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Using the System Complexity Metric (SCM) to Compare CO2 Removal Systems

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A fundamental cause of difficulty in large engineering projects is their inherent complexity. An impression of complexity occurs if a system is simply difficult to understand, where there is no obvious mental model that correctly predicts its behavior. Higher system complexity is usually associated with higher cost and higher failure rate. Complexity is perceived if a system has many diverse components, multiple interactions and feedback loops, transients and dynamic behavior, and unanticipated failure modes. Identifying and removing these signs of complexity should improve performance and reduce the cost and failure rate. Complexity can be directly measured by the number of components and their interactions. The System Complexity Metric (SCM) is defined as the sum of the number of parts in a system, N, plus the number of the one-way interconnections between them, I. SCM = N + I. The SCM is easily determined by direct inspection of the system block diagram. SCM can be used to compare systems and to guide their redesign to reduce cost and failure rate. Carbon dioxide removal systems are analyzed using SCM, cost, and failure rate. As in previous work, cost is directly proportional to SCM and that failure rate increases as a power of SCM for large differences in SCM. The SCM ranking of carbon dioxide removal systems is the same as their ranking in detailed analysis and practice.

Nomenclature

ACRS = Advanced Carbon-formation Reactor System
ECLSS = Environmental Control and Life Support System
ESM = Equivalent System Mass
ISS = International Space Station
SCM = System Complexity Metric

I. Introduction

THE simple definition of complexity is the property of having a large number of different parts and many interconnections between them. More parts and more interconnections can be expected to reduce comprehension, create design difficulty, increase cost, and increase failure rate. The System Complexity Metric (SCM) is equal to the number of different subsystems or nodes in the system plus the total number of one-way interconnections between them. If there are N different nodes, the minimum number of internal one-way interconnections is I = N – 1, and the minimum SCM for a system of N subsystems is SCM = N + I = 2 N – 1. The maximum number of one-way connections is I = N (N - 1), and the maximum SCM = N + I = N^2. The SCM can be found by direct inspection of the system block diagram and it can be used to estimate and compare system costs and failure rates.[1]

II. The System Complexity Metric (SCM) for a Single Level System with N Nodes

The SCM is equal to the number of subsystems or nodes plus the one-way interfaces between them. The SCM is directly determined by examining the system block diagram and counting the numbers of nodes and interfaces. Figure 1 shows how the minimum and maximum SCM increase with N, according to the equations above.

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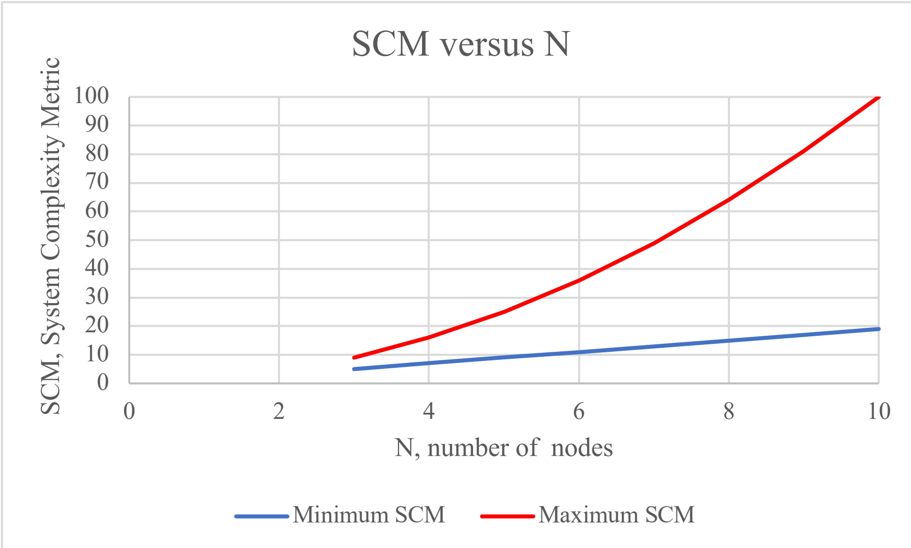


Figure 1. Minimum SCM = 2 N – 1 and maximum SCM = N^2.

The highest values of SCM are caused by a higher number of interconnections between subsystems.[1]

III. The System Complexity Metric (SCM) for Multilevel Systems with L Levels

In order to reduce complexity, systems are usually designed in hierarchical layers with each layer consisting of largely isolated subsystems. Figure 2 shows the SCM for a system with N = 100 nodes organized into different numbers of levels, L, and split into S = 5 subunits for each lower level.

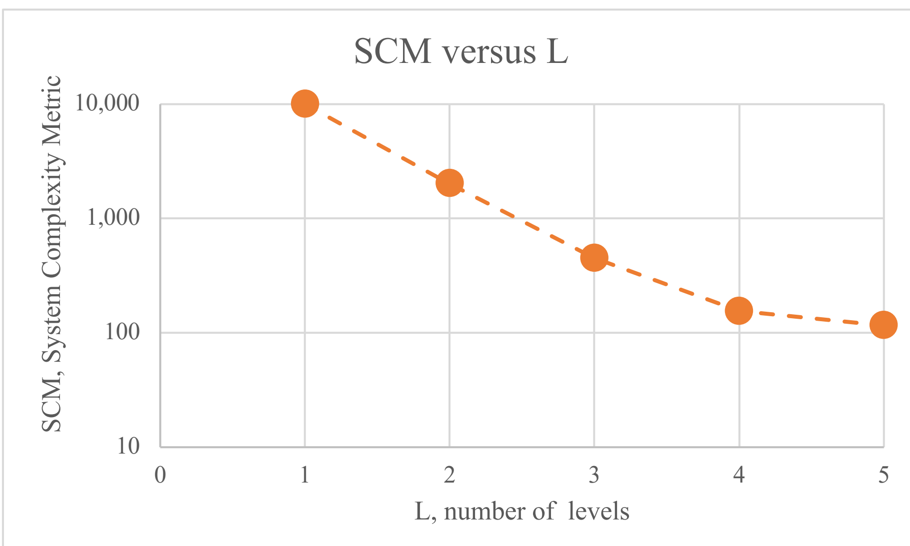


Figure 2. The SCM for L levels each with S = 5 subunits.

A single level, L = 1, has maximum SCM = N^2 = 10,000. A two-level system, L = 2, has a maximum system level one SCM = S^2 = 25, and a maximum subsystem level two SCM = N^2/S = 2,000, since there are S level two subunits each with SCM = $(N/S)^2$. As levels are successively added, the lowest level has a maximum SCM = N^2/S^{L-1} and all the higher levels have S = 5 nodes or units and a maximum SCM = S^2 = 25. For N = 100 original nodes and successive splitting into S = 5 subunits at each lower level, a hierarchy of level L = 4 or 5 reduces the original maximum SCM by two orders of magnitude.

The maximum SCM for a hierarchical system decreases logarithmically with the number of levels. The decrease in maximum SCM from 4 to 5 levels is proportionally less because the subsystems in the fourth level have few nodes and little complexity to remove. The maximum total SCM = $(L-1) S^2 + N^2/S^{L-1}$.[1]

IV. SCM Analysis of CO2 Reduction Technologies

Previous analysis compared four carbon dioxide reduction systems, Sabatier, Bosch, Advanced Carbon-formation Reactor System (ACRS), and Carbon Dioxide Electrolysis. Schematics were obtained and reliability was estimated based on parts count and parts reliability.[2] This is the usual approach to providing an initial estimate of system reliability but it really gives a lower bound on failure rate since most failures are due to system design and operational problems. The actual initial failure rate can be estimated as some multiple of the parts-based failure rate estimate.[3] Since both the SCM and the initial failure rate depend on the parts count, they are correlated. Previous work on the International Space Station (ISS) Environmental Control and Life Support System (ECLSS) showed that the much higher operational failure rates were also correlated with the SCM.[1]

A. The SCM's of the four CO2 reduction technologies

Reliability was estimated for the four carbon dioxide reduction systems based on parts count and estimated parts reliability.[2] The schematics used in that paper are used to compute the number of nodes, N, the number of one-way interfaces, I, and the SCM. These are shown on Table 1.

Table 1. SCMs for the Sabatier, Bosch, ACRS, and Carbon Dioxide Electrolysis.

	Sabatier	Bosch	ACRS	CO2 Electrolysis
Nodes, N	5	6	8	8
Interfaces, I	15	16	26	30
System Complexity Metric, SCM	20	22	34	38

The earlier paper on SCM[1] included valves, filters, and sensors in the SCM, so that the Sabatier there had N = 11, I = 20, and SCM = 31. The omission of valves, filters, and sensors is considered an improvement, since the major components count for most cost, failures, and multiple interconnection complexity.

V. Cost Analysis of CO2 Reduction Technologies

The costs to develop the four carbon dioxide reduction systems are estimated using a standard cost model.

A. Development Cost Estimation

Development cost includes DDT&E (Design, Development, Test, and Engineering) and hardware production. Development cost can be estimated using the Advanced Missions Cost Model (AMCM). The model is a single equation using mass, quantity, mission type, number of design generations, and technical difficulty to estimate the total cost for DDT&E and production.

The AMCM formula for the cost of DDT&E and production in millions of 1999 dollars is:

$$\text{Cost} = 5.65 * 10^{-4}\, Q^{0.59}\, M^{0.66}\, 80.6^{S}\, (3.81 * 10^{-55})^{(1/(IOC-1900))}\, B^{-0.36}\, 1.57^{D}$$

Q is the total quantity of development and production units, M is the system dry mass in pounds, S is the specification according to the type of mission (2.13 for human habitat, 2.39 for planetary base, 2.46 for crewed planetary lander), IOC is the year of initial operation capability, B is the block or hardware design generation (1 for new design, 2 for second generation), and D is the estimated difficulty (0 for average, 2.5 for extremely difficult, and -2.5 for extremely easy).[4]

B. Carbon Dioxide Reduction System Costs

The cost to develop a single unit is estimated for the four carbon dioxide reduction systems as shown in Table 2.

Table 2. Hardware unit costs for the Sabatier, Bosch, ACRS, and Carbon Dioxide Electrolysis

AMCM parameter		Sabatier	Bosch	ACRS	CO2 Electrolysis
Q	Quantity	1	1	1	1
M	Mass, lb	9.9	224.6	396.0	545.6
M	Mass, kg	18	102.1	180.0	248.0
S	Specification	2.13	2.13	2.13	2.13
IOC	Initial date	2030	2030	2030	2030
B	Block	2	2	1	1
D	Difficulty	1	1	1	1
	Hardware development cost, $M per unit	13.8	108.5	201.9	249.5

The costs are for a single unit. Q = 1. The masses M are for single units, regardless of their capacity or the number needed on a particular mission. The Sabatier mass, the Bosch mass, and the ACRS mass are from Eckart[5] and ARC.[6] The CO2 Electrolysis mass is from Holquist.[7]

The specification, S, and the initial operation capability date, IOC, are the same for all the systems. The specification, S, is 2.13 for a human habitat. A Mars base would have a higher specification of 2.39. The Initial Operating Capability was set at IOC = 2030.

The block or hardware design generation, B, was set to 3 for the next Sabatier, reflecting ISS selection bench testing and deployment on ISS. B was set to 2, second generation, reflecting ISS selection bench testing. B was set to 1 for ACRS and CO2 electrolysis, corresponding to a new design. The recycling development difficulty, D, was set to 1, more than average, for high reliability systems.

VI. Reliability Analysis of CO2 Reduction Technologies

Table 3 shows the estimated failure rates based on the parts' failure rates.

Table 3. Estimated failure rates.

	Sabatier	Bosch	ACRS	CO2 electrolysis
Failure rate per 10,000 hours	3.2	5.1	6.2	5.1

The failure rates were estimated in previous work.[2] Most of the failure rates are taken directly from a reliability study of a Sabatier-based atmosphere control system. The others are estimated based on similarity to other components in the Sabatier study.

The system failure rate is simply the sum of all the component failure rates. Thus, the failure rate for the Bosch system is obtained by multiplying the number of components of each type times that component type's failure rate per hour, then adding up the failure rates of all the types of components.

The Bosch system has a failure rate of 5.1 failures per 10,000 hours, which is 417 days or 1.14 years. A failure can be expected every 82 days. For a long duration mission, spares must be provided with a capability for repairs. The Sabatier system has a failure rate of 3.2 failures per 10,000 hours, significantly less than the Bosch.

The failure rate of the ACRS is 6.2 per 10,000 hours. The ACRS has a higher failure rate than Bosch or Sabatier, corresponding to its higher parts count. The carbon dioxide electrolysis system has a failure rate of 5.1 failures per 10,000 hours, identical to that of the Bosch system.

The failure rate is nearly directly proportionally to the parts count. Failure rate per 10,000 hours = 0.1 * total parts count, with errors of no more than 10% and usually 2 or 3%. This correspondence occurs because most of the components have a failure rate of 0.1 per 10,000 hours. Components with much lower failure rates add little to the system failure rate. Components having higher failure rates, such as the Bosch, Sabatier, carbon formation, and CO/H2 reactors, can contribute more than 10% to the overall failure rate.

VII. The SCM as a Predictor of Cost and Failure Rate

Table 4 shows the System Complexity Metric (SCM), estimated costs, and estimated failure rates for the four carbon dioxide reduction systems from the previous tables.

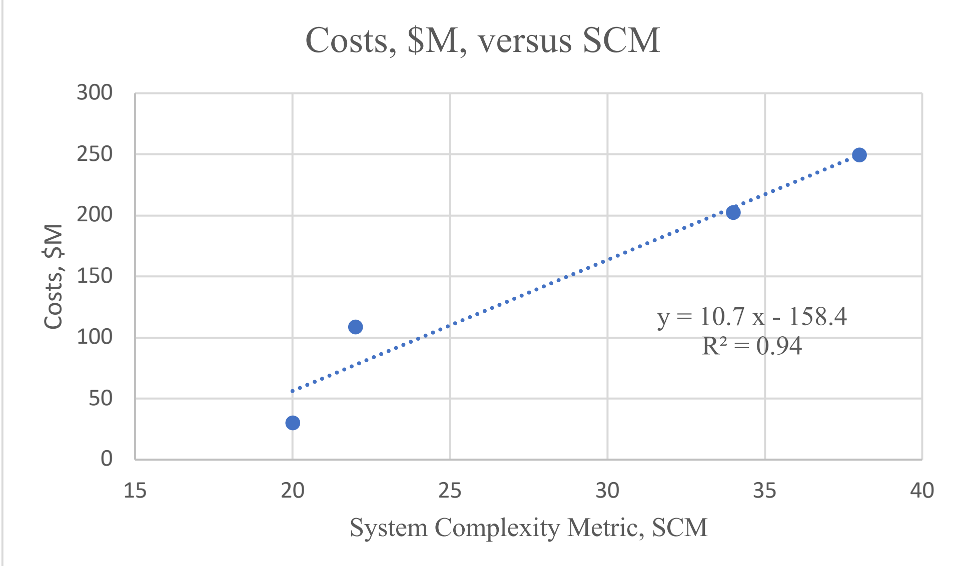
Table 4. SCM, costs, and estimated failure rates for the CO2 reduction systems.

	Sabatier	Bosch	ACRS	CO2 Electrolysis
System Complexity Metric, SCM	20	22	34	38
Cost	29.76	108.52	201.88	249.46
Failure rate per 10,000 hours	3.2	5.1	6.2	5.1

A. Cost versus SCM

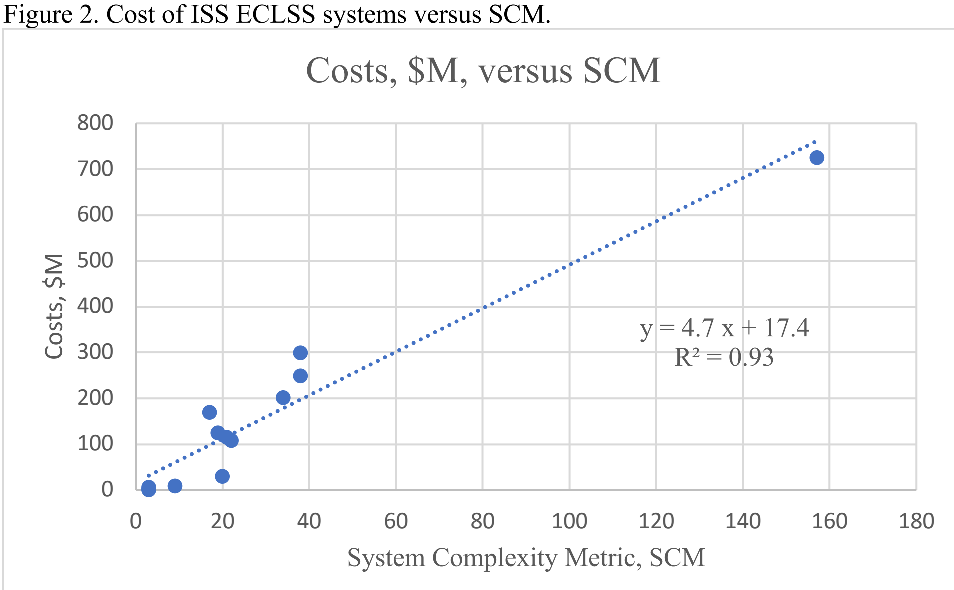
The estimated cost of the CO2 reduction systems is plotted versus SCM in Figure 1.

Figure 1. Cost of the CO2 reduction systems versus SCM.



The estimated costs of the CO2 reduction systems are very highly corelated with their SCMs, a 0.94 goodness of fit for the linear regression model shown. Figure 2 includes additional data from the previous SCM paper.[1] The SCM values were recomputed to eliminate valves, filters, and sensors and their interconnections.

Figure 2. Cost of ISS ECLSS systems versus SCM.



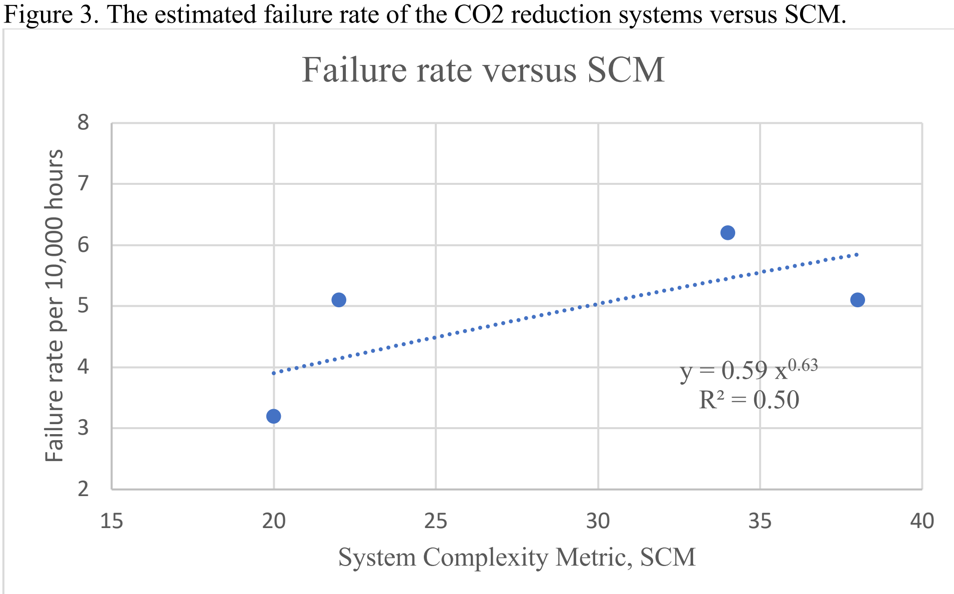
The CO2 reduction systems data from Table 4 and Figure 1 is augmented with data on water tanks, oxygen tanks and LiOH cannisters at SCM =3, these three resupply systems combined at SCM =9, the ISS Carbon Dioxide Removal System, Urine Processor Assembly, Oxygen Generator Assembly, and Urine processor Assembly at SCMs from 17 to 38, and the entire ISS ECLSS at SCM = 157.

Again, the estimated costs are very highly corelated with their SCMs, a 0.93 goodness of fit for the linear regression model shown. In both figures the cost trendline is close to 5 SCM. For similar systems or for a wide range of SCMs, SCM seems to be a good predictor of estimated cost. However, there is a wide scatter of costs for the different ISS ECLSS subsystems having SCMs from 20 to 40.

B. Failure rate versus SCM

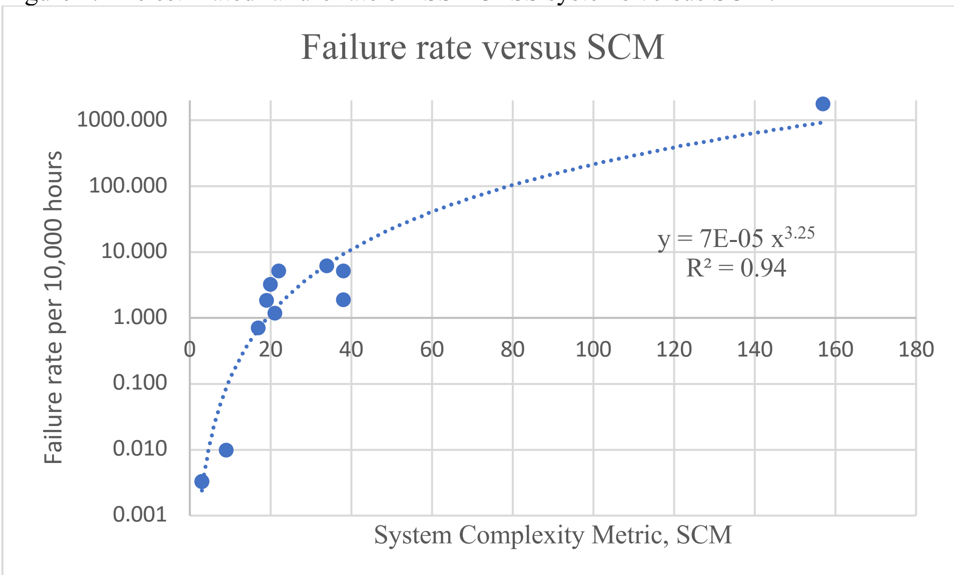
The estimated failure rate of the CO2 reduction systems is plotted versus SCM in Figure 3.

Figure 3. The estimated failure rate of the CO2 reduction systems versus SCM.



The exponential trendline shows failure rate increasing as the 0.63 power of SCM, but the goodness of fit is only 0.5, indicating that SCM is not a strong determinant of failure rate. However, the range of failure rates is quite small, only a factor of 2, from about 3 to about 6 failures per 10,000 hours. Failure rates can easily vary by factors of 10 or 100. Figure 4 includes additional data from the previous SCM paper.[1] The SCM values were recomputed to eliminate valves, filters, and sensors and their interconnections.

Figure 4. The estimated failure rate of ISS ECLSS systems versus SCM.



The exponential trendline shows failure rate increasing as the 3.25 power of SCM, with a goodness of fit is of 0.94. For a wide range of SCMs, SCM seems to be a good predictor of estimated failure rate. However, there is a wide scatter of failure rates for the different ISS ECLSS subsystems having SCMs from 20 to 40.

C. Further detailed comparison of the CO2 reduction systems

The four carbon dioxide reduction systems were also compared based on the extensive literature.[8] The purpose of the SCM is to support preliminary technology comparisons. Does further analysis and experience support the initial indications of SCM?

The initial choice for ISS was Bosch, because it required no venting of gases and could provide nearly full oxygen recovery. Sabatier was later selected for ISS over Bosch because of its lower mass, higher reliability, and many other factors.

In the dozens of carbon dioxide reduction system trade studies, the Sabatier system was selected with only two exceptions. Sabatier has a strong advantage in ESM over Bosch and ACRS. Bosch is the next most attractive candidate, but two studies found that resupplying water would be more efficient than using Bosch. A later study specifically looking for alternates to Sabatier identified Bosch and Carbon Dioxide Electrolysis as the best prospects.

Sabatier seems to have been the inevitable choice, with Bosch the best alternative followed by ACRS and Carbon Dioxide Electrolysis. This ordering corresponds exactly to the increasing SCM of the four carbon dioxide reduction systems.

VIII. Discussion of the System Complexity Metric (SCM)

The use and the dependability of the complexity and other metrics are discussed.

A. Use of ESM and SCM

When the Equivalent System Mass (ESM) metric was initially intended for preliminary screening of a set of technologies intended for the same purpose, based on launch mass.[9] After the less suitable candidates were eliminated, the remaining technologies can be considered using the usual multifactor trade-off process. ESM includes the mass of the system hardware and spares plus the allocated masses of the pressurized volume, power, and colling needed to support the systems. Surprisingly, the space life support program adopted ESM as the almost exclusive metric for technology selection. This extended use of ESM can be considered mistaken, since ESM does not include most of the relevant decision factors and since the new much lower launch cost makes ESM a minor contributor to total cost. The SCM was developed to replace ESM in its originally intended use, initial technology screening.

SCM is very suitable for initial technology screening because SCM can be easily determined by direct inspection of the system schematic and because SCM is a good indicator of the expected cost and reliability. SCM gives a good relative prediction of the cost estimated by a well-known cost model, without the need to estimate the mass and other parameters required by the cost model. SCM gives a good relative prediction of the failure rate estimated by the usual parts-based method, without the need identify the parts failure rates as required by the reliability method. A technology ranking based on the SCM can be used for preliminary screening and to guide further analysis.

B. Dependability of SCM and ESM

Because the SCM is easily determinable by direct inspection, it is difficult to dispute or manipulate. It may seem surprising, but metrics that are used to select projects or allocate funding are nearly always adjusted to produce a result predetermined by other factors.[10] "The possibility of … corruption of measures creates doubts that extend to all measurements."[11]

Two technology trade-off studies using ESM are notable. In the 1990's NASA was interested in applying biology in life support recycling and in growing plants for food in space. This seemed reasonable when closure was the accepted life support metric but ESM had then replaced closure and ESM analysis had to be favorably adjusted to justify these important on-going projects. One study contradicted previous analysis, finding that a favored bioreactor water processor had about seven times higher ESM than competing non-biological systems.[12] Management reorganized and formalized ESM analysis so that in the future there would be "no surprises." Another study found, contrary to previous analysis, that the large mass and power of plant growth chambers makes growing food require much more ESM than supplying food even for decade-long missions.[13] A study of management metrics concluded that they cannot be trusted.[10] The problems of using metrics are nearly inescapable.[11]

IX. Conclusion

The System Complexity Metric (SCM) is defined as equal to the sum of the number of parts in a system, N, plus the sum of the one-way interconnections between them, I. SCM = N + I. The SCM is easily determined by direct inspection of the system block diagram. The estimated life support system cost was found to be directly proportional to SCM and for large differences in SCM the estimated failure rate increased as roughly the third power of SCM. SCM is a good predictor of the relative estimated cost and failure rate produced by deeper analysis.

The SCM is intended to be used for initial comparison and screening of new systems with little definition beyond their block diagrams. Because of its simplicity and simple calculation, SCM is more difficult to manipulate than most metrics. Complexity is a fundamental system property and using the SCM to measure it can improve system comparison and help guide design.

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