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Improvement Curve Cost Model and Revenue Cost Model

Ashutosh R. Nandeshwar and Dr. Robert C. Creese, PE CCE

After 20-30 years ships are at the end of their effective service life [9] and they are then dismantled. Ship dismantling in the US is quite different from in developing countries, and ship deconstruction costs are much higher in the US. The ship deconstructors in developing countries earn significant profits because of lower recycling costs of the ships and higher resale values of the scrap. Previous cost models [4,3] developed estimated the cost of ship deconstruction, but the improvement effects from learning were not included. The data on the ship deconstruction cost were sparse, and the improvement curve or learning curve theory was applied to the available data to develop an improvement curve cost model for ship deconstruction.

IMPROVEMENT CURVES

T.P. Wright [11] introduced the concept of learning curves or improvement curves for premanufactured assemblies in 1936. Wright described a basic theory for obtaining cost estimates based on repetitive production of assemblies. The theory is that the direct labor workhours necessary to complete a unit of production will decrease by a constant percentage each time the production quantity is doubled. If the rate of improvement were 20 percent between doubled quantities, then the learning percent would be 80 percent (100 - 20 = 80). The term *improvement* is preferred over *learning*, as a 20 percent improvement is better than a 10 percent improvement, whereas in learning an 80 percent learning rate is better than a 90 percent learning rate, which is contrary to most people's expectations. The most common applications occur in the instances where units of the same type are produced, such as airplane assemblies or ships and where the unit costs are extremely high and the production quantities are relatively low; less than 1,000 and usually less than 100 units. The improvement curves are also known as progress curves. The most common form of the relationship between inputs per product is a linear log-log model in the form of the function:

$$Y = a X^{b}$$

(equation 1)

where

Y = input cost for the x^{th} unit,

X = cumulative number of units produced,

a = input cost for the first unit, and

b = improvement exponent.

The improvement exponent is calculated by

$$b = \frac{\log\left(\frac{100-I}{100}\right)}{\log 2}$$

(equation 2)

where

I = improvement rate.

Table 1 shows an example of constant reduction as the production quantity is doubled. The time taken for the first unit is 100%. At a 10 percent improvement, the average time taken for the second unit is 90 percent of the time taken for the first unit. By the time the fourth unit is reached, the unit time taken for the fourth unit is 90% X 90% = 81%, and so on. These values can be plotted on as shown in Figure 1 and on log-log paper as shown in Figure 2. Figure 2 shows straight lines for both ratios.

WRIGHT MODEL AND CRAWFORD MODEL

The Wright model introduced the concept that as the total volume of units produced is doubled, the average cost per unit decreases by some constant percentage, which is given by equation 1.

Equation 3 gives the cumulative time for the production of N units as per the Wright model.

$$TC_W(N) = a X^{b+1}$$

(equation 3)

where

TCW = total cumulative time (cost) of the Wright model.

The cumulative time to produce N units can be obtained by the Crawford model as given by equation 4.

$$TC_C(N) = \frac{a}{b+1} \times \left[\left(N+0.5\right)^{\mathbf{b+1}} - 0.5^{\mathbf{b+1}} \right]$$

(equation 4)

Table 1—Unit Time for Two Different Improvement Ratios

Number of Units In Sequence	10 Percent Improvement (90 Percent Learning Ratio)		20 Percent Improvement (80 Percent Learning Ratio)	
	Unit Time	Cumulative Time	Unit Time	Cumulative Time
1	100.0	100.0	100.0	100.0
2	90.0	180.0	80.0	160.0
4	81.0	324.0	64.0	256.0
8	72.9	583.2	51.2	409.6
16	65.6	1,049.8	40.9	654.4
32	59.0	1,889.6	32.8	1,049.6
64	53.1	3,401.2	26.2	1,679.4
128	47.8	6,122.2	21.0	2,687.0

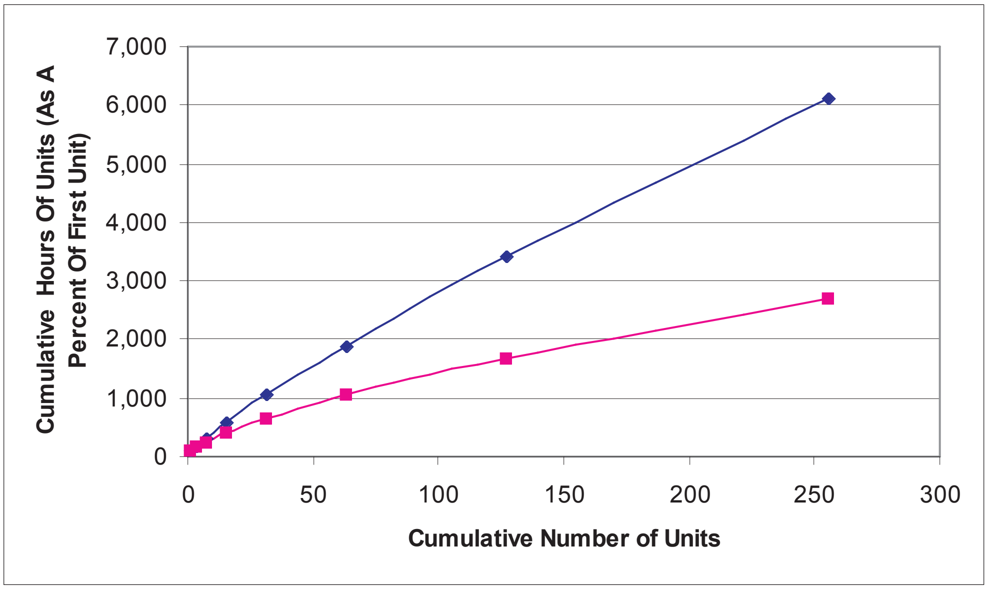

Figure 1—Improvement Curves

where
TC_C = total cumulative time (cost) of the Crawford model for N units.

IMPROVEMENT CURVE COST MODEL FOR SHIP DECONSTRUCTION

The application of improvement curve theory to ship deconstruction requires modification, as the ships are not the same size even though they may be in the same class. The recent data indicated the ship size varied between 3,000 and 6,000 tons, so the traditional discrete number of ships was not used. Instead, the variable selected was the total tonnage of ships by a particular ship deconstruction contractor. The initial costs for the deconstruction of a military ship in the US were over $1,000/LSW ton. The corresponding cost for ship deconstruction of merchant ships in developing nations was less than $200/LSW ton. The net costs, after revenues were considered, initially were still more than $1,000/LSW ton in the US, whereas the developing nations were making a profit. Parts of the cost differences were due to lower labor costs, lower overhead and administrative costs, less stringent environmental controls, and poor safety regulations in developing countries, even though the US had higher productivity levels. The cost reductions from improvements in work methods and scheduling due to experience are expected to reduce the net costs in the US to the $200-$400/LSW ton level if the ships are scrapped on a continuing basis.

The US Navy provided cost data [1, 2] on several ships that had been deconstructed or were in process of being deconstructed. Since the ships were of different sizes, the improvement analysis used the tonnage of the ships rather than the number of ships. The data were analyzed for two different ship deconstruction contractors on a cumulative tonnage basis. The data that were provided gave an average cost per ton, so the Wright model was used rather than the Crawford model for determining the improvement

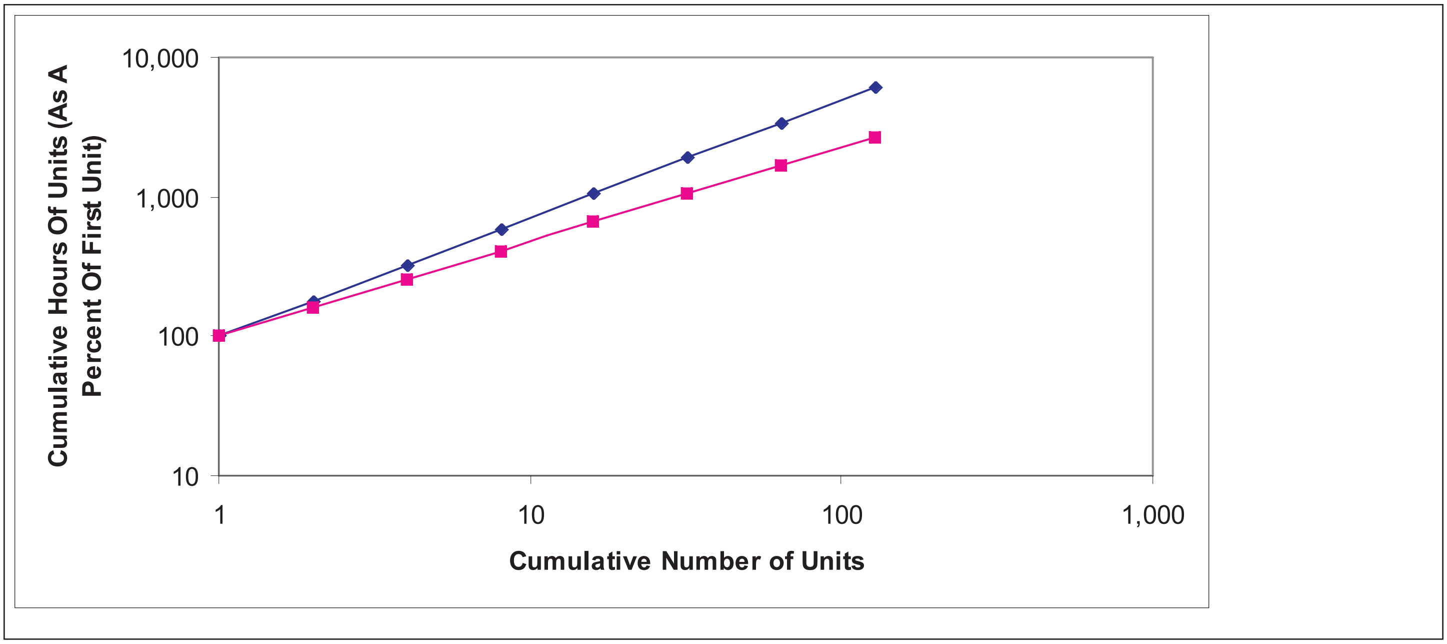

Figure 2—Improvement Curves on Log-Log Paper

rates. The data were presented as net cost, which did not include the proceeds. One of the contractors reported no proceeds, as they sent the scrap to a subcontractor for final processing and allowed the subcontractor to keep all proceeds. The first contractor reported no proceeds after the first contract, so the value calculated for the first ship was assumed to apply to the following ships, although it was much lower than the value of the other contractor or that estimated by the revenue model developed. The first contractor did the initial deconstruction and gave the materials to a subcontractor who completed the deconstruction process for the value of the scrap materials. The data utilized for the models developed are presented in Table 2.

The value of the proceeds reported by the second contractor was approximately $190/LSW ton and that calculated by the revenue model was $209/LSW ton. Regression was used to determine the intercept of 13,786(a) and the slope of 0.7386(b+1) as indicated by the equation in Figure 3. The intercept of 5,829 and the slope of 0.7971 were found for the second contractor, as shown in Figure 4. The improvement rate (I) for the first contractor was determined from equation 2 to be 16.33%.

The percentage errors in estimation of cumulative cost/ton and the unit cost of the ships for both contractors are given in Table 3. It can be observed from Table 3 that the percentage error values of the estimated cumulative total cost/ton were low and ranged from -7.3 to +4.1 (%) for the first contractor and from -1.2 to +0.9 (%) for the second contractor. Whereas the percentage errors for the estimated unit costs were higher than the cumulative costs ranging from -15.8 to +19.0 (%) for the first contractor and from -12.4 to +2.9 (%) for the second contractor. The mean square errors of the estimated cumulative total cost/ton for the first and the second contractors were 2,455 and 139, respectively. The mean square errors of the estimated unit cost/ton for the first and the second contractors were 17,752 and 2,000, respectively. The mean square errors for the second contractor were lower, which indicates that the estimates for the second contractor were better and more accurate than those of the first contractor.

Part of the differences in revenues could be attributed to the variation in metal scrap prices, as the scrap market is a very volatile market and the composition of the ship could be different from the estimated values. The total deconstruction costs would be the total costs to the Navy plus the retained proceeds. The learning would occur over the total costs and not the net costs. There were variations in the LSW values for the ships from different sources as well as the cost values, so the models can be considered to have budget estimating accuracy, which ranges from minus 15 to plus 30 percent for predicting the future costs.

The improvement rate for the first contractor was over 16 percent and that of the second contractor was 13 percent. These improvement rates are consistent with labor-intensive processes, which are expected to have improvement rates between 13 and 20 percent. The second contractor started at a lower total cost, so the amount of improvement by the second contractor was less. The first contractor had inconsistencies in that its costs did not decrease continuously from ship to ship and the unit costs actually increased for the fourth ship. This inconsistency may have been the result of a time period between ships that resulted in unlearning, as some deconstruction team members may have left, and new team members would need to be trained. This resulted in a greater error in the prediction of costs. Although the improvement rate of the first contractor were greater, it would be years before that contractor would reach the same cost level as the second contractor, as the initial cost was more than 50 percent higher for the first contractor.

The model developed allows the user to predict the cost for the next ship based upon the curves developed from the existing data or by entering data for a new contractor. The improvement curves could be adjusted when additional data is obtained, and by using techniques to give more weight to the most recent data, the results could be improved.

The improvement curve cost model also allowed the user to enter the improvement rate (%), revenue ($/LSW ton) cumulative tonnage (LSW), and cumulative cost ($) for ships deconstructed

Table 2—Results for Improvement Curve Development for Two Ship Deconstruction Contractors

Ship Contractor # 1

Ship	LSW (Tons)	Navy Net cost ($)	Navy Net ($/ton)	Proceeds ($)	Total Estimated Deconstruction Cost ($)	Total Cost/Ton ($/ton)	Cumulative Total ($)	Cumulative Tons (LSW)	Cumulative Cost/Ton ($/ton)	Model Cumulative Cost/Ton ($/ton)	Model Cumulative Cost ($)	Model Ship Cost ($)	Model Unit Ship Cost/Ton ($/ton)	ModelNet Cost/Ton ($/ton)
	(1)	(2)	(3)	(4)	(5)=(2)+(4)	(6)=(5)/(1)	(7)=Cumm(5)	(8)=Cumm(1)	(9)=(7)/(8)	(10)=a*(8)^b	(11)= (8)*(10)	(12)=diff(11)	(13)=(12)/(1)	(14)=(13)- Proceeds/Ton
1	3,243	5,166,018	1,593	467,196	5,633,213	1,737	5,633,213	3,243	1,737	1,666	5,402,860	5,402,860	1,666	1,516
2	3,200	2,599,994	812	NR*	3,079,994	962	8,713,207	6,443	1,352	1,392	8,970,792	3,567,932	1,115	965
3	5,600	3,713,176	663	NR	4,553,176	813	13,266,383	12,043	1,102	1,182	14,238,653	5,267,862	941	791
4	5,600	4,888,597	873	NR	5,728,587	1,023	18,994,970	17,643	1,077	1,070	18,878,030	4,639,377	828	678
5	2,700	1,960,163	726	NR	2,365,163	876	21,360,133	20,343	1,050	1,031	20,971,698	2,093,668	775	625
6	3,300	2,154,158	653	NR	2,649,158	803	24,009,291	23,643	1,015	991	23,434,463	2,462,765	746	596
7	5,200	2,609,301	502	NR	3,389,301	652	27,398,592	28,843	950	941	27,140,893	3,706,430	713	563

* NR implies none reported. The value of $ 150/LSW was assumed for proceeds when values were not given to find the total costs (144 $/LSW was the value for the first year)

a= 13,786, b = -0.2614.

Ship Contractor # 2

Ship	LSW (Tons)	Navy Net Cost ($)	Navy Net Cost ($/ton)	Proceeds ($)	Total Estimated Deconstruction Cost ($)	Total Cost/ton ($/ton)	Cumulative Total Cost ($)	Cumulative Tons (LSW)	Cumulative Cost/tons ($/ton)	Model Cumulative Cost/Ton ($,ton)	Model Cumulative Cost ($)	Model Ship Cost ($)	Model Unit Ship Cost/Ton ($/ton)	Model Net Cost/Ton ($/ton)
	(1)	(2)	(3)	(4)	(5)=(2)+(4)	(6)=(5)/(1)	(7)=Cumm(5)	(8)=Cumm(1)	(9)=(7)/(8)	(10)=a*(8)^b	(11)= (8)*(10)	(12)=diff(11)	(13)=(12)/(1)	(14)=(13)- Proceeds/Ton
1	3,209	2,997,529	922	613,899	3,611,428	1,125	3,611,428	3,209	1,125	1,133	3,634,518	3,634,518	1,133	944
2	3,300	2,268,025	687	566,668	2,834,693	859	6,446,121	6,509	990	981	6,386,630	2,752,112	834	663
3	6,000	3,263,308	544	1,133,770	4,397,078	733	10,843,199	12,509	867	859	10,750,178	4,363,548	727	538
4	3,250	1,315,137	405	617,436	1,932,573	595	12,775,772	15,759	811	820	12,923,187	2,173,009	669	480

** Model Net Cost is model ship cost minus actual proceeds per net ton

a=5,829, b=-0.2029

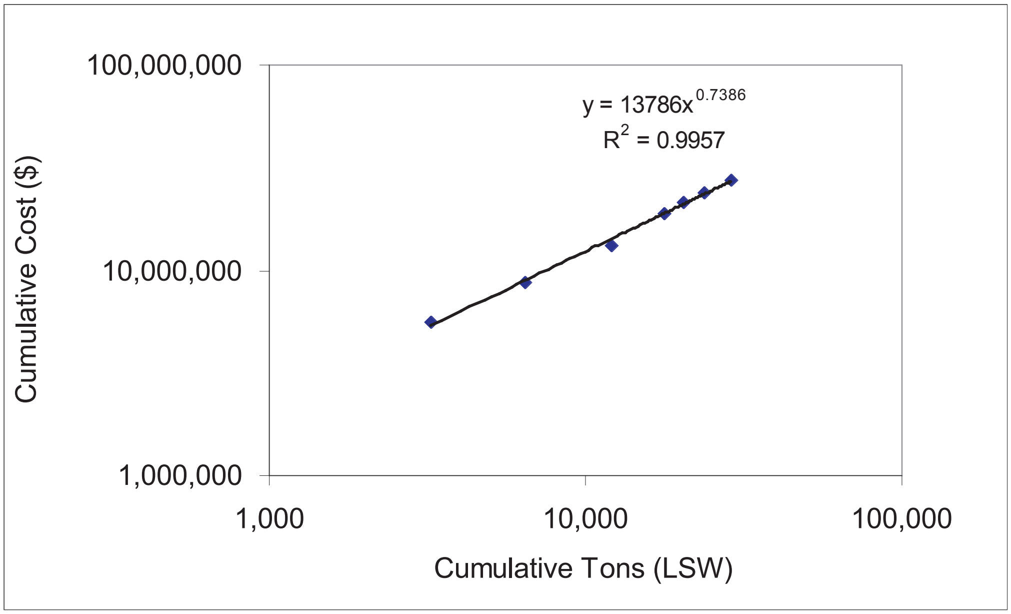

Figure 3—Actual Data Plotted on a Log-Log Paper for the First Contractor

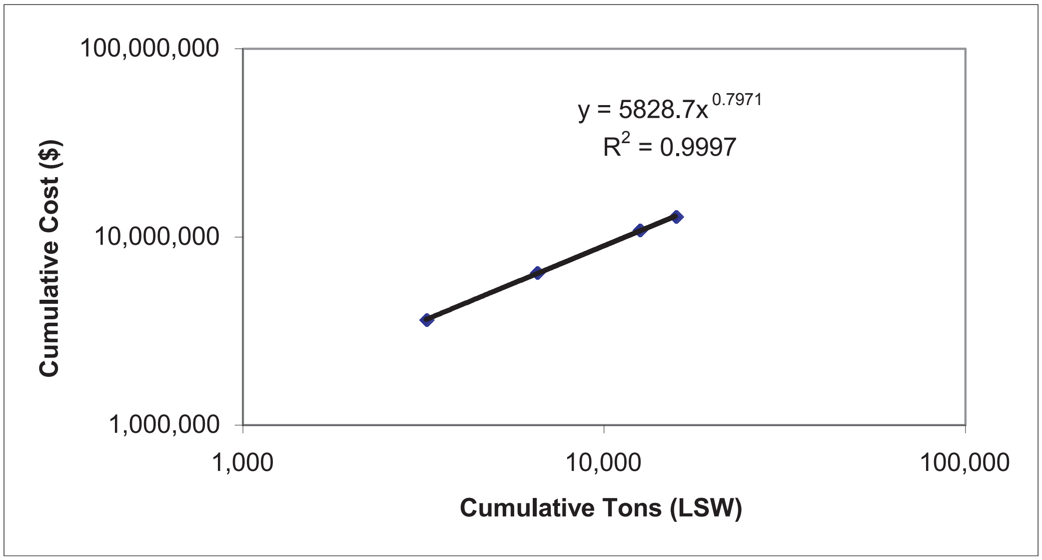

Figure 4—Actual Data Plotted on a Log-Log Paper for the Second Contractor

by the contractor. The model can calculate the deconstruction cost for the next ship using this desired improvement rate. An example of the input data is given in Table 4, and the results obtained are given in Table 5. As indicated by Table 5, results obtained for the user input are the same results obtained for the East Coast and Gulf Coast deconstruction companies. If a new user is anticipated, the total cumulative tonnage entered would be 1, and the estimated cost for that first ton would be between $3,000 and $15,000 when the improvement rates are between 13 and 20 percent.

REVENUE COST MODEL FOR SHIP DECONSTRUCTION

The revenues obtained from the deconstruction of a ship are an important item for determining the net cost for the deconstruction of a ship. The revenues can lower the total deconstruction cost by 20 percent or more in the deconstruction of US Navy and MARAD ships as the ship deconstruction companies become more efficient in the ship deconstruction process. Revenues are the major item in the disposal of ships in the international market, as the ship revenues must exceed the total costs, which include the deconstruction costs, ship purchase costs, and towing costs. The major factors in the revenue model are the amounts of materials recovered, the type of materials recovered, and the revenues

Table 3—Percentage Error Values for Cumulative Cost/Ton and Unit Cost/Ton for Both Contractors

	Ship	Cumulative Tons (LSW)	Cumulative Total cost/ton ($/ton)	Estimated Cumulative Total cost/ton ($/ton)	Percentage Error (%)	Unit cost/ton ($/ton)	Estimated Unit cost/ton ($/ton)	Percentage Error (%)
FC*	1	3,243	1,737	1,666	4.1	1,737	1,666	4.1
	2	6,443	1,352	1,392	-3.0	962	1,115	-15.8
	3	12,043	1,102	1,182	-7.3	813	941	-15.7
	4	17,643	1,077	1,070	0.6	1,023	828	19.0
	5	20,343	1,050	1,031	1.8	876	775	11.5
	6	23,643	1,015	991	2.4	803	746	7.0
	7	28,843	950	941	0.9	652	713	-9.4
SC*	1	3,209	1,125	1,133	-0.6	1,125	1,133	-0.6
	2	6,509	990	981	0.9	859	834	2.9
	3	12,509	867	859	0.9	733	727	0.8
	4	15,759	811	820	-1.2	595	669	-12.4

*FC = First Contractor, SC = Second Contractor

Table 4—Input Data for the Improvement Curve Cost Model

	East Coast Deconstruction	Gulf Coast Deconstruction
Light Ship Weight (LSW)	5000	5000
Improvement Rate (%)	16.33*	13.11*
Proceeds/Ton ($/LSW)	150	150
Total Cumulative Tonnage (LSW)	28,843*	15,759*
Total Cumulative Cost ($)	27,388,153*	12,923,187*

Note: * These values are fixed in the model and cannot be changed.

Table 5—Output of the Improvement Curve Cost Model

	East Coast Deconstruction	Gulf Coast Deconstruction
Total Cost for Breaking the Ship ($)	3,452,760	3,174,549
Cost/Ton for Breaking the Ship ($/LSW)	691	635
Net Navy Cost ($)	2,702,760	2,424,549
Deconstruction Cost/Ton for Navy ($/LSW)	541	485

for the different materials recovered. The revenues from military ships are approximately 50 percent higher than those obtained from a cargo or merchant ship per LSW ton.

The distribution of materials in a ship is critical and estimates from various sources [2, 7, 5, 4, 8, 3] were used to develop the data in Table 6. The data was a composite of all the sources, and not from one particular source. The data was for two types of ships: a surface combatant (military) ship and a merchant ship. The surface combatant has higher priced alloys and will result in a higher revenue value per light ship weight (LSW) ton. For the computer model, the nonrecyclable waste was adjusted to reflect changes the user may make to the base data, so the total percentage would remain 100 percent.

The revenue data in Table 7 was developed from several sources [2, 5, 4, 10, 6]. The estimated revenues by the model of $209/LSW ton for the surface combatant and $134/LSW for the merchant ship are close to the adjusted value of $214/LSW ton for DD-966 (with a waste of 9% instead of 25% as reported [2]) and the value of $ 135/LSW used in the MARAD report [7]. The revenue model permits the user to alter the revenue values for current market prices as well as current percentages of materials for the recyclable and nonrecyclable waste, as scrap prices are highly

Table 6—Estimated Compositions of Ships for Deconstruction

Ship Type	**Surface Combatant**	**Merchant Ship**
	(Percent material)	(Percent material)
Recyclable Waste		
Ferrous Metals		
Carbon Steel	65.5	78.3
Stainless Steel	0.7	8.7
Other	7.1	0.0
Non-Ferrous Metals		
Copper Base Alloys		
Copper-Nickel	1.2	1.0
Brass-Bronze	1.5	0.0
Aluminum	6.7	0.0
Lead	5.6	0.0
Marketable Scrap		
Artifacts & Components	2.7	3.0
Non-Recyclable Waste	9.0	9.0
Total	**100.0**	**100.0**

Table 7—Estimated Revenues from Ship Recyclable Materials

Ship Type	**Revenue**	**Surface Combatant**		**Merchant Ship**	
	($/Ton)	**%**	**$**	**%**	**$**
Recyclable Waste					
Ferrous Metals					
Carbon Steel	80	65.5	52.40	78.3	62.64
Stainless Steel	500	0.7	3.50	8.7	43.50
Other	30	7.1	2.13	0.00	0.00
Non-Ferrous Metals					
Copper Base Alloys					
Copper-Nickel	2000	1.2	24.00	1.0	20.00
Brass-Bronze	1100	1.5	16.5	0.00	0.00
Aluminum	1200	6.7	80.4	0.00	0.00
Lead	400	5.6	22.4	0.00	0.00
Marketable Scrap					
Artifacts & Components	250	2.7	6.75	3.0	7.50
Non-Recyclable Waste	**0**	**9.0**	**0.00**	**9.0**	**0.00**
Total		**100**	**208.08**	**100.0**	**133.64**

volatile. As can be seen in Table 6, the revenues per ton for the copper base alloys (copper-nickel and brass-bronze) and aluminum exceed $1,000/ton. Changes in these prices can have a major impact on the revenues. Stainless steel and lead revenues are also high compared to carbon steel, which was the largest material component. In the military ships, the nonferrous materials are the major source of revenues, whereas in the merchant/cargo ships, the ferrous materials represent the major source of revenue.

The improvement model provides an estimate of the cost reductions obtained by repeating the deconstruction process on similar ships. An improvement curve model was developed to predict the total deconstruction cost/ton ($/LSW) and the net Navy cost/ton ($/LSW) for the next ship on the basis of learning by the ship deconstructors. The improvement cost model can predict the total deconstruction cost ($/LSW) for the next ship based upon the input of the total cumulative tonnage (LSW tons), the total cumulative cost ($) for that cumulative tonnage, and the improvement rate. A revenue model was developed to give an estimate on the revenues generated by the deconstruction of either a merchant ship or a surface combatant ship. The revenue model calculates the revenues per net LSW ton for the merchant/cargo ships and the surface combatant (military) ships based upon the estimated ship compositions and scrap prices for the materials.

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Ashutosh R. Nandeshwar
West Virginia University
Department of Industrial and Management Systems Engineering
College of Engineering and Mineral Resources
PO Box 6070
Morgantown, WV 26506-6070
E-mail: ashutoshnandeshwar@hotmail.com

Dr. Robert C. Creese, PE CCE
West Virginia University
Department of Industrial and Management Systems Engineering
College of Engineering and Mineral Resources
PO Box 6070
Morgantown, WV 26506-6070
E-mail: robert.creese@mail.wvu.edu