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Multiscale Life-Cycle Assessment

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SLCA Generic Matrix - UH-60L

	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Scores
Pre Manufacture	.5	.5	1	.5	.5	0	3.0
Product Manufacture	0	2	2	1.75	2	1.5	9.25
Product Delivery	4	2.75	4	1	2.5	3.5	17.75
Product Use	.75	2	3	.5	0	2.75	9.0
Field Service	1.5	2.75	1.5	2	2.25	0	10.0
End of Life	0	.75	.75	1.5	2	.75	5.75
Column Scores	6.75	10.75	12.25	7.25	9.25	8.5	

Total Score: 54.8 /144 38%

4	= Acceptable without review
3.0 – 3.9	= Acceptable with review
2.0 – 2.9	= Tolerable
1.0 – 1.9	= Undesirable
0 - .9	= Unacceptable

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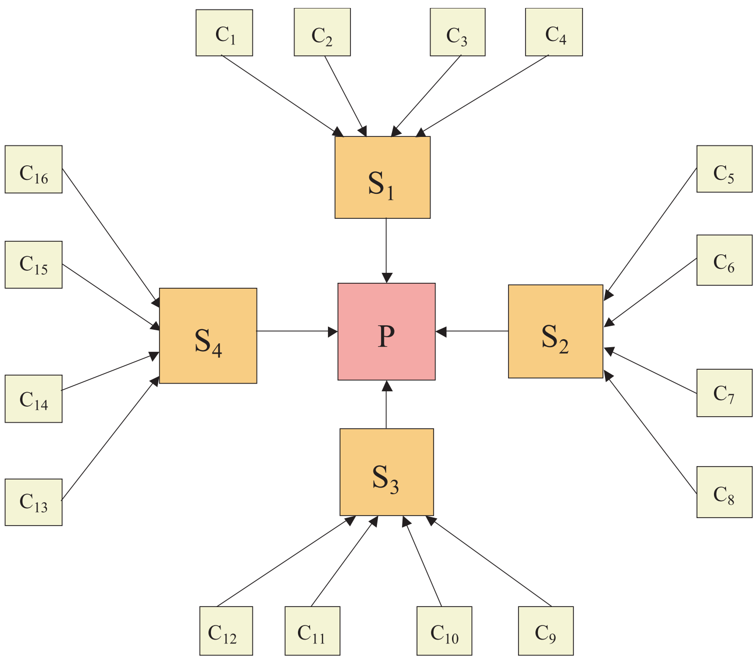
ABSTRACT

A streamlined life-cycle assessment (SLCA) is typically performed at the scale of the completed product. One could also, however, perform SLCAs on components or subsystems (moving down in scale) or on all a corporation's products (moving up in scale). By analogy with biological ecology, it seems likely that analyses at different scales would ask different questions and reveal different insights. In this study, multiscale streamlined LCA (SLCA) is explored by comparing results for high-performance aircraft at the subsystem, product, and corporate levels. The results clearly show that SLCA results differ substantially among the major subsystems of a complex product in ways not derivable from a systems-level SLCA, and that results at different levels tend to serve different corporate users. Similar benefits are obtained when comparing results for a single product with those for several corporate products. Thus, considerable advantage is likely to result from the performance of multiscale life-cycle analyses.

INTRODUCTION

Companies seeking to evaluate their environmental performance often perform life-cycle assessments (LCAs), generally at the scale of the finished product. In such studies, the environmental implications of product design, use of materials, emissions, and so forth are evaluated at each product life stage from raw material extractions to final discard. Products are made up of subsystems and discrete components, however, and may themselves aggregate to larger and more complex products. The situation is pictured schematically in Figure 1, in which a corporation manufacturing four products, each with four major subsystems, is schematically illustrated. To a first approximation, we anticipate that the environmental attributes of a subsystem are determined by those of its components, of a product by those of its subsystems, and of a corporation by those of its products. If those attributes can be captured by life-cycle assessment (LCA) approaches, we might therefore expect that the results of LCAs for the four components of a subsystem would aggregate to give an LCA for the subsystem, that subsystem LCAs would aggregate to give those of the overall product, and that product LCAs would aggregate to give that for the corporation.

Figure 1 Linking the attributes of components (Cx) to the subsystems (Sx) and the product (P) of which they are a part.



Biological ecology provides a useful perspective on this cross-scale challenge. In that field, much research is done at the organism scale, the ecosystem scale, the landscape scale, etc. Nonetheless, the potential for multiscale analyses to reveal information not obvious at a single scale is widely recognized, system attributes at one scale being reflected in complex ways in the system attributes of scales higher and lower (Levin *et al.* 1997). Multiscale system-oriented studies are admittedly difficult, but are increasingly regarded as crucial to a workable understanding of the operation of natural systems (Gunderson and Holling, 2002).

A generic LCA for an industrial product attempts to assess the environmental impacts of its constituent materials from their extraction to their incorporation into the product (Guinée *et al.* 2002). This approach is not one that crosses scales, however, because it takes no account of the potential influences and impacts of assemblages and linkages. How might LCAs, largely focused on products (e.g., Kummerer *et al.* 1996; Jönsson *et al.* 1998; Sataki and Oishi, 1998), occasionally on subsystems or components (e.g., Milà *et al.* 1998; Lippiatt and Boyles, 2001), address a multiscale perspective, and what might be learned from it?

Comprehensive LCAs involve extensive data sets related to materials quantities, emission rates, environmental responses, level of detail, and other factors. As a consequence, they tend to require significant financial and personnel resources, and to take many months to complete. Alternative approaches, termed "streamlined life-cycle assessments" (SLCAs), seek to preserve the power of and confidence in the LCA approach in demonstrating environmentally-problematic attributes at each life stage, while doing so more quickly and cheaply (Graedel, 1998; Hunt et al. 1998).

To investigate the utility of cross-scale environmental product analysis, we have performed streamlined life-cycle assessments (SLCA) of four high performance vehicles manufactured by the Sikorsky Aircraft Corporation, a division of United Technologies Corporation (UTC): the Sikorsky UH-60L "Blackhawk" helicopter, the MH-60R and MH-60S marine helicopters, and the RAH-66 "Comanche" helicopter. We began by evaluating the UH-60L helicopter as a composite product. We then performed SLCAs on the four principal subsystems that comprise it:

- Airframe (the structural framework of the vehicle and its landing gear)
- Avionics (the hydraulic and mechanical control systems)
- Electronics (sensors, displays, monitoring and communications systems)
- System dynamics (the engines, transmissions, and rotor blades)

For each subsystem, we considered as well some of the environmental attributes of the components. These results were then used to produce an aggregated SLCA for the entire product. We then compared the aggregated SLCA results for the UH-60L with those for the SLCA of the overall product in stand-alone assessment. Finally, we repeated this operation for the other three helicopters and aggregated the results for all four to arrive at an environmental assessment of the products of the corporation.

THE STREAMLINED LIFE-CYCLE ASSESSMENT MATRIX

Comprehensive life-cycle assessment techniques (e.g., Curran, 1996; Guinée *et al.* 2002) have in many cases given way to SLCA approaches, especially with the recognition that in cases where quantitation is not possible (for reasons of time or cost, for example), "qualitative aspects can – and should – be taken into account" (Guinée *et al.* 2002). In this spirit, we have used SLCA approaches (as have others, e.g., Eagan and Weinberg, 1997; Hoffman, 1997; Graedel, 1998) in this study. These approaches feature semi-quantitative assessment matrices in which a full range of environmental concerns and life stages are addressed.

Our assessment system, which meets the SLCA criteria of efficiency and reliability, has as its central feature an assessment matrix, one dimension of which is life-cycle stages and the other of which is environment, health, and safety (EHS) concerns (Graedel, 1998; Table 1). In this approach, the assessor studies the product design, manufacture, packaging, product use, in-service maintenance, and likely disposal scenario and assigns to each element of the matrix an integer rating from 0 (highest impact, a very negative evaluation) to 4 (lowest impact, an exemplary evaluation). Since the approach is not quantitative per se, the results are not strictly a measure of EHS performance, but rather an estimate of the potential for improvement in EHS performance.

Table 1 The Streamlined Life-Cycle Assessment Matrix*

Life Stage	Environment, Health, and Safety Concern					
	Biodiversity/ materials	Energy use	Solid residues	Liquid residues	Gaseous residues	Worker Safety
Premanufacture	1,1	1,2	1,3	1,4	1,5	1,6
Manufacture	2,1	2,2	2,3	2,4	2,5	2,6
Product Delivery	3,1	3,2	3,3	3,4	3,5	3,6
Product Use	4,1	4,2	4,3	4,4	4,5	4,6
In-Service Maintenance	5,1	5,2	5,3	5,4	5,5	5,6
Product End-of-Life	6,1	6,2	6,3	6,4	6,5	6,6

* The numbers in each box are the matrix element indices.

In essence, what the assessor is doing is providing a figure of merit to approximate the result of the more formal LCA inventory analysis and impact analysis stages. She or he is guided in this task by experience, a design and manufacturing survey, appropriate checklists, and other information.

The process described here is purposely qualitative and utilitarian, but does provide a numerical end point against which to measure improvement.

Once an evaluation has been made for each matrix element, the overall rating is computed as the sum of the matrix element values:

$$R = \sum\sum M_{ij}$$

The method draws on earlier SLCA approaches (Graedel, 1998; Graedel *et al.* 1998) that utilized five life stages and five EHS concerns, but adds field service as an additional life stage and safety as an additional ESH concern. The resulting matrix is a 6 x 6 version, with 36 matrix elements. With a maximum matrix element rating of 4, this gives a maximum matrix rating of 144. Results can be expressed either as the absolute sum of the evaluations or as a percentage of the maximum possible rating.

INITIAL SLCA PRODUCT EVALUATION

The SLCA for the UH-60L helicopter was performed by a team of 18 Sikorsky employees with a wide range of specialties and responsibilities – design, manufacturing, field maintenance, environmental performance, sales, etc. The team was divided into four groups, each of which completed the entire SLCA over a period of several days, following guidelines and checklists throughout (Graedel, 1998). The authors of the present paper tabulated and averaged the results, producing the matrix illustrated in Figure 2.

The SLCA results highlight a number of areas in which performance is deemed unacceptable. Most of these occur either in the premanufacture life stage or in the materials choice EHS concern. Residues, especially during product use, are also issues for concern. In contrast, product delivery scores are high and solid residue generation respectable. Overall, however, the aircraft receives only a 38% score, indicating that many opportunities exist to improve its environmental performance.

Figure 2 SLCA matrix for the UH-60L, as originally evaluated. The color code is as follows: 4 – dark green; 3.0-3.9 – light green; 2.0-2.9 – light yellow; 1.0-1.9 – gold; <1.0 – red.

SLCA Matrix for the UH-60L

		Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Scores
Pre Manufacture	.5	.5	1	.5	.5	0	3.0
Product Manufacture	0	2	2	1.75	2	1.5	9.25
Product Delivery	4	2.75	4	1	2.5	3.5	17.75
Product Use	.75	2	3	.5	0	2.75	9.0
Field Service	1.5	2.75	1.5	2	2.25	0	10.0
End of Life	0	.75	.75	1.5	2	.75	5.75
Column Scores	6.75	10.75	12.25	7.25	9.25	8.5	Total Score: 54.8 /144 38%

4 = Acceptable without review

2.0 – 2.9 = Tolerable

3.0 – 3.9 = Acceptable with review

1.0 – 1.9 = Undesirable

0 - .9 = Unacceptable

SLCAs OF SUBSYSTEMS

Subsystem SLCAs were carried out by employee teams particularly knowledgeable about the specific subsystems being evaluated. The 6 x 6 matrix that was employed for the overall product was also used for the product subsystems. As with the generic overall assessment, the teams were given several days to complete their evaluations. The results are discussed below.

Airframe

The SLCA matrix results for the airframe subsystem are shown in Figure 3a. The total score (73/144) indicates about a 51% EHS performance overall. Individual matrix elements present the rating for a particular life stage-EHS concern combination. For example, the score of 4 for matrix element 3,3 reflects the absence of solid residue generation during the product delivery stage. In contrast to this exemplary rating, the score of 0 for matrix element 2,1 refers to the choice of one or more UTC materials of concern in the manufacturing process. The row and column scores function as indicators of superior or unsatisfactory performance across the spectrum of EHS concerns or across all life stages, rather than for a single matrix element. Consider the row scores – clearly the premanufacture and end of life phases are the most problematic. Product delivery scores very highly, and the product use score is satisfactory. The column scores indicate that materials choice and safety are significant concerns. Many of the low scores are related to the use of toxic materials, particularly chromium and cadmium.

Figure 3a The SLCA matrix for the (a) airframe subsystem, (b) avionics subsystem, (c) electronics subsystem, (d) system dynamics.

SLCA Matrix – Airframe

	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Scores
Pre Manufacture	0	1	2	3	1	0	7
Product Manufacture	0	2	2	1	3	1	9
Product Delivery	4	4	4	4	3	4	23
Product Use	1	3	4	3	3	3	17
Field Service	1	3	2	2	3	0	11
End of Life	0	0	0	3	3	0	6
Column Scores	6	13	14	16	16	8	Total Score : 73/144 50.6%

4 = Acceptable with out review
2 = Tol erable
3 = Acceptable with review
1 = Undesirable
0 = Unacceptable

Avionics

The SLCA matrix results for the avionics subsystem are shown in Figure 3b. The avionics score (74/144) indicates about a 51% EHS performance overall. This results from poor EHS performance during manufacturing and disposal, and good EHS performance during product delivery and use. The premanufacture row score is exceptionally low, reflecting the use by suppliers of a number of UTC materials of concern.

Figure 3b SLCA Matrix – Avionics

SLCA Matrix – Avionics

	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Scores
Pre Manufacture	0	0	0	1	0	0	1
Product Manufacture	0	2	1	1	1	0	5
Product Delivery	1	2	1	4	1	4	13
Product Use	4	3	4	4	4	4	23
Field Service	4	3	4	4	4	4	23
End of Life	0	0	0	4	4	1	9
Column Scores	9	10	10	18	14	13	Total Score: 74/144 51%

4 = Acceptable with out review
2 = Tol erable
3 = Acceptable with review
1 = Undesirable
0 = Unacceptable

Electronics

The SLCA matrix results for the electronics subsystem are shown in Figure 3c. The overall score (91/144) indicates about a 63% EHS performance, the highest of any of the subsystems. Individual matrix element ratings indicate only one perfect score (lack of liquid residues in product use). In most other cases, minor residues or energy use result in scores of 3 or 2. Of the row scores, only the end of life phase appears in serious need of design attention.

Figure 3c – SLCA Matrix – Electronics

SLCA Matrix – Electronics

	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Scores
Pre Manufacture	3	2	3	3	3	3	17
Product Manufacture	3	3	2	3	3	3	17
Product Delivery	2	2	2	3	3	3	15
Product Use	2	3	3	4	3	2	17
Field Service	3	3	2	2	3	1	14
End of Life	1	1	1	3	3	2	11
Column Scores	14	14	13	18	18	14	Total Score: 91/144 63%

4 = Acceptable with out review
2 = Tolerable
3 = Acceptable with review
1 = Undesirable
0 = Unacceptable

System Dynamics

The SLCA matrix results for the system dynamics subsystem are shown in Figure 3d. System dynamics receives a score of 54/144 and about a 38% EHS performance overall, which suggests that this subsystem has the most potential for improvement. Consider the row scores – clearly the premanufacture and end of life phases are the most problematic, though none of the totals except that for product delivery scores very highly. The column scores indicate that materials choice, liquid residues, and safety are significant concerns.

Figure 3d – SLCA Matrix – System Dynamics

SLCA Matrix – System Dynamics

	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Score
Pre Manufacture	1	1	1	1	1	0	5
Product Manufacture	0	2	2	2	2	1	9
Product Delivery	4	3	4	1	3	3	18
Product Use	0	2	3	0	0	2	7
Field Service	1	3	0	2	3	0	9
End of Life	0	1	0	1	3	1	6
Column Scores	6	12	10	7	12	7	Total Score: 54/144 37.5%

4 = Acceptable with out review; 2 = Tol erable

3 = Acceptable with review; 1 = Undesirable; 0 = Unacceptable

AGGREGATED SYSTEM SLCA

The aggregated SLCA matrix for the UH-60L is shown in Figure 4a, where the scores for each matrix element are generated by averaging the four scores from the subsystem SLCAs. The total score for the entire aircraft (73.5/144) indicates about a 51% EHS performance overall. Two life stages – premanufacture and end of life – show up as scoring rather poorly. The row score for product manufacture is little better. Product delivery, product use, and field service score higher, though plenty of room for improvement remains. The column scores suggest that the most attention needs to be paid to materials choice and safety, though no single EHS concern receives particularly high ratings. In general, matrix elements with scores above 3.0 indicate satisfactory performance across all subsystems of the product; those below 2.0 indicate the reverse.

While the information from Figure 4a is quite useful, it can have a tendency to mask additional important information. This difficulty is avoided by plotting the color-coded results of each of the subsystem SLCAs together, as shown in Figure 4b. Consider matrix element 2,2: energy use in product manufacture. The average score, 2.25, turns out to be the average of four nearly equal scores, and the middling performance impression given by Figure 4a for that matrix element is quite appropriate. In contrast, consider matrix element 5,1: materials choice at the field service life stage. Here the exact same average score, 2.25, results from high scores for avionics and electrical subsystems and low scores for the airframe and system dynamics subsystems.

Figure 4a **The SLCA matrix for the UH-60L product as derived from the subsystem assessments. (a) with each matrix element averaged and given in solid color, (b) with each matrix element indicating the subsystem assessments.**

SLCA Aggregate Matrix – Subsystem Averages

	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Scores
Pre Manufacture	1	1	1.50	2	1.25	0.75	7.50
Product Manufacture	0.75	2.25	1.75	1.75	2.25	1.25	10
Product Delivery	2.75	2.75	2.75	3	2.50	3.50	17.25
Product Use	1.75	2.75	3.50	2.75	2.50	2.75	16
Field Service	2.25	3.00	2.50	2.50	3.25	1.25	14.75
End of Life	0.25	0.50	0.25	2.75	3.25	1	8
Column Score	8.75	12.25	12.25	14.75	15	10.5	Total Score: 73.5/144 51%

4 = Acceptable without review

2.0 – 2.9 = Tolerable

3.0 – 3.9 = Acceptable with review

1.0 – 1.9 = Undesirable

0 - .9 = Unacceptable

Figure 4b **The SLCA Aggregate Matrix – Subsystem Assessments**

SLCA Aggregate Matrix – Subsystem Averages

	Materials Choice		Energy Use		Solid Residues		Liquid Residues		Gaseous Residues		Safety		Row Scores	
Pre Manufacture	0	3	0	2	0	3	1	3	0	3	0	3	1	17
	0	1	1	1	2	1	3	1	1	1	0	0	7	5
Product Manufacture	0	3	2	3	1	2	1	3	1	3	0	3	5	17
	0	0	2	2	2	2	1	2	3	2	1	1	9	9
Product Delivery	1	2	2	2	1	2	4	3	1	3	4	3	13	15
	4	4	4	3	4	4	4	1	3	3	4	3	23	18
Product Use	4	2	3	3	4	3	4	4	4	3	4	2	23	17
	1	0	3	2	4	3	3	0	3	0	3	2	17	7
Field Service	4	3	3	3	4	2	4	2	4	3	4	1	23	14
	1	1	3	3	2	0	2	2	3	3	0	0	11	9
End of Life	0	1	0	1	0	1	4	3	4	3	1	2	9	11
	0	0	0	1	0	0	3	1	3	3	0	1	6	6
Column Scores	9	14	10	14	10	13	18	18	14	18	13	14		
	6	6	13	12	14	10	16	7	16	12	8	7		

Total Scores:

74	91
73	54

4 = Acceptable without review

3 = Acceptable with review

2 = Tolerable

1 = Undesirable

0 = Unacceptable

Key:

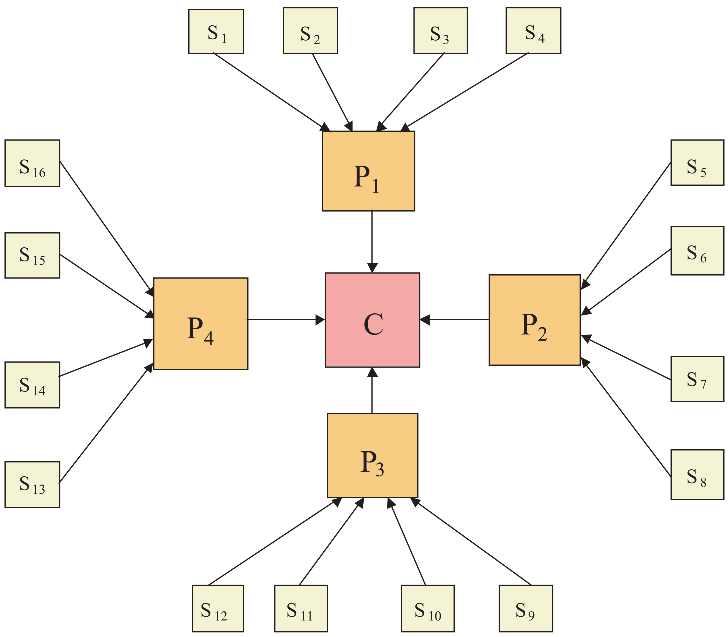
Avionics	Electrical
Air Frame	System Dynamics

A PRELIMINARY SIKORSKY PRODUCT LINE ENVIRONMENTAL EVALUATION

In the same way that evolution of components and subsystems led to the product analysis (Figure 1), evolution of subsystem and products led to a corporate analysis (Figure 5). In 2002, studies similar to the one discussed above were performed on the Sikorsky UH-60L and RAH-66 helicopters.

The results from that study and the present one can be averaged to provide a preliminary product line environmental evaluation for the Sikorsky Aircraft Corporation as a whole. As additional Sikorsky products are evaluated by these approaches, the corporate assessment will become increasingly useful as a measure of overall corporate design for environment and safety.

Figure 5 The linking of the attributes of subsystems (Sx) to the products (Px) and the corporation (C) of which they are a part.



Airframe

The corporate environmental matrix for Sikorsky airframe subsystems is shown in Figure 6a. To construct this figure, appropriate values from each of the four aircraft were averaged. The resultant score (82/144) indicates about a 57% performance for these subsystems overall. The individual subsystem scores are identical for the 60-series aircraft, and are much higher for the RAH-66. An example of why this occurs is matrix element 2,3: solid residue in product manufacture. The fiber-reinforced polymer body material is much more efficient to form and install, and generates much less scrap. Differences for other matrix elements can also be traced to the high-tech design and materials composition of the RAH-66.

Electrical/Avionics

The environmental matrix for Sikorsky electrical/avionics subsystems is shown in Figure 6b. The score (99.2/144) indicates about a 69% EHS performance overall. The RAH-66 again ranks much higher than the other vehicles.

Dynamics

The environmental matrix for Sikorsky propulsion and dynamics subsystems are combined, because that approach was used in assessing the UH-60L and RAH-66 vehicles. The result, shown in Figure 6c, suggests that these subsystems have the most potential for improvement, the score of (74.9/144) indicating about a 52% EHS performance overall. Again the RAH-66 is the highest scoring vehicle, the UH-60L the lowest. Matrix element 5,3: solid residues in field service, provides a dramatic example of vehicle differences.

System SLCA

The combined environmental matrix for four Sikorsky aircraft is shown in Figure 7, where the scores for each matrix element are generated by averaging the three scores from the corporate subsystem SLCAs. The overall corporate score (84.8/144) indicates about a 59% environmental performance overall. Two life stages – premanufacture and end of life – show up as scoring rather poorly. The column scores suggest that the most attention needs to be paid to materials choice and safety, though no single EHS concern receives particularly high ratings.

Figure 6a Composite SLCA matrices from Sikorsky Aircraft Corporation's products. Each diagram provides evaluations for four aircraft: UH-6oL (upper left), RAH-66 (upper right), MH-6oR (lower left), and MH-6oS (lower right). (a) Airframe subsystems; (b) avionics and electrical subsystems, (c) propulsion and dynamics.

22. Composite SLCA Matrix for Aircraft Airframes — UH-60L, RAH-66, MH-60R, MH-60S

	Material Choice		Energy Use		Solid Residues		Liquid Residues		Gaseous Residues		Safety		Row Score	
Pre Manufacture	0.0	3.0	1.0	2.0	2.0	2.0	3.0	4.0	1.0	3.0	0.0	3.0	7.0	17.0
	1.0	0.0	1.0	1.0	1.0	2.0	2.0	3.0	1.0	1.0	1.0	0.0	7.0	7.0
Product Manufacture	0.0	2.0	2.0	2.0	2.0	3.0	1.0	3.0	3.0	4.0	1.0	3.0	9.0	17.0
	1.0	0.0	2.0	2.0	2.0	2.0	3.0	1.0	2.0	3.0	3.0	1.0	13.0	9.0
Product Delivery	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.0	4.0	4.0	3.0	23.0	23.0
	4.0	4.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	3.0	3.0	4.0	22.0	23.0
Product Use	1.0	3.0	3.0	3.0	4.0	3.0	3.0	4.0	3.0	3.0	3.0	3.0	17.0	19.0
	0.0	1.0	2.0	3.0	3.0	4.0	3.0	3.0	3.0	3.0	2.0	3.0	13.0	17.0
Field Service	1.0	4.0	3.0	3.0	2.0	3.0	2.0	3.0	3.0	3.0	0.0	2.0	11.0	18.0
	2.0	1.0	3.0	3.0	1.0	2.0	2.0	2.0	3.0	3.0	2.0	0.0	13.0	11.0
End of Life	0.0	2.0	0.0	3.0	0.0	1.0	3.0	3.0	3.0	4.0	0.0	2.0	6.0	15.0
	0.0	0.0	0.0	0.0	1.0	0.0	1.0	3.0	2.0	3.0	1.0	0.0	5.0	6.0
Column Score	6.0	18.0	13.0	17.0	14.0	16.0	16.0	21.0	16.0	21.0	8.0	16.0	73.0	109.0
	8.0	6.0	11.0	13.0	12.0	14.0	15.0	16.0	15.0	16.0	12.0	8.0	73.0	73.0

4.0 = Acceptable Without Review
2.0 - 2.9 = Tolerable
3.0 - 3.9 = Acceptable With Review
1.0 - 1.9 = Undesirable
0 - .9 = Unacceptable

Product Key

UH-60L	RAH-66
MH-60R	MH-60S

Figure 6b Composite SLCA matrices for Aircraft Avionics and Electronics

23. Composite SLCA Matrix for Aircraft Avionics & Electronics — UH-60L, RAH-66, MH-60R, MH-60S

	Material Choice		Energy Use		Solid Residues		Liquid Residues		Gaseous Residues		Safety		Row Score	
Pre Manufacture	1.5	3.0	1.0	4.0	1.5	3.0	2.0	4.0	1.5	4.0	1.5	3.0	9.0	21.0
	2.0	2.0	1.0	1.0	1.0	1.0	4.0	4.0	0.0	0.0	1.8	1.8	9.8	9.8
Product Manufacture	1.5	2.0	2.5	3.0	1.5	3.0	2.0	3.0	2.0	3.0	1.5	3.0	11.0	17.0
	0.0	0.0	2.0	2.0	1.0	1.0	3.0	3.0	3.0	3.0	2.0	2.0	11.0	11.0
Product Delivery	1.5	4.0	2.0	4.0	1.5	4.0	3.5	4.0	2.0	4.0	3.5	4.0	14.0	24.0
	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.6	3.6	23.6	23.6
Product Use	3.0	4.0	3.0	4.0	3.5	4.0	4.0	4.0	3.5	4.0	3.0	4.0	20.0	24.0
	3.0	3.0	3.0	3.0	4.0	4.0	4.0	4.0	3.0	3.0	2.6	2.6	19.6	19.6
Field Service	3.5	3.0	3.0	3.0	3.0	3.0	3.0	4.0	3.5	4.0	2.5	4.0	18.5	21.0
	2.0	2.0	3.0	3.0	4.0	4.0	4.0	4.0	3.0	3.0	2.0	2.0	18.0	18.0
End of Life	0.5	3.0	0.5	3.0	0.5	3.0	3.5	4.0	3.5	3.0	1.5	3.0	10.0	19.0
	1.0	1.0	0.0	0.0	2.0	2.0	4.0	4.0	3.0	3.0	2.2	2.2	12.2	12.2
Column Score	11.5	19.0	12.0	21.0	11.5	20.0	18.0	23.0	16.0	22.0	13.5	21.0	82.5	126.0
	12.0	12.0	13.0	13.0	16.0	16.0	23.0	23.0	16.0	161.0	14.2	14.2	94.2	94.2

4.0 = Acceptable Without Review
2.0 - 2.9 = Tolerable
3.0 - 3.9 = Acceptable With Review
1.0 - 1.9 = Undesirable
0 - .9 = Unacceptable

Product Key

UH-60L	RAH-66
MH-60R	MH-60S

Figure 6c Composite SLCA matrices for Aircraft Propulsion and Dynamics

24. Composite SLCA Matrix for Aircraft Propulsion & Dynamics UH-60L, RAH-66, MH-60R, MH-60S

	Material Choice		Energy Use		Solid Residues		Liquid Residues		Gaseous Residues		Safety		Row Score	
Pre Manufacture	1.0	3.0	1.0	2.0	1.0	2.0	1.0	4.0	1.0	4.0	0.0	3.0	5.0	18.0
	1.4	1.4	1.6	1.6	1.5	1.5	1.8	1.8	1.9	1.9	2.9	2.9	11.0	11.0
Product Manufacture	0.0	4.0	2.0	1.0	2.0	4.0	2.0	3.0	2.0	4.0	1.0	2.0	9.0	18.0
	0.8	0.8	2.3	2.3	2.1	2.1	2.6	2.6	2.1	2.1	2.2	2.2	12.0	12.0
Product Delivery	4.0	3.0	3.0	4.0	4.0	4.0	1.0	4.0	3.0	4.0	3.0	3.0	18.0	22.0
	3.9	3.9	2.6	2.6	4.0	4.0	2.3	2.3	2.6	2.6	3.7	3.7	19.0	19.0
Product Use	0.0	1.0	2.0	4.0	3.0	4.0	0.0	4.0	0.0	4.0	2.0	3.0	7.0	20.0
	0.8	0.8	2.3	2.3	2.4	2.4	1.3	1.3	1.3	1.3	2.6	2.6	10.5	10.5
Field Service	1.0	4.0	3.0	4.0	0.0	3.0	2.0	1.0	3.0	4.0	0.0	3.0	9.0	19.0
	1.1	1.1	3.0	3.0	0.8	0.8	1.9	1.9	2.4	2.4	2.1	2.1	11.2	11.2
End of Life	0.0	3.0	1.0	1.0	0.0	1.0	1.0	3.0	3.0	2.0	1.0	3.0	6.0	13.0
	0.5	0.5	1.3	1.3	0.9	0.9	1.9	1.9	3.1	3.1	2.1	2.1	9.7	9.7
Column Score	6.0	18.0	12.0	16.0	10.0	18.0	7.0	19.0	12.0	22.0	7.0	17.0	54.0	110.0
	8.4	8.4	13.0	13.0	11.6	11.6	11.6	11.6	13.4	13.4	15.4	9.8	73.4	73.4

4.0 = Acceptable Without Review

2.0 - 2.9 = Tolerable

3.0 - 3.9 = Acceptable With Review

1.0 - 1.9 = Undesirable

0 - .9 = Unacceptable

Product Key

UH-60L	RAH-66
MH-60R	MH-60S

Figure 8 plots the color-coded results of the subsystem SLCAs together, demonstrating in an overall fashion the general EHS superiority of the RAH-66. From a corporate standpoint, however, the clearest message is that increased attention to the end of life phase (for the overall products and especially for replaceable subsystems) is a prime target for improved environmental performance.

Figure 7 The averaged SLCA matrix for the four corporate aircraft.

25. Averaged SLCA Matrix for All Aircraft UH-60L, RAH-66, MH-60R, & MH-60S

	Material Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Score
Pre Manufacture	1.7	1.6	1.6	2.7	1.8	1.7	11.1
Product Manufacture	1.2	2.1	2.2	2.6	2.7	2.0	12.8
Product Delivery	3.6	3.2	3.7	3.3	3.3	3.4	20.5
Product Use	1.7	2.8	3.3	2.6	2.6	2.7	15.7
Field Service	2.3	3.1	2.2	2.5	3.1	1.8	15.0
End of Life	1.0	1.0	1.1	2.6	3.0	1.7	10.4
Column Score	11.5	13.9	14.0	16.4	16.5	13.3	85.4 / 144 59%

4.0 = Acceptable Without Review

2.0 - 2.9 = Tolerable

3.0 - 3.9 = Acceptable With Review

1.0 - 1.9 = Undesirable

0 - .9 = Unacceptable

Figure 8 The composite SLCA matrix for the four corporate aircraft.

		Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Safety	Row Scores
Pre Manufacture	.5	.5	1	.5	.5	0	3.0
Product Manufacture	0	2	2	1.75	2	1.5	9.25
Product Delivery	4	2.75	4	1	2.5	3.5	17.75
Product Use	.75	2	3	.5	0	2.75	9.0
Field Service	1.5	2.75	1.5	2	2.25	0	10.0
End of Life	0	.75	.75	1.5	2	.75	5.75
Column Scores	6.75	10.75	12.25	7.25	9.25	8.5	Total Score: 54.8 /144 38%

- 4 = Acceptable without review
- 3.0 – 3.9 = Acceptable with review
- 2.0 – 2.9 = Tolerable
- 1.0 – 1.9 = Undesirable
- 0 - .9 = Unacceptable

DISCUSSION

Although the general sense of these results is regarded as robust, only a modest amount of confidence should be placed on any single entry in the ratings. The ratings were produced on rather short time frames, and should not be considered definitive – a review of the ratings and the rationale for scoring may change some of the rankings somewhat. Overall, however, the results are a workable guide to the steps needed to gradually transform the individual products and the Sikorsky Aircraft Corporation as a whole into an increasingly superior EHS performer.

The Sikorsky UH-60L is a product typical of today's high technology, design, and manufacturing, and is developed and produced by a corporation with a strong environmental commitment. In the introduction to this paper, we asked whether an aggregated LCA/SLCA on such a product would differ from a generic LCA/SLCA for the same product, why that might be (if so), and what useful new information might result from a multi-scale LCA/SLCA approach. The assessments described above now permit us to address these questions.

First, do the assessments produce different results? A comparison of the row and column scores of the generic SLCA of Figure 2 with those of the aggregated SLCA of Figure 4a demonstrates the following:

- The premanufacture life stage scoring is quite different, with much lower scores in the generic SLCA;
- The scores for the "in-house" life stages of product manufacture and product delivery are very similar;

- The product use and field service life stages are significantly lower in the generic SLCA;
- The liquid and gaseous residue EHS concerns have scores that are significantly lower in the generic SLCA;
- The overall total score of the generic SLCA is markedly lower than that of the aggregated SLCA.

Why are these differences present? We offer three explanations, each applicable to some of the differences noted above but not to others:

- *More Detailed Knowledge*. An evaluation team examining a product as a whole is unlikely to be as knowledgeable about the detailed environmental attributes of a subsystem as would be a team addressing only the subsystem. This option seems a likely explanation for the difference in scoring in matrix element 3,3 (solid residues) generated during product delivery.
- *Seriousness of Environmental Impact*. An aggregated score is made up of a group of lower-scale scores, and inherently combines a range of performances. Poor performance by a single subsystem, however, may be sufficiently severe as to outweigh good performance by the others. An example in the present case is matrix element 4,5 (gaseous residues) in product use. Figure 4a provides a tolerable score of 2.5 for this aggregated result, but Figure 2 provides an unacceptable score of 0. Figure 4b reveals that only the system dynamics subsystem is problematic here, but the emissions of carbon dioxide are of sufficient concern that the performance of a single subsystem determines an arguably proper score of 0 on the generic matrix.
- *New Behavior at Higher Scale Levels*. Scientists in various fields have known for some time that nonlinearities or thresholds in complex systems manifest themselves differently at different scales. For example, arrhythmic behavior of the human heart is not predictable by summing the behavior of the cells of the heart (Noble, 2002). In the multi-scale SLCA for the UH-60L, it appears that such a situation arises with the end-of-life stage. Here the subsystems themselves are moderately capable of being recycled, but when they are combined, materials are merged into complex structures much more difficult to transform into reusable materials upon obsolescence.

To some degree, the differences between the generic and aggregate matrices may reflect the algorithm used for aggregation. We have chosen to use simple averaging as a logical and transparent approach, but might instead have employed a lexical approach (Rawls, 1971) in which there is a hierarchy of decision-making. This latter approach, if developed algorithmically, might better link the analytic levels, but hierarchical decision-making tends to be contentious, and thus a poor choice for this initial cross-scale study.

The benefits of a multi-scale analysis can perhaps be best appreciated by considering how designers might respond to the results. For example, the generic LCA/SLCA would identify gaseous residues during product use (matrix element 4,5) as a high concern. That concern would then be conveyed to all of the subsystem design teams, where increased efforts by three of the four would produce negligible improvement. In contrast, a multiscale LCA/SLCA, as done here, singles out the system dynamics team as the focus for improved engineering on this topic, leaving the other subsystem design teams to pursue issues more relevant to their own portion of the product system.

It seems clear from this work that much is to be gained by performing multiscale LCAs/SLCAs. For some life stage-EHS concern pairings, cross-scale aggregation appears valid; for others it clearly does not. In the present instance, the results offer substantial guidance to product designers developing new designs or modifying existing ones. Some areas that were highlighted were already well recognized (e.g., gaseous residues in product use), while others (e.g., the need to work with suppliers at the premanufacture stage) had not been.

In particular, the ability of the SLCAs to provide unique and helpful advice when performed at both the system and subsystem levels had not been anticipated.

It is worth recognizing that different analytical levels tend to serve different types of users. At component and subsystem levels, the design team is the primary target for the information. At higher levels, those principally interested will often be product management and marketing teams. Environmentalists and other external constituencies are probably most interested in the highest analytical level regardless of how comprehensive it may be.

As a result of this research, and of the apparent benefits of multiscale approaches, we encourage more studies of cross-scale LCAs/SLCAs. Such work is needed both to support and extend this analysis, and to better understand the process of assessment of technology-environment interactions.

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The Center for Industrial Ecology (CIE) at the Yale School of Forestry & Environmental Studies is dedicated to the promotion of research, teaching, and outreach in industrial ecology. The field is focused on the concept that an industrial system should be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems approach that seeks to optimize the total materials cycle–from virgin material, to finished material, to component, to product, to obsolete product, to ultimate disposal. The field is sometimes termed "the science and technology of sustainability."

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