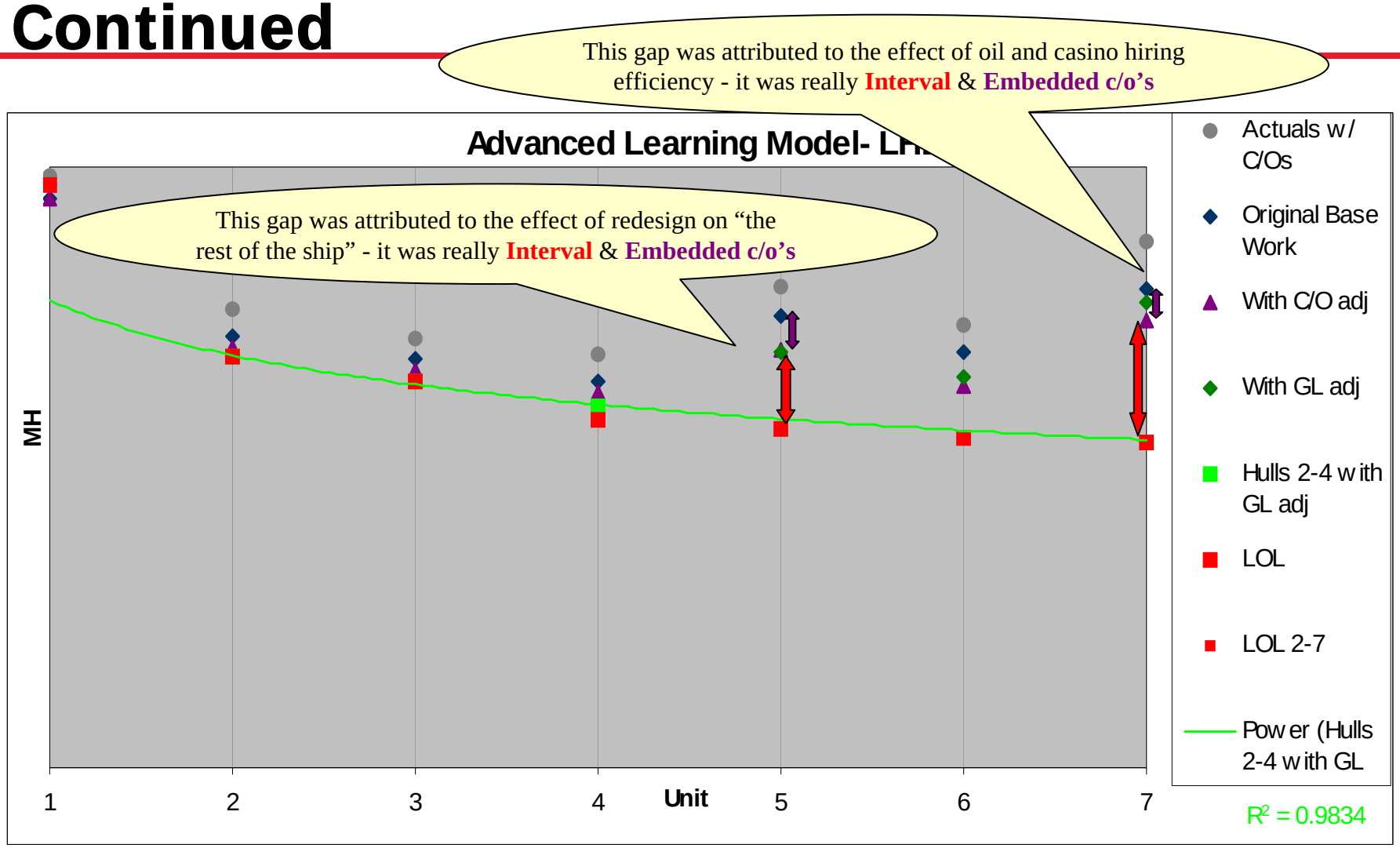
Advanced Learning Model: LHD Analysis Continued



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Change Order Model

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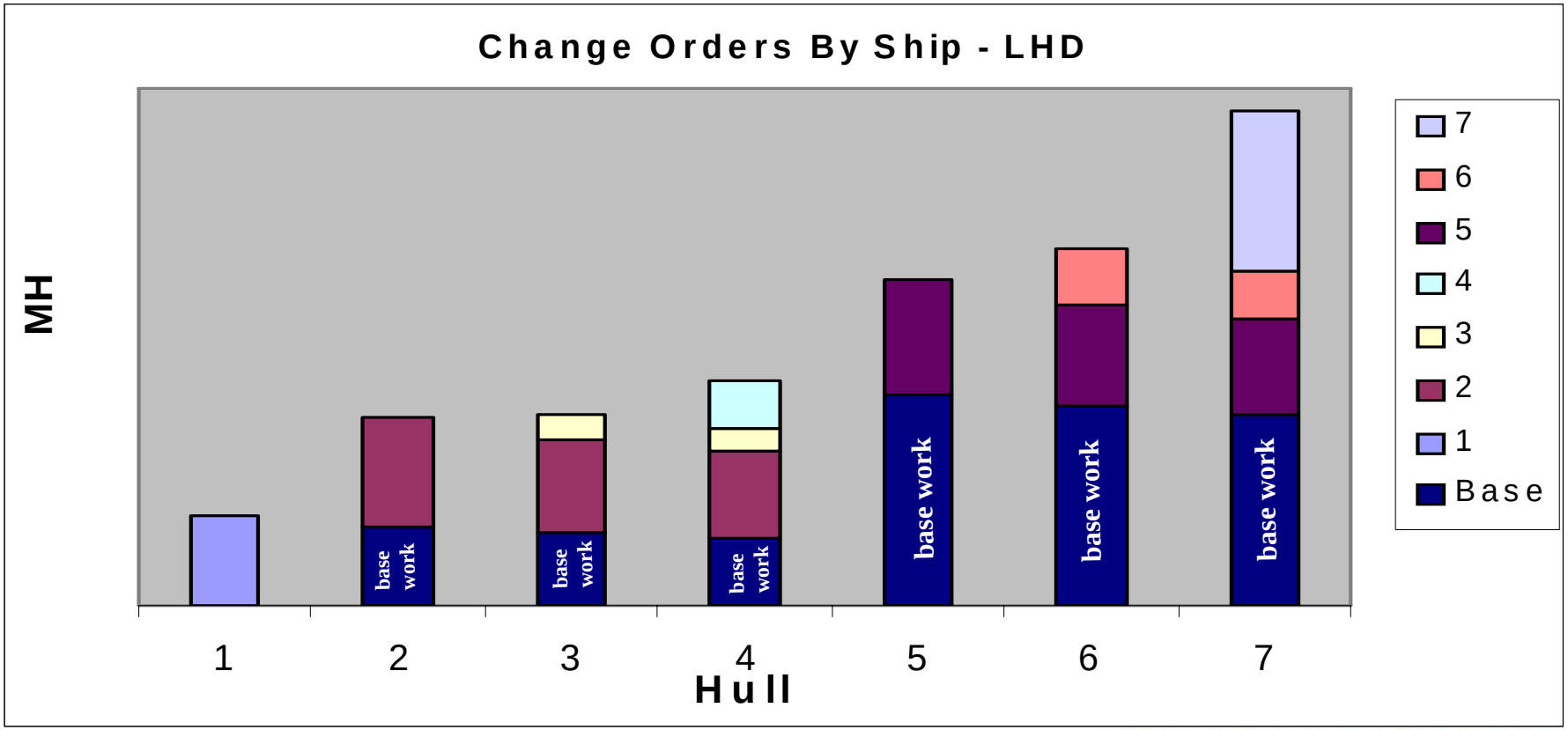
- **Interviewed senior engineers at Ingalls to determine where C/Os were absorbed into base work (reconciled with LHD RFPs)**
- **Results:**



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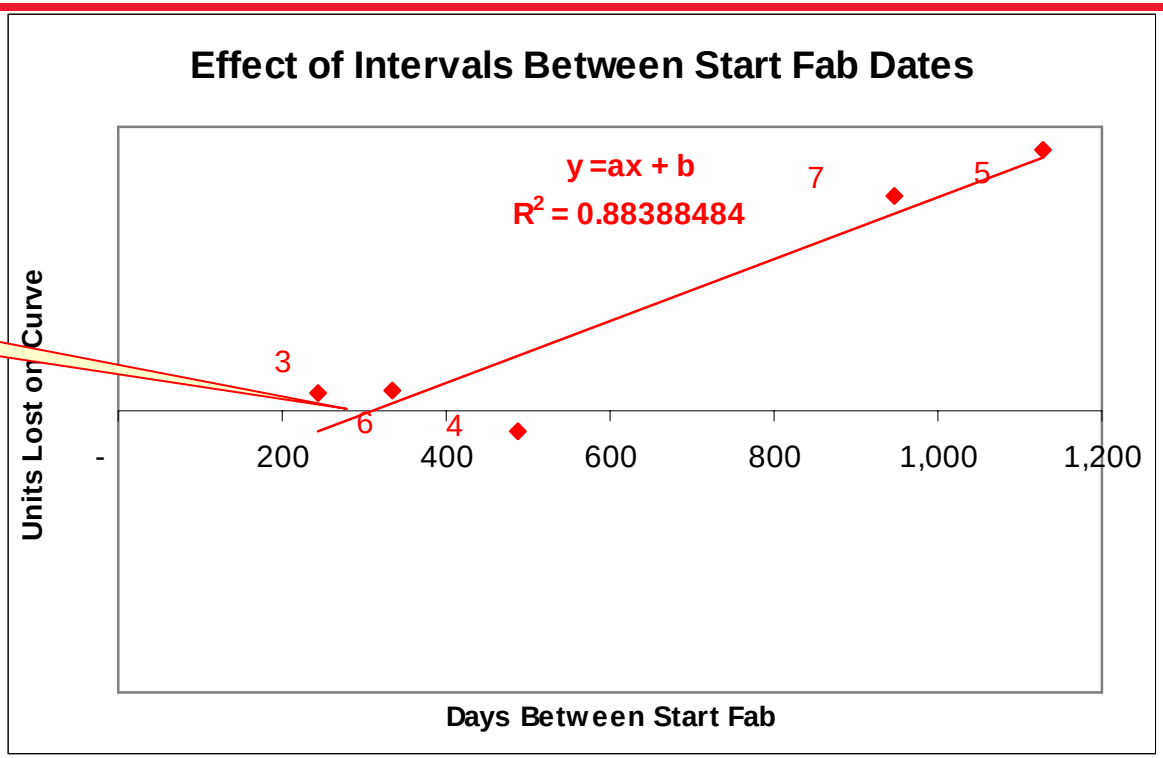
Interval Model

Analysis for Step 5

No-loss-of-learning point



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9421793
R Square	0.887701833
Adjusted R Sq	0.850269111
Standard Erro	0.623900889
Observations	5

ANOVA

	df	SS	MS	F	ignificance F
Regression	1	9.230961	9.230961	23.71459	0.016545
Residual	3	1.167757	0.389252		
Total	4	10.39872			

Regression is significant at $\alpha = 0.05$ (p-value = 0.017)

	Coefficients	andard Err	t Stat	P-value	Lower 95%	Upper 95%	ower 95.0%	pper 95.0%
Intercept	-1.238166072	0.575543	-2.1513	0.12056	-3.0698	0.593468	-3.0698	0.593468
X Variable 1		0.000802	4.869763	0.016545	0.001354	0.006461	0.001354	0.006461

Notes:

1) *LDH 1 was omitted from the regression because LHD 1 has no interval by definition (there is no previous ship). LHD 2 was omitted because second ships have inordinately long gaps always, and do not seem to belong to the rest of the family.*
2) *R^2 and significance improve considerably with Keel Laying data*

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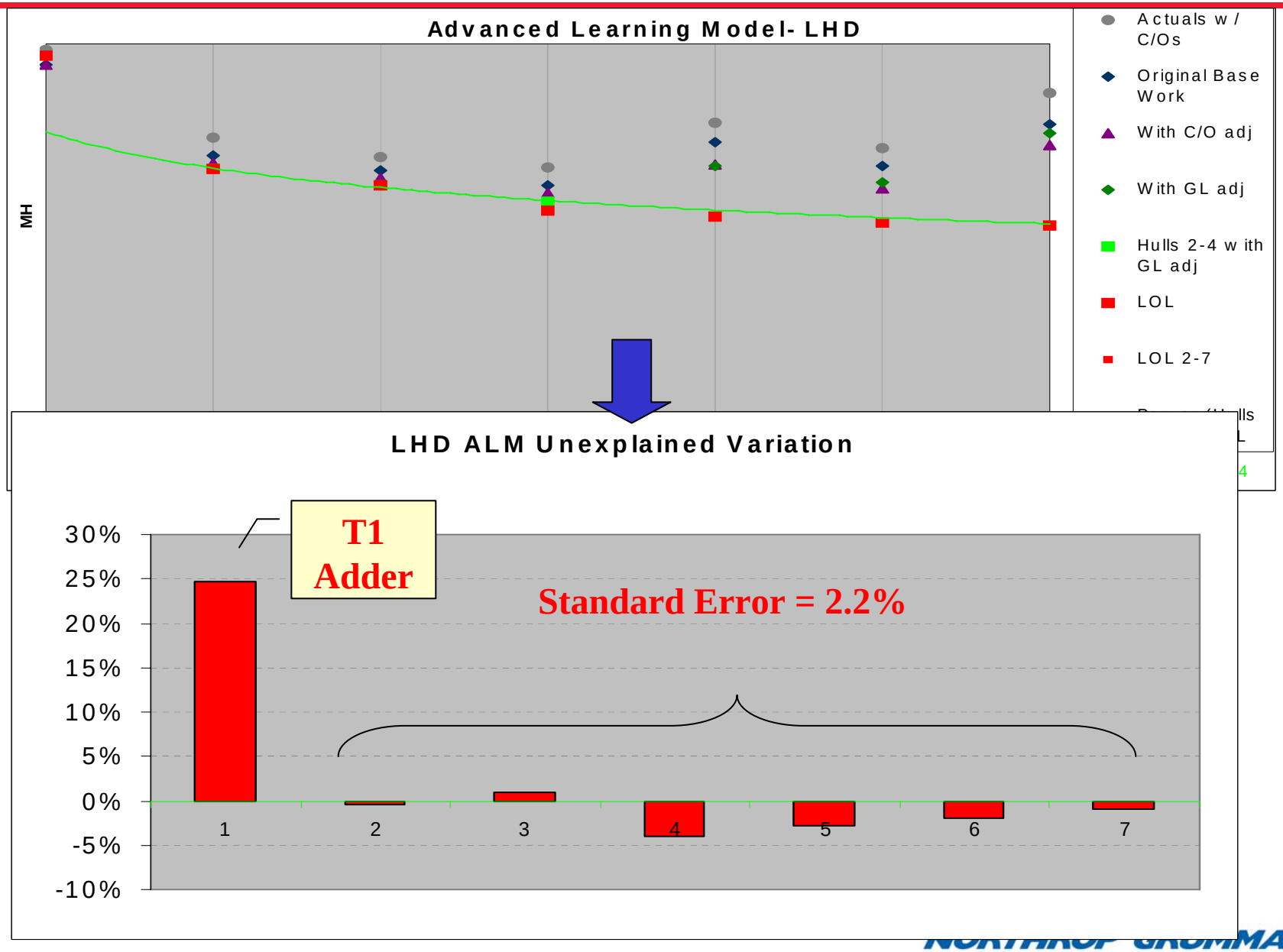
ALM 1 Unexplained Variation – LHD Analysis



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Meta-analysis and Mutual Confirmation

- **To summarize the results of the two models taken alone:**
  - The DDG model is valid, as far as statistics can take us
  - The LHD model is also valid
  - We can use either
  - The LHD model represents a second ship class and was undertaken to confirm the DDG model, after the DDG model was complete
- **Taken together, the LHD and DDG models are much stronger than either alone**
- **The models are mutually confirming**
  - Taken alone, the DDG analysis has the usual weaknesses of "first models"
    - Although reasonable, the adjustments were taken with a view to arrive at a smooth learning curve
      - Statistically, this amounts to an uncredited "loss of degrees of freedom"
      - Alternatively, a hostile view can arise that the "data was cooked"
    - The LHD model alleviates this concern
      - Since the steps taken with DDG were replicated in LHD and the same result was obtained, it was not dumb luck or manipulation
  - Taken alone, the LHD analysis lacks data across the full spectrum of interval length
    - The DDG model alleviates this concern
- **The significance of the entire analysis is the product of the significance of each**
  - This is called meta-analysis and is a well known statistical technique
  - The combined test is thus performed at the significance level of $0.05^2 = 0.0025$ (.25%) and passes with a combined P value of (0.011)(0.0165) = 0.000182 (.0182%)

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Slide 21

ERD1 I believe the correct meta-analysis is as follows

DDG Significance of .011
LHD Significance of.0165

Probability that both are correct =
(1-.011)x(1-.0165)
0.989x0.9835 = 0.9726815
1 - .973 = .027 < .05
Q.E.D. the models taken together are significant
Eric Druker, 5/31/2007

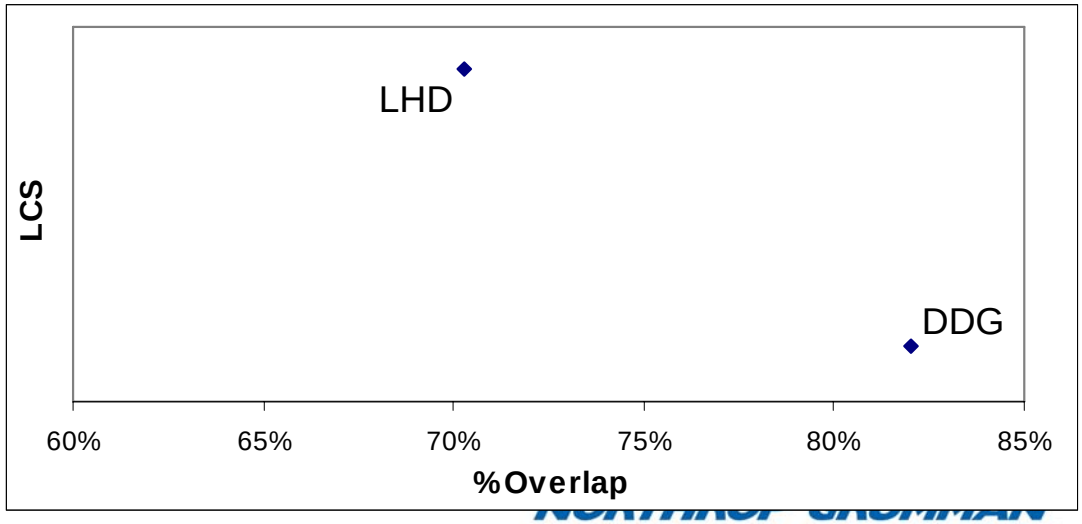
The Transition from Interval to % Overlap

- The Interval Model demonstrates a relationship between schedule and LC slope within a given ship class
  - In its original form, this model could not be extrapolated for use in other ship classes
- To solve this, "days between ship starts" were translated into "% overlap" for both classes (DDG and LHD)
  - % Overlap: (Delivery Date (lead ship) – Keel Date (follow ship)) / Duration (lead ship)
  - Duration (days): Delivery Date – Keel Date
  - I.e., the % that LHD 4 overlaps with LHD 3 is found as follows:
    - (Delivery Date (LHD 3) – Keel Date (LHD 4))/ Duration (LHD 3)
- The observed learning curve slope was plotted against the average percent overlap of the ships which demonstrated the learning curve
- The graph *suggests* a relationship between % overlap and LCS

An Illustration of the Two Metrics

---------- Lead ship Duration = 16
---- Interval = 4
---------- Overlap = 12 = 75%
---------- Follow ship Duration = 16

Time >



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ALM 3 - % Overlap and LC

- The suggestion from the previous graph prompted an investigation of other ship classes
- A learning curve slope and associated average % overlap were found for:
  - DDG Ingalls, Aegis
  - LHD Ingalls, amphibious, very large
  - CG 47 Ingalls, Aegis
  - CGN 38 Newport News, nuclear
  - MHC Avondale, composite hull, mine hunter, very small
  - SSN 688 Newport News, nuclear, submarine
- When graphed along with DDG and LHD, a relationship between % overlap and LC was evident
- This relationship can be used to predict the LC of a future class with a known schedule (absent effects of Change Orders and Green Labor)
- This result is remarkable on it's own, but especially when the wide diversity of the ship types is taken into account

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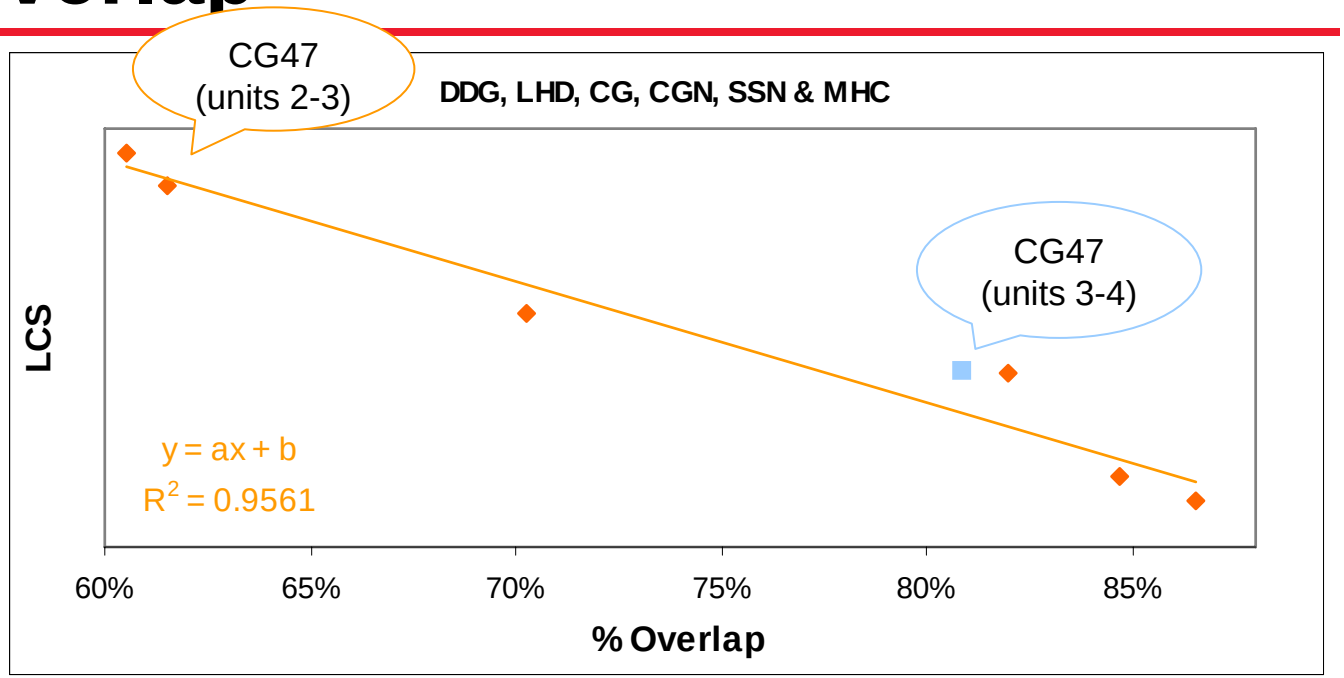
LCS vs. % Overlap



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.97778437
R Square	0.95606228
Adjusted R Square	0.94507785
Standard Error	0.0145826
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.018508806	0.01850881	87.037946	0.000734819
Residual	4	0.000850609	0.00021265		
Total	5	0.019359414			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.25779617	0.041795155	30.0943058	7.261E-06	1.14175422	1.37383813	1.14175422	1.37383813
X Variable 1		0.055700939	-9.329413	0.0007348	-0.67430767	-0.3650065	-0.6743077	-0.3650065

- The **orange points** were used in the regression; the **blue point** is a second point from the CG47 class which follows the same trend as the other data
- **This point** experienced a significantly different LCS and % overlap than the **point** used in the regression

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Implications and Bold Claims

- **It very much appears that ships of very different size, complexity, density, mission, hull material, shape, and builder can all be characterized, as far as LC, through the proxy variable of duration**
- **We have anecdotal evidence that other commodities, UAVs and satellites, may fit right along the same line.**
  - We assert that this is true, and are in the midst of demonstrating it
  - Even if it is not true, we assert that different commodities have their own coherent line
- **This may all seem hard to believe, but remember that LC is an amazingly robust application that works uniformly across almost all commodities … perhaps it should not surprise us that, being a universal phenomenon, it has universal traits?**
- **If it is true … *the results for the implications for cost estimation are profound, because LC has been very elusive in prediction, and yet is the dominant factor in program costs***

The authors have a deep-seated belief in what we call "beautiful numbers and beautiful relationships" which we hold to be all around us … Dirac shared this belief!

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ALM 2 – The Enterprise Model

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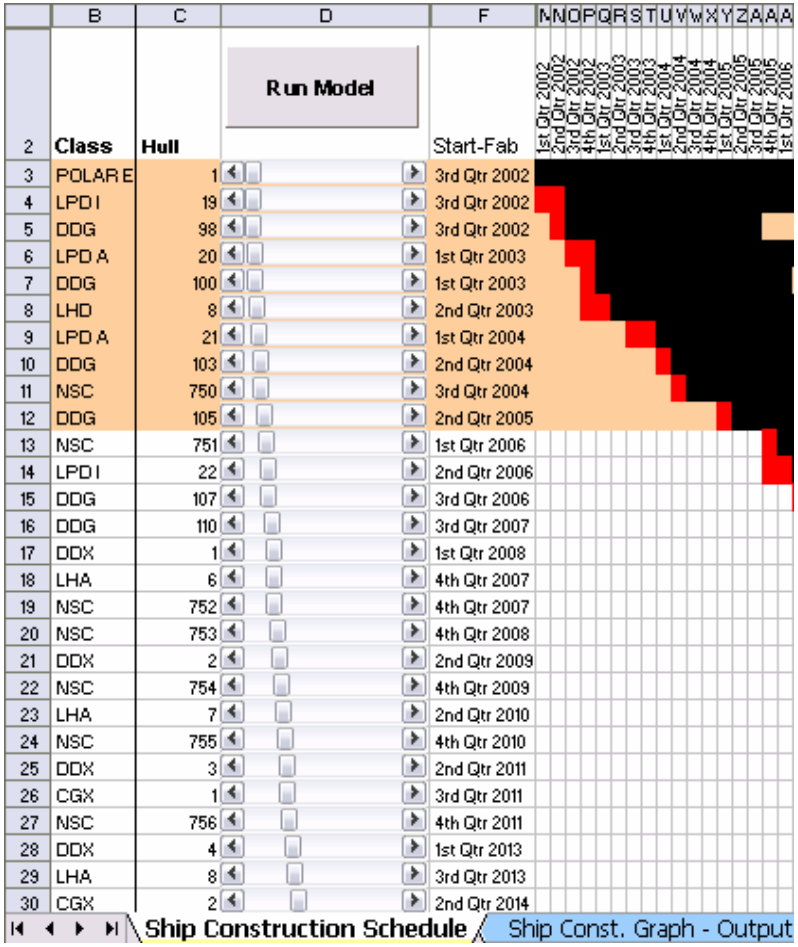
ALM 2 The Enterprise Model

Ship Construction Schedule Generator

- **ALM 2 is a visual basic model that extends the results of ALM 2 (and, when re-coded, ALM 3) to an entire shipyard enterprise**
- **The model is easily loaded with all ships in the enterprise**
  - Schedules and durations
  - Preliminary MH estimates for first ships (T1s)
  - Indicator of lead ship (extra change orders)
  - Indicator of first-ship-lead-yard (T1 Adders)
  - Indicators for planned flight changes (extra change orders)
- **The model produces:**
  - ALM estimates for all ships
  - Interactions among ships via Green Labor
  - Ship-by-ship labor profiles



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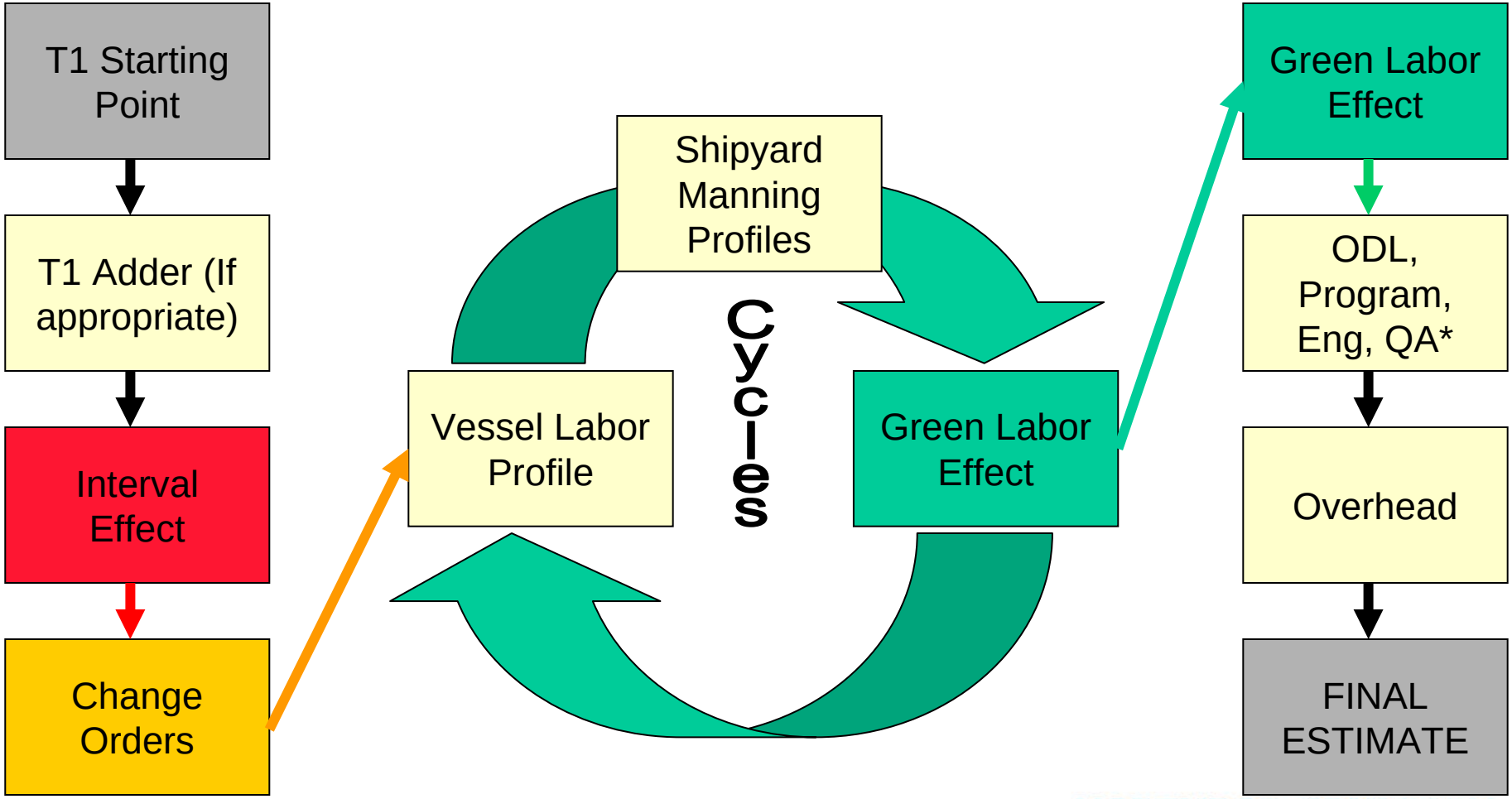
ALM-2 Model Summary

- ALM 2 is a Visual Basic model that creates an entire enterprise schedule
- ALM 2 can model the enterprise effect of new ships, and the converging “feedback loop” of the Green Labor effect (increased inefficiency of added GL -> more hiring -> labor rises for all ships-> more hiring)
- The problem had been to specify the LC of a new class, ALM 3 will remove that last hurdle



*Overhead computed on all labor minus QA

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Advanced Topics

Implications & The Way Forward for ALM 3

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From Loss of Learning (LOL) to Change in LC (CLC)

- **The ALM is a work-in-progress,**
  - This brief has been in work since 2003, this is version 39
- **The very next step is to generalize to other commodities, we will then re-frame the ship analysis**
  - Until a May 2007, the model was stated in terms of Loss of Learning with increased interval between Start Fab
  - We are in the midst of a restatement of the model in terms of
    - Keel Date, a more reliable metric
    - % Overlap, which is a simple scale change, but which appears to unify ship classes onto a similar scale
    - We already did this successfully for DDG and LHD
- **After that we may restate the model into Change in Learning Curve**
  - This would be ALM 4
  - This is proving problematic, but we are hopeful that the math will work out well and the model will be more general than ALM 1
  - We have shown that this works for two CG 47 ship pairs, units 2-3 and 3-4
  - We hope to demonstrate a graph of % Overlap vs. LC for an entire ship class, pair-wise, and that various ship classes will plot on one graph and line in the same way
    - This has already been tentatively shown for the two CG 47 pairs
- **Difficulties**
  - We note that if overlap is less than 49.4%, there will be no learning, so we must cap the expression
  - The linear equation gives no way to predict loss of learning beyond one full unit
    - We may need to use the linear overlap to predict LC and the interval version to predict ship-by-ship loss of learning

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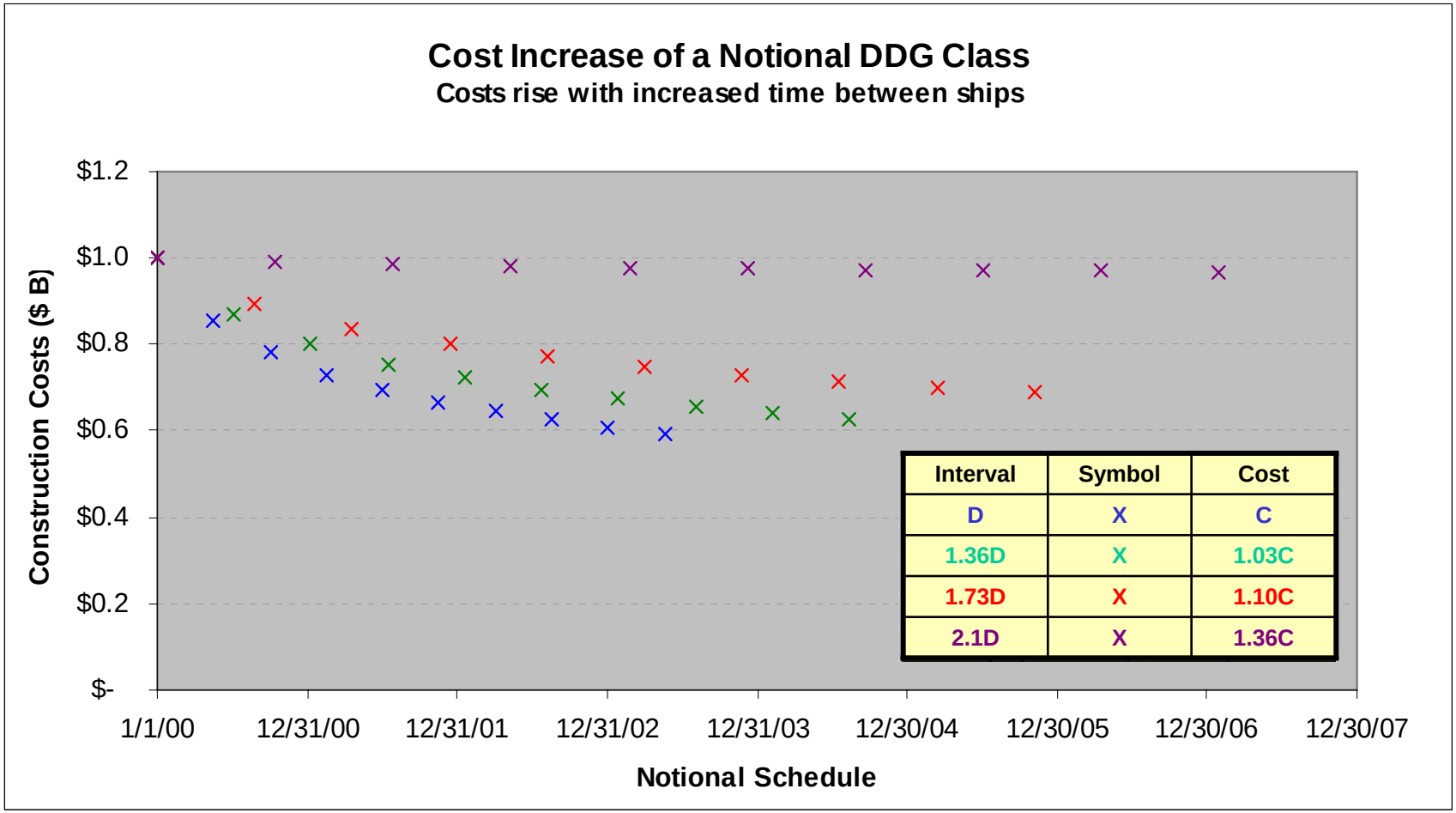
Observation: The Effect of Construction Stretch-out on Labor Cost

- A notional 10-ship class is shown with increasing intervals between Start Fab for all ships – a uniform stretch-out
- As ship intervals increase, learning is increasingly lost until there is no learning
- This is the Loss-of-Learning view; the changing-LC view would be similar



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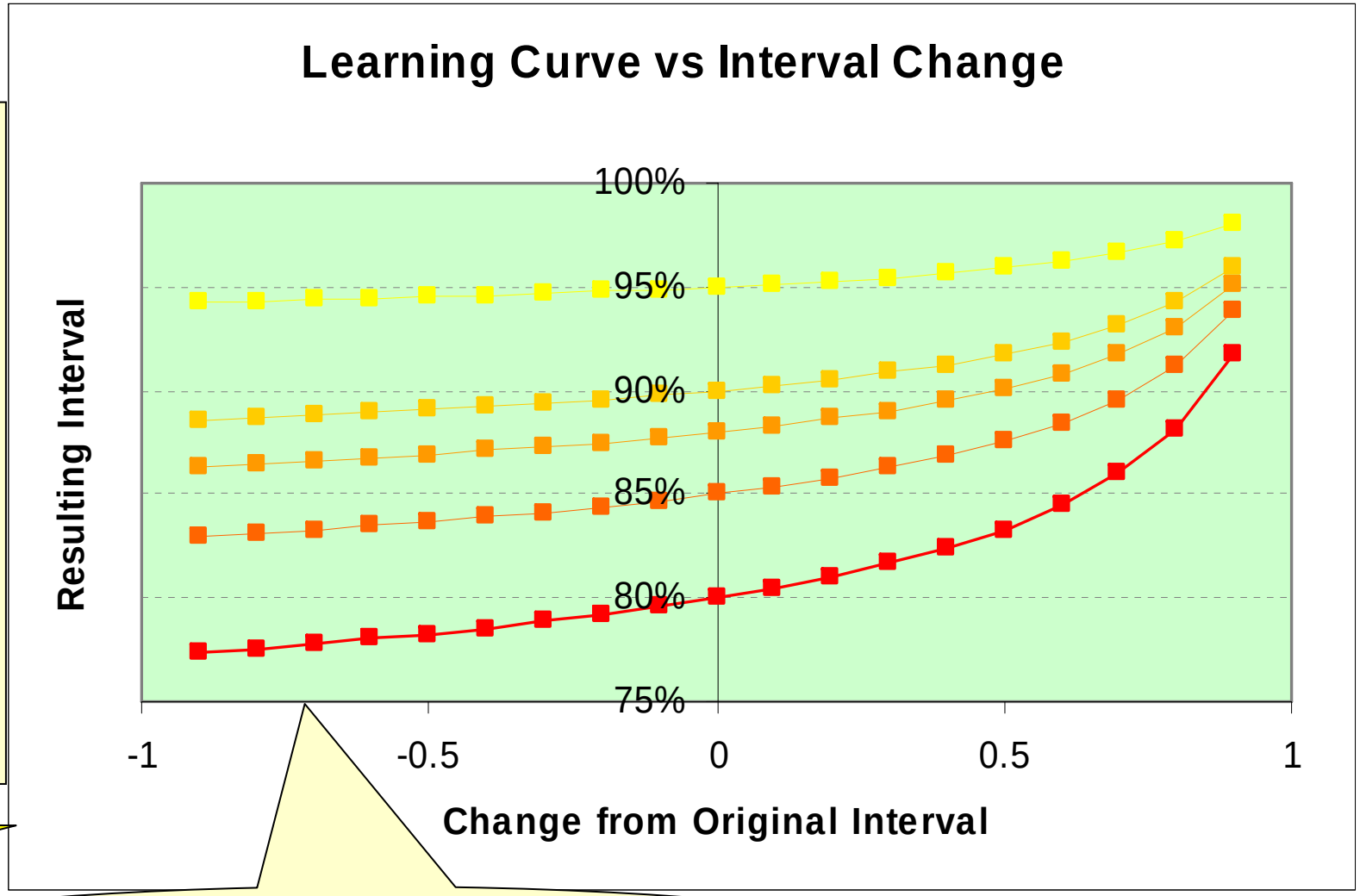
Observation: Learning Curve Changes with Interval!

- **Assuming the ALM is correct, what happens if <u>all</u> ships are spaced wider or closer?**

- "Nearly perfect" smooth LCs result from uniform spacing
- Perhaps there are neither optimal intervals nor natural LCs
- Research topic: Is there a way to predict the "right" initial curve and interval as a function of size or construction duration?



An old slide came true!!

This part of the graph has practical limits - if shipbuilding teams can't roll from ship to ship, there will be no learning

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Conclusions

- **The ALM 1 gives us a coherent picture of the past in the backward-looking model**
  - DDG ALM is complete
    - Demonstrates underlying LC for DDG
  - LHD ALM is complete and acts to verify the DDG ALM
    - Demonstrates underlying LC for LHD
- **The ALM 1 is also a Forward-looking Model that can handle most likely disturbances to cost improvement in the future:**
    - Green Labor
    - Intervals between Start Fab
    - Change orders – including c/o's absorbed into base work
- **The ALM 2 extends the findings of the ALM 1 to a shipyard-wide enterprise**
- **The ALM 3 is a *minor change* to the ALM 1 and a *major breakthrough* in Learning Curve determination:**
  - Shifts the basis of the ALM 1 from days between Start Fab to percent overlap, and allows us to move to other classes
  - Shows that percent overlap or production durations may be the only variable needed to predict LC for a ship class
    - We are investigating the clearly close resemblance of "Loss of Learning" to "Change in LC slope" … in CG 47 we observed the latter … we may end up changing the entire algebraic expression of ALM 1 from the former to the latter
    - The ALM 3 may apply to other (All, Large, Complex?) commodities

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