

Using the System Complexity Metric (SCM) to Compare CO₂ Reduction 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 reduction 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 reduction 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 $SCM = N + I = 2N - 1$. 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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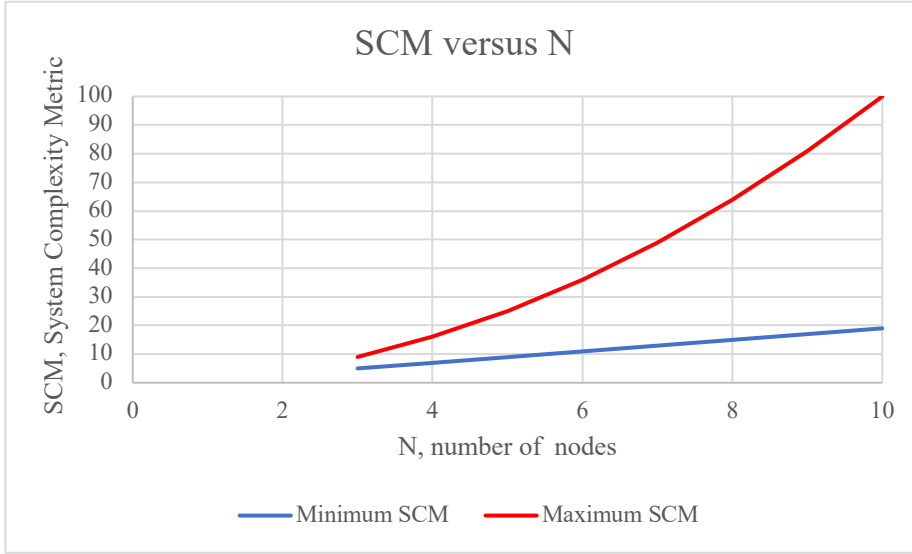


Figure 1. Minimum $SCM = 2N - 1$ and maximum $SCM = N^2$.

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.

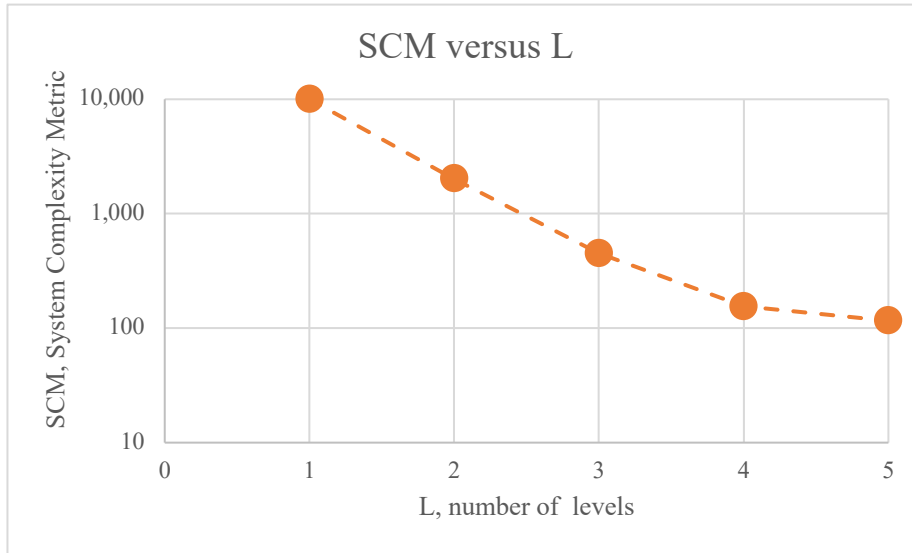


Figure 2. The SCM for L levels each with $S = 5$ subunits.

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

A. Previous Work

The SCM was originally developed in “The System Complexity Metric (SCM) Predicts System Costs and Failure Rates.”¹ That paper derived the SCM directly from the usual definition of complexity as the property of having a large number of different parts and interconnections between them. Complexity is an important general topic in engineering and much work has been done. A widely used software complexity metric is based on a simple formula similar to the SCM but has evolved to high complexity. Some analysis shows that something as simple as counting the lines of code can give better results. There is some work on a hardware complexity metric that provides insight into how system architecture affects complexity.

IV. SCM Computation for Sabatier CO₂ Reduction

The SCM is measured by counting the numbers of nodes and one-way interfaces in the system block diagram.

A. The Amount of Detail in the SCM

Since one use of the SCM is to compare system designs, the SCMs of different designs should be computed in the same way and with the same level of detail. Since another use of the SCM is as a predictor of cost and reliability, the identified nodes should be the major components responsible for most cost, failures, and interconnection complexity. Minor components such as valves, filters, and sensors can be omitted since these components have low cost and their reliability is well understood. However, they can cause reliability and maintenance problems and must be considered in the actual reliability analysis. Including these small valves, filters, and sensors in the SCM seems a distraction from comparing fundamental architectural differences. However, a higher number of sensors can indicate greater care for operational reliability. Engineering prototypes often have many sensors to aid design and these may be removed in operational systems to reduce the problems caused by intermittent and failed sensors. In contrast, high reliability systems often have many sensors and perform diligent tracking of all anomalies. The essential purpose of computing the SCM is compare and improve the potential cost and reliability of alternate system architectures.

B. Computing the SCM for the Sabatier Reactor

The SCM is computed using two different Sabatier schematics in two ways, first counting all parts and interfaces and then including only the major parts and their interfaces while ignoring the valves, filters, and sensors. The first paper on SCM¹ included valves but not filters and sensors in the SCM, so the SCM there had an intermediate value between those computed here. The new omission of valves, filters, and sensors is expected to give a more accurate comparison. Figure 3 shows a core component schematic of the Sabatier System.

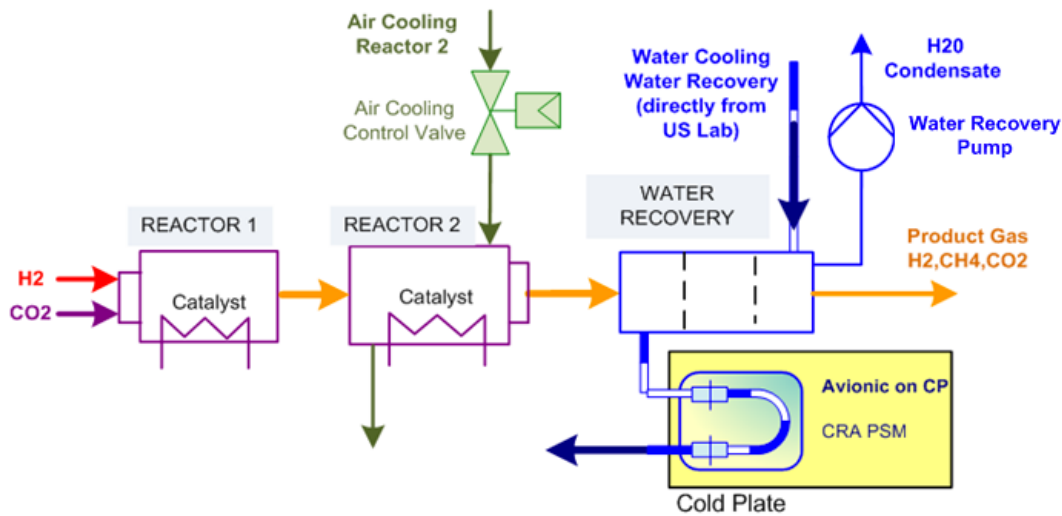


Figure 3. Core component schematic from ICES 2016-391.²

Figure 4 shows an earlier much more detailed schematic of the Sabatier system with valves, filters, and sensors.

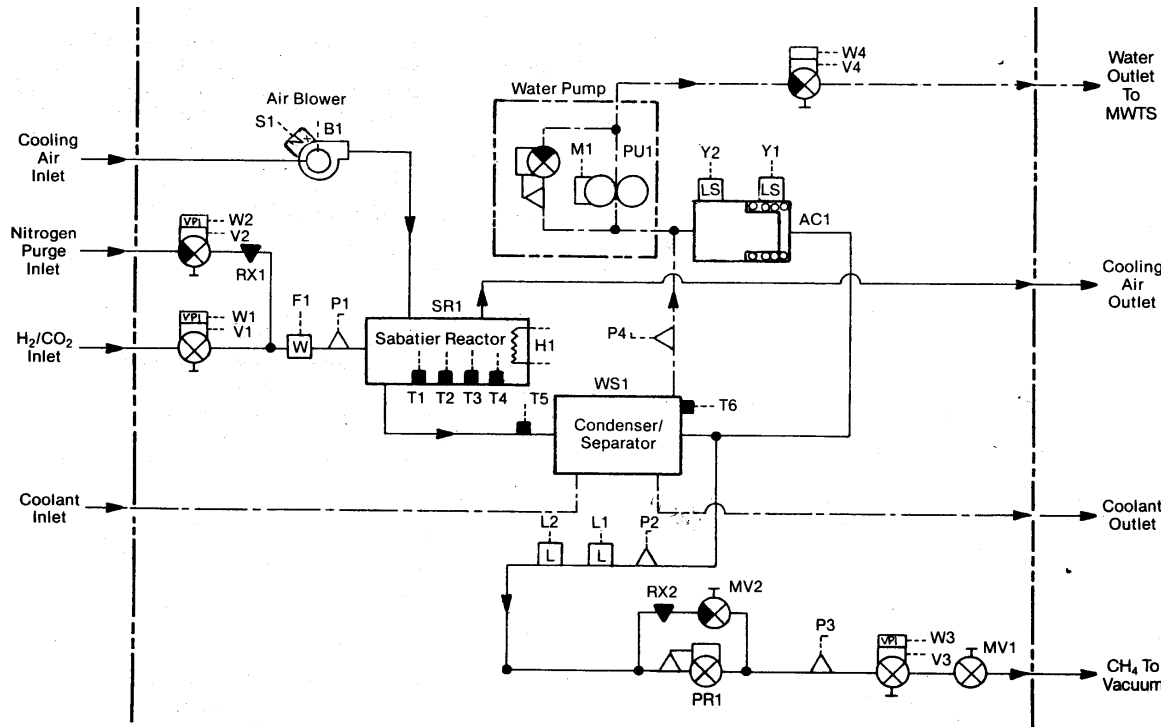


Figure 4. A detailed Sabatier schematic with valves, filters, and sensors from 851343.³

Table 1 shows the results of computing the SCM for both schematics with and without the valves, filters and sensors. The SCMs without valves, filters, and sensors are identical even though the parts differ slightly.

Table 1. Sabatier SCM for all parts and without valves, filters, and sensors.

Source	2016-391		851343	
Method	All parts	Without valves, filters, and sensors	All parts	Without valves, filters, and sensors
N	6	5	25	5
I	13	12	21	12
SCM = N + I	19	17	46	17

Figure 3 has 6 parts including the Air Cooling Control Valve and 5 when it is not counted. Removing the Air Cooling Control Valve deletes one part and one interconnection, and the SCM declines by 2. Figure 4 includes valves, V, flow sensors, W, pressure sensors, P, temperature sensors, T, flow restrictors, RX, level sensors, Y, liquid traps, L, pressure regulators, PR, and manual valves, MV, and an accumulator, AC. The SCM for all parts is 46, but this is reduced to 17 when the valves, filters, sensors, etc. are not counted. The SCM including only major components is the same, 17, computed from both schematics. Figure 3 lacks the blower but has an extra Sabatier reactor, so the parts lists are different. The schematics were drawn thirty years apart and a blower is probably not included now because ISS cooling is provided. Adding a single part and its interface would change SCM only by 2. The computation of SCM using only the major components is simple and seems reasonably robust.

V. 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.⁴ 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.⁵ 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.⁴ 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 2.

Table 2. SCMs for the Sabatier, Bosch, ACRS, and Carbon Dioxide Electrolysis.

	Sabatier	Bosch	ACRS	CO2 Electrolysis
Nodes, N	5	6	8	8
Interfaces, I	12	16	26	30
System Complexity Metric, SCM	17	22	34	38

VI. 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).⁶

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 3.

Table 3. 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	484.0	224.6	396.0	545.6
M Mass, kg	220.0	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	3	2	1	1
D Difficulty	1	1	1	1
Hardware development cost, \$M per unit	156.0	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 is from Jones⁷ and O'Neil et al.⁸ The Bosch mass, and the ACRS mass are from Eckart⁹ and ARC.¹⁰ The CO2 Electrolysis mass is from Holquist.¹¹

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 for Bosch, 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 higher reliability systems.

VII. Reliability Analysis of CO₂ Reduction Technologies

Table 4 shows the estimated failure rates based on the parts' failure rates.

Table 4. Estimated failure rates.

	Sabatier	Bosch	ACRS	CO ₂ electrolysis
Failure rate per 10,000 hours	3.2	5.1	6.2	5.1

The failure rates were estimated in previous work.⁴ Most of the failure rates are taken directly from a reliability study of a Sabatier-based atmosphere control system. The other system's reliability is 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.

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

Table 5 shows the System Complexity Metric (SCM), estimated costs, and estimated failure rates for the four carbon dioxide reduction systems from the previous tables.

Table 5. SCM, costs, and estimated failure rates for the CO₂ reduction systems.

	Sabatier	Bosch	ACRS	CO ₂ Electrolysis
System Complexity Metric, SCM	17	22	34	38
Cost	156.0	108.2	201.9	249.5
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 5.

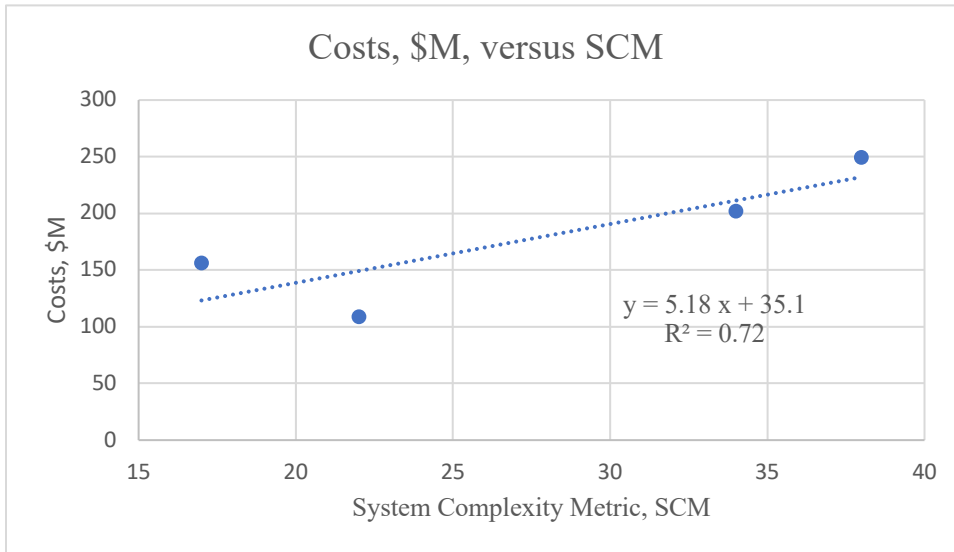


Figure 5. Cost of the CO₂ reduction systems versus SCM.

Costs and SCM are reasonably correlated with a 0.72 goodness of fit for the linear regression model shown. The estimated costs of the CO₂ reduction systems do increase with SCM. An SCM of 20 predicts a cost of 139 \$M and an SCM of 40 predicts a cost of 242 \$M. Using this data, a 100% increase in SCM produces a 74% increase in cost. Considering that carefully estimated costs are often overrun two or three times and that project decisions and budget limits strongly affect costs, an SCM difference less than factor of three is not a very strong decision factor.

Figure 6 includes additional data from the original SCM paper.¹ The SCM values were recomputed to include only major parts without valves, filters, and sensors and their interconnections.

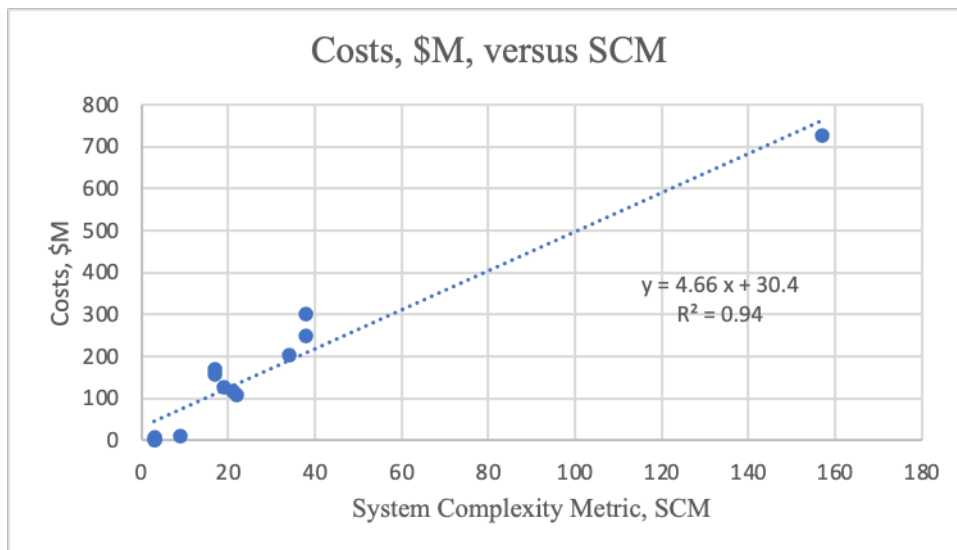


Figure 6. Cost of ISS ECLSS systems versus SCM.

The CO₂ reduction systems data from Table 4 and Figure 5 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.

Here the estimated costs are highly correlated with their SCMs, a 0.94 goodness of fit for the linear regression model shown. The cost trendline is close to that in Figure 5 for CO₂ reduction systems only. The slope is 4.66 here rather than 5.18. Here an SCM of 20 predicts a cost of 124 \$M and an SCM of 40 predicts a cost of 217 \$M. A 100% increase in SCM produces a 75% increase in cost, close to the previous 74% increase. The costs range from 3 million to 726 million, two orders of magnitude. It appears that an SCM ratio of 5, 10, or more is a strong indicator of significantly different cost.

B. Failure Rate Versus SCM

The estimated failure rate of the CO₂ reduction systems is plotted versus SCM in Figure 7.

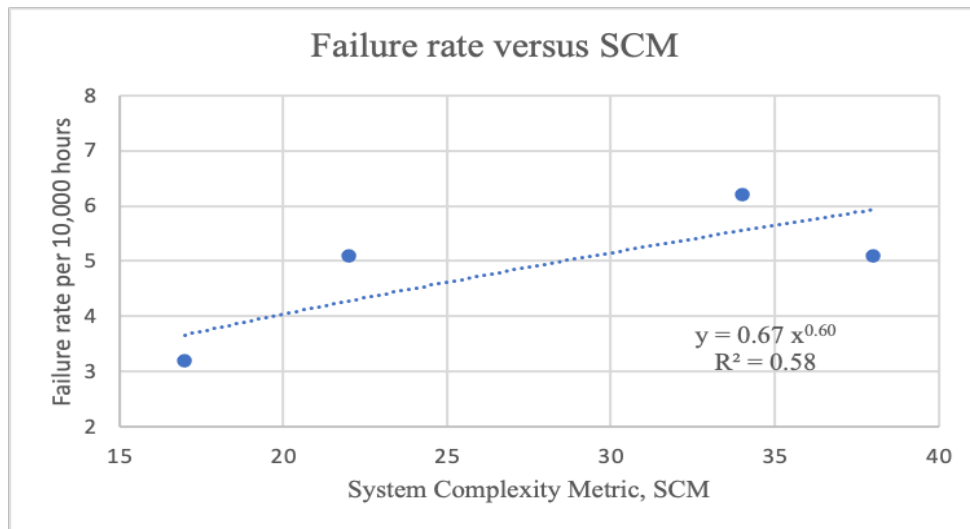


Figure 7. The estimated failure rate of the CO₂ reduction systems versus SCM.

The exponential trendline shows failure rate increasing as the 0.60 power of SCM, but the goodness of fit is only 0.58, indicating that SCM variations in this range are not a strong predictor 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 8 includes additional data from the first SCM paper.¹ The SCM values were recomputed to eliminate valves, filters, and sensors and their interconnections.

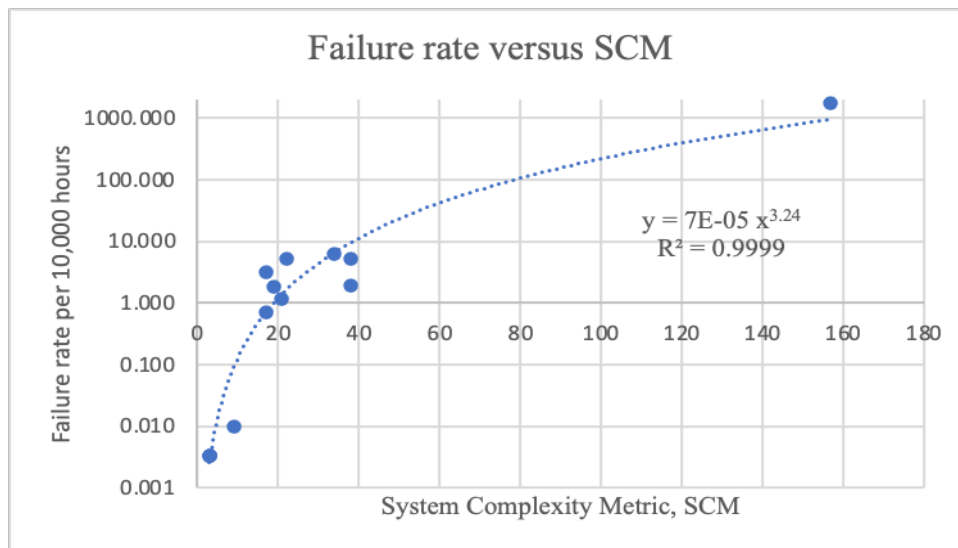


Figure 8. The estimated failure rate of ISS ECLSS systems versus SCM.

The exponential trendline shows failure rate increasing as the 3.24 power of SCM, with a surprising goodness of fit of 0.9999. Over this wide range of SCMs, SCM seems to be a good predictor of estimated failure rate. A difference in failure rate by a factor of ten can be considered a significant design differentiator. Multiplying the SCM by a factor of 2.04 would multiply the estimated failure rate by 10 and multiplying the SCM by a factor of 2 would increase failure rate by a factor of 9.45. An SCM ratio of a factor of 3 or more can be considered a strong decision factor.

C. Further Analysis and Selection of the CO₂ Reduction Systems

The four carbon dioxide reduction systems were also compared based on the extensive literature.¹² 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 then expected 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. Bosch was 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.

D. Sources of Uncertainty in SCM and in the Weight of SCM

Although the SCM of a system can be directly computed by counting the major parts and their one-way interconnections on the system schematic, many sources of error and uncertainty can affect both the compute SCM and its usefulness in predicting cost and reliability. The first concern is the quality and detail of the system schematic. Figure 3 shows only 5 core components and a single valve for the Sabatier, while Figure 4 shows 5 core components and 20 valves, filters, sensors, etc. The computed SCM is the same at 17 but it seems it could easily have been different by 2 or 3, or about 6 to 9%. A potential problem (not occurring here) in counting the number of interconnections is that the lines connecting the nodes may lack arrowheads, so that it may be difficult to distinguish one-way and two-way interconnections.

The second concern is in correctly identifying all the complex major subsystems. The cold plate in Figure 3 and the accumulator in Figure 4 are less complex than the Sabatier reactor but more complex than valves, etc. A previous assessment of SCM included valves but not filters and sensors. Using the same definition of major subsystems reduces uncertainty, but changing the cut point may change the relative SCM.

How strongly does the complexity measured by SMC actually determine cost and reliability? Clearly adding a major component will increase cost, but the cost of the system will be more than the sum of the costs of the subsystems. Half the total cost may be for integration and test and the count of one-way interconnections is intended to reflect this system level cost. If two systems have subsystems with widely different costs or interconnections with widely different difficulty, their costs will be much more different than their SCMs indicate. Similarly, adding a major component will increase the failure rate, but the total failure rate will be more than the sum of the failure rates of the subsystems. Much of the failure rate will be due to system level interactions and again the count of one-way interconnections is intended to reflect this system level failure rate. SCM is computed as if all the major components make the same contribution to the system cost and failure rate. SCM is useful in comparing system designs only if the ratio of their SCMs is greater than 3 to 5. To compare systems with similar SCMs, the subsystem costs and failure rates should be directly estimated. An example of a clear discrimination by SCM would be between lithium hydroxide canisters, SCM 3, and the carbon dioxide removal system, SCM 33.¹ An example of a marginal discrimination based on SCM would be between Sabatier and Bosch versus ACRS and CO₂ Electrolysis, SCM ratio of about 2, in this paper.

IX. Comparison of Equivalent System Mass (ESM) and the System Complexity Metric (SCM)

The Equivalent System Mass (ESM) is a measure of total system launch mass. It is “the sum of the life support system mass and appropriate fractions of supporting system masses, including pressurized volume, power generation, cooling, and crew time.”¹³ The ESM guidelines recognize that factors other than mass are also

important. “ESM should rarely be the only metric applied in a trade study. As a cost metric, ESM may not be capable of capturing reliability, safety and performance differences between trade study options.”¹³

ESM reflects only launch cost. ESM was specifically developed to avoid the mention of dollar costs. “ESM is typically used as a transportation cost measure in ALS (Advanced Life Support) trade studies, to avoid the complications, both technical and political, of using dollar costs for comparisons.”¹³

Systems are compared assuming they have the same reliability. “Comparison of two systems or subsystems with ESM is only valid for those systems or subsystems that satisfy the same life support product quantity, product quality, reliability and safety requirements.”¹⁴

ESM was initially intended for preliminary screening of a set of technologies intended for the same purpose. “Another word of caution about the equivalent-mass concept - it provides only a rough order-of-magnitude calculation for comparing LSS (life Support System) configurations in the very early stages of mission planning.”¹⁵

ESM measures only launch cost. Dollar costs and differences in reliability are not considered. ESM provides only rough order of magnitude discrimination between systems. The SCM was developed to replace ESM in its originally intended use, initial technology screening, and to focus attention on the cost and reliability factors not included in ESM.

SCM is suitable for initial technology screening because SCM can be directly determined by inspection of the system schematic and because an SCM difference of half an order-of-magnitude seems to indicate relative cost and reliability. SCM predicts relative cost as estimated by a well-known cost model, without the need to determine the mass and other parameters required by the cost model. SCM predicts the failure rate as estimated by the usual parts-based method, without the need identify the parts failure rates as usually required. A technology ranking based on the SCM can be used for preliminary screening. Further analysis is needed if the SCMs are not sufficiently different.

X. 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 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 costs and failure rates 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. 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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