The System Complexity Metric (SCM) Predicts System Costs and Failure Rates

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A complex system has many parts and interactions and so is difficult to understand. Systems with higher complexity generally have higher costs and failure rates. A System Complexity Metric (SCM) is defined to be the sum of the number of nodes, N, in the system block diagram plus the number of one-way interactions, I, between the nodes. SCM = N + I. SCMs are easily determined by direct inspection of high level block diagrams of life support systems. System cost was found to be directly proportional to SCM. The system MTBF (Mean Time Before Failure) is the inverse of the system failure rate. MTBF = 1/f. The system MTBF was found to be proportional to $SCM^{-2.2}$ for estimated preflight MTBFs. As is typical for systems that are not extensively tested and redesigned to eliminate unexpected failure modes, the life support flight failure rates were about ten times higher than the preflight estimates and the MTBFs one-tenth the preflight estimates. The system MTBF was found to be proportional to $SCM^{-2.6}$ for observed flight MTBFs.

Nomenclature

4BMS	=	Four Bed Molecular Sieve
AMCM	=	Advanced Missions Cost Model
BVAD	=	Baseline Values and Assumptions Document
CDRA	=	Carbon Dioxide Removal Assembly
COPV	=	Composite Overwrapped Pressure Vessel
CRS	=	Carbon Dioxide Reduction System
DDT&E	=	Design, Development, Test and Evaluation
ECLSS	=	Environmental Control and Life Support system
f	=	Failure rate per hour = 1/MTBF
ISS	=	International Space Station
LiOH	=	Lithium hydroxide
MTBF	=	Mean Time Before Failure in hours, MTBF = 1/f
OGS	=	Oxygen Generation System
ORU	=	Orbital Replacement Unit
SCM	=	System Complexity Metric
UPA	=	Urine Processor Assembly
WPA	=	Water Processor Assembly

Mathematical symbols

I	=	number of one way Interfaces in the system
L	=	number of Levels in the system hierarchy
N	=	number of Nodes in the system
S	=	number of Subsystems per system

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I. Introduction

A basic engineering definition of complexity is the property of having a large number of different parts and interconnections between them. More parts and more interconnections can be expected to impair understanding, create design difficulty, increase cost, and decrease reliability. The proposed 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 can be used to estimate and compare system cost and reliability.

II. The System Complexity Metric (SCM) for a Single Level Connected Black Box System

Direct measures of system complexity are based on the system structure, the number of subsystems and their interfaces. The structural complexity of a system can be determined by examining the system block diagram and counting the numbers of subsystems or nodes and interfaces. Some polygons that can represent system block diagrams are shown in Figure 1. (Mathemania)

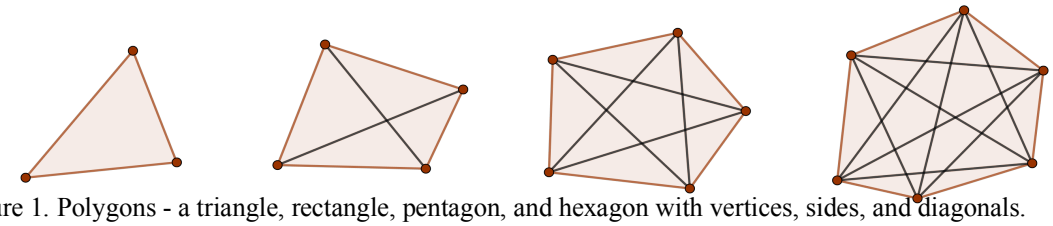


Figure 1. Polygons - a triangle, rectangle, pentagon, and hexagon with vertices, sides, and diagonals.

Table 1 shows the number of nodes or subsystems and the number of interfaces for different polygons.

Table 1. System block diagrams and structural complexity metrics.

Polygon	Triangle	Square	Pentagon	Decagon	100 sided	N sided
N, number of nodes or subsystems	3	4	5	10	100	N
I, number of one way interfaces						
Min I	2	3	4	9	99	N - 1
Max I if all one way	3	6	10	45	4,950	N(N-1)/2
Max I if all two way	6	12	20	90	9,900	N(N-1)
System Complexity Metric (SCM) = N + I						
Min SCM	5	7	9	19	199	2 N - 1
Max SCM if all I one way	6	10	15	55	5,050	$(N^2 + N)/2$
Max SCM if all I two way	9	16	25	100	10,000	N^2

A. The System Design Process and the System Complexity Metric (SCM)

The usual design process produces hierarchical systems with a limited number of subsystems and interconnections between them. The system requirements are developed first and then assigned in related groups to subsystems and down to lower level assemblies. One objective is to have most interfaces within the subsystems, so that the subsystems have few interconnections. Another objective is to have relatively few subsystems, so that they can be easily considered. Usually the subsystems can be treated as "block boxes." They have a defined internal process with a few inputs and outputs. The system level design process does not have to consider the details of the subsystems.

The most fundamental part of the system cost is the sum of the subsystem costs. This sum of subsystem costs is sometimes offered as the initial system cost estimate. The most fundamental part of the system failure rate is the sum of the subsystem failure rates. This sum of subsystem failure rates is sometimes offered as the initial system failure rate estimate. These engineering bottom-up estimates are usually much lower than the actual costs or failure rates. The problem with the bottom-up estimates is that they do not include system level design, integration, and test, which can easily account for more than half of the final cost. In aerospace during the '60's, satellite costs were estimated as half due to the components, often bought outside, and half due to systems design, integration, and test, this real work done in-house. The System Complexity Metric (SCM) is intended to help produce better cost and reliability estimates than the component-based bottom-up estimates by reflecting system complexity.

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

The previous section considered a single level connected black box system. It computed the SCM = N + I, where N was the number of black box nodes and I was the total number of one way interconnections between them. For N nodes, the number of interconnections varied from N – 1 to N(N-1) and the SCM varied from 2 N -1 to N^2. Two level and multilevel systems are considered next.

A. The Multilevel System Complexity Metric (SCM) for Two Levels

Suppose that the original system level with N nodes is divided into S subsystems. Each subsystem has N/S nodes and each has a maximum SCM = $(N/S)^2$. Since there are S subsystems, the maximum total complexity of the subsystem level is S $(N/S)^2 = N^2/S$. The higher system level has S subsystems, so the maximum SCM of the system level is S^2. The maximum total SCM of the partitioned two level system is SCM = $S^2 + N^2/S$. Since S is usually much less than N, the partitioned two level system has much lower maximum complexity than the original system. $S^2 + N^2/S << N^2$. Table 2 shows the maximum System Complexity Metric, SCM, for two level systems with different numbers of nodes, N, and subsystems, S.

Table 2. Maximum SCM for two level systems with different N and S.

N, number of nodes	10	20	30	100	SCM reduction ~ 1/S, N large
N^2	100	400	900	10,000	
S, number of subsystems					
2	4 + 50 = 54	4 + 200 = 204	4 + 450 = 454	4 + 5,000 = 5,004	1/2
3	9 + 33 = 42	9 + 133 = 142	9 + 300 = 309	9 + 3,333 = 3,342	1/3
4	16 + 25 = 41	16 + 100 = 116	16 + 225 = 241	16 + 2,500 = 1,516	1/4
5	25 + 20 = 45	25 + 80 =105	25 + 180 = 205	25 + 2,000 = 2,025	1/5

The SCM reduction achieved by dividing a system into S subsystems is approximately 1/S for a large number of nodes, N.

B. The Multilevel System Complexity Metric (SCM) for Three to Five Levels

The process of dividing the system into subsystems can be continued by dividing each subsystem into subsubsystems to further reduce the total complexity and the complexity of the smallest design units. Table 3 shows the maximum SCM for a system with 100 nodes organized into different numbers of levels, L, and split into S subunits for each lower level.

Table 3. Maximum SCM for a system with N = 100, S = 5 shows the maximum SCM for a system with 100 nodes organized into different numbers of levels, L.

L, levels	1	2	3	4	5	Maximum total SCM	
1	$N^2 = 10{,}000$					10,000	Maximum total SCM = $(L-1)\ S^2 + N^2/S^{L-1}$
2	$S^2 = 25$	$N^2/S = 2{,}000$				2,025	
3	$S^2 = 25$	$S^2 = 25$	$N^2/S^2 = 400$			450	
4	$S^2 = 25$	$S^2 = 25$	$S^2 = 25$	$N^2/S^3 = 80$		155	
5	$S^2 = 25$	$S^2 = 25$	$S^2 = 25$	$S^2 = 25$	$N^2/S^4 = 16$	116	

A single level, L = 1, has maximum SCM = N^2 = 10,000. A two level system, L = 2, has a maximum system level (L = 1) SCM = S^2 = 25, and a maximum subsystem level (L = 2) SCM = N^2/S = 2,000. 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.

IV. ISS ECLSS and Storage Block Diagrams and SCMs

The SCMs are found for the ISS ECLSS and its major subsystems.

A. The ISS ECLSS

The block diagram of the ISS ECLSS is shown in 2.

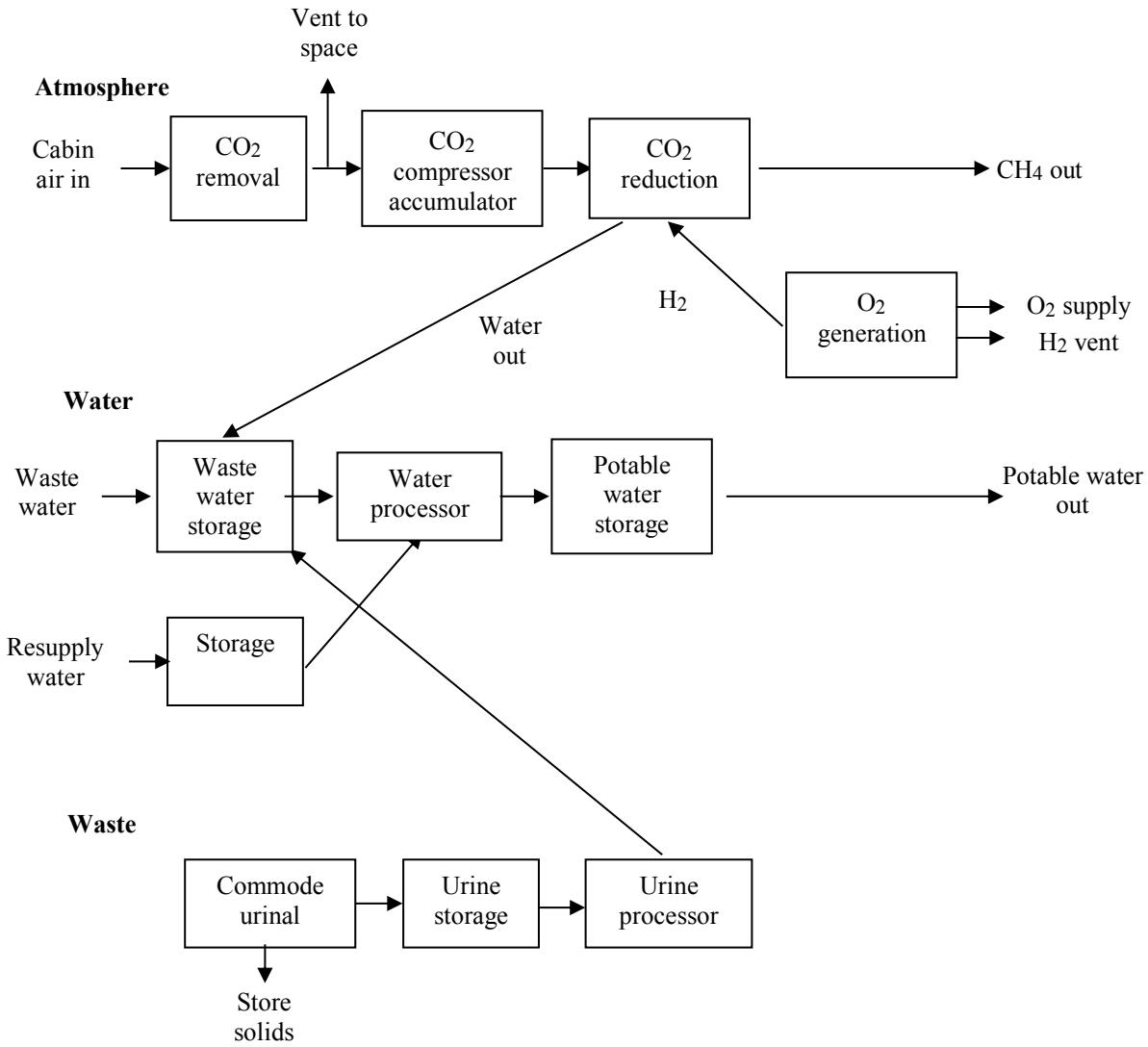


Figure 2. The ISS ECLSS block diagram

The ISS life support system contains atmosphere, water and waste recycling processors. The five major subsystems are carbon dioxide removal, carbon dioxide reduction, oxygen generation, water processing, and urine processing. The four bed molecular sieve (4BMS) carbon dioxide removal system is designed to allow the carbon dioxide to be vented to space or to be delivered to the Sabatier carbon dioxide reduction system. The electrolysis oxygen generator provides oxygen directly to the cabin atmosphere. The product hydrogen can be vented overboard or used for carbon dioxide reduction. Waste hygiene water and cabin condensate are stored and routed through the potable water processor to a potable storage tank. Resupply water delivered by Progress or other resupply vehicles is usually run through the water processor before potable use. Urine is pumped from the urinal to the urine processor and the distillate is combined with other wastewater. The commode compacts and bags feces. Solid wastes and feces are usually loaded into a Progress vehicle and burned up during Earth reentry. (Carrasquillo and Bertotto, 1999) (Bagdigian and Ogle, 2001)

B. The ISS ECLSS Urine Processor Assembly (UPA)

Figure 3 shows the urine processor block diagram.

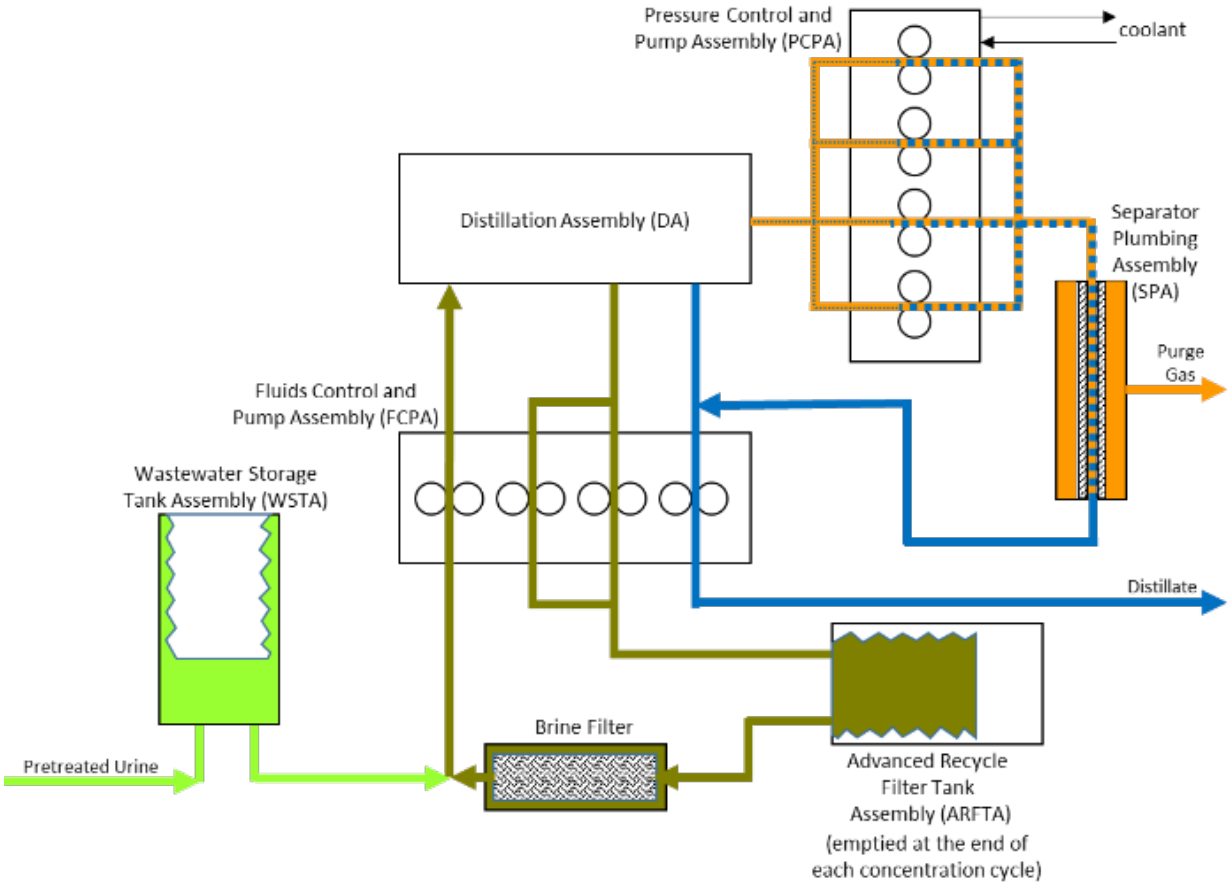


Figure 3. The urine processor block diagram. (Bagdigian et al. 2105-094)

The Urine Processor Assembly (UPA) is packaged into seven Orbital Replacement Units (ORUs). Pretreated urine is delivered to the UPA. The urine is temporarily stored in the Wastewater Storage Tank Assembly (WSTA). The Fluids Control and Pump Assembly (FCPA) moves urine from the WSTA into the Distillation Assembly (DA), recycles the concentrated waste from the DA into the Advanced Recycle Filter Tank Assembly (ARFTA) and back to the DA, and pumps distillate from the DA out to the Water Processor Assembly (WPA). The DA is the heart of the UPA, and consists of a rotating centrifuge where water is evaporated from the recirculated urine/brine at low pressure. (Bagdigian et al. 2105-094)

C. The Other ISS ECLSS Subsystems Have Similar Block Diagrams

Similar block diagrams for the WPA and Oxygen Generator Assembly (OGA) are provided in the same reference as the UPA in Figure 3. (Bagdigian et al. 2105-094) A similar block diagram of the Carbon Dioxide Removal Assembly (CDRA), also known as the Four Bed Molecular Sieve (4BMS), was used. (Giesy et al. 2017-111) The Sabatier or Carbon Dioxide Reduction System (CRS) block diagram is given in (Jones 2011-5271).

D. The ISS ECLSS System Complexity Metrics (SCMs)

Table 4 gives the System Complexity Metrics (SCMs) for the ISS ECLSS and its major subsystems.

Table 4. SCMs for the ISS UPA, WPA, OGA, CDRA, CRS, and ECLSS

Name	Acronym	Nodes, N	Interfaces, I	System Complexity Metric, SCM
Urine Processor Assembly	UPA	7	12	19
Water Processor Assembly	WPA	18	23	41
Oxygen Generator Assembly	OGA	14	19	33
Carbon Dioxide Removal Assembly	CDRA, 4BMS	12	21	33
Carbon Dioxide Reduction System	CRS, Sabatier	11	20	31
Total ECLSS subsystems				157
ISS ECLSS level		11	18	29
ECLSS level plus subsystems				186

The average of the five ECLSS subsystems is SCM = 31. The two layer ISS ECLSS and its five major subsystems have a total SCM = 157 + 29 = 186.

E. The Storage Tanks System Complexity Metrics (SCMs)

Table 5 gives System Complexity Metrics (SCMs) for a life support resupply and storage system.

Table 5. SCMs for the LiOH canister, oxygen tank, and water tank

Name	Nodes, N	Interfaces, I	System Complexity Metric, SCM
LiOH canister	1	2	3
Oxygen tank	1	2	2
Water tank	1	2	2
Total storage subsystems	3	6	10
Storage system level	3	0	3
System level plus subsystems			13

The LiOH cannister is flow through, with two interfaces, an input and output. The oxygen and water tanks also have a two way interface, input and output. The tank and cannister storage system is simply a large net or unpressurized container without active interfaces to the containers.

V. ISS ECLSS and Storage Costs

The costs to develop ISS ECLSS subsystems and life support storage systems are estimated.

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). (Guerra and Shishko, 2000, pp. 946-7)

The cost to develop a single unit is estimated for the ISS ECLSS subsystems and alternate storage systems. The cost for multiple units and redundant systems, and for launch and operations costs is not considered here.

B. ISS and Storage Unit Costs

The unit cost for a LiOH canister, oxygen tank, water tank, carbon dioxide removal subsystem, carbon dioxide reduction subsystem, oxygen generation subsystem, water processing subsystem, and urine processing subsystem are shown in Table 6.

Table 6. The unit costs of storage systems and ISS ECLSS subsystems.

AMCM parameter		LiOH canister	Oxygen tank	Water tank	Carbon dioxide removal	Carbon dioxide reduction	Oxygen generation	Water processing	Urine processing
Q	Quantity	1	1	1	1	1	1	1	1
M	Container mass, lb	3.1	27.9	46.6	442	9.9	249	1047.2	282
M	Container mass, kg	1.4	12.7	21.2	201	18	113	476	128
S	Specification	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13
IOC	Initial date	2030	2030	2030	2030	2030	2030	2030	2030
B	Block	7	20	2	2	2	2	2	2
D	Difficulty	-3	-3	-3	1	1	1	1	1
	Hardware development cost, $M per unit	0.7	2.0	6.3	170	13.8	116	300	126

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. A storage or resupply life support system provides oxygen and water in storage tanks. Carbon dioxide is removed using lithium hydroxide (LiOH). A space qualified oxygen tank weighs 12.7 kg and contains 35.4 kg of oxygen. (Orbital DS436, 2016) A space station water tank weighs 21.2 kg and holds 103 kg of water. (Carrasquillo, Reuter and Philistine, 1997) The filled shuttle LiOH canister weighed 7 kg and was rated at 4 crewmember-days, and the mass of LiOH per canister was about 1.5 kg/crewmember-day. (Doll and Eckart, 1996, pp. 553-4) (Matty, 2008) The mass of the canister alone is estimated to be about 20 percent of the 7 kg or 1.4 kg.

The ISS ECLSS subsystem masses are from (Carrasquillo, Reuter and Philistine, 1997) except that the carbon dioxide reduction system is from (Eckart, 1996, p. 197) and (ARC, 1990). Each storage supports a different number of crewmember-days and each recycling system supports a different number of crewmembers.

The specification, S, and the initial operation capability date, IOC, are the same for all the hardware. 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.

LiOH has been primary on all human missions except Skylab and ISS, so counting Mercury, Gemini, Apollo transit and lander, shuttle, and spacelab, the block, B, is estimated at 7. (Wieland, 1994, p. 281) The Shuttle had twenty-four internal gas pressure vessels, many of different design, but the technology has been improved. The ISS has thirteen different types of on-board pressure vessels, some in multiple copies. Orbital ATK has produced 20 different pressure vessels for space use. (Jones, 2017-89) The oxygen tank block, B, is estimated at 20. Water tanks have been used on all human missions but designs have changed. The block, B, is estimated at 2, assuming ISS is a second generation design. (Wieland, 1994, p. 281) The LiOH and tank difficulty was set to D = -3, very extremely easy, below the intended range of the AMCM.

For all the ISS ECLSS subsystems the block, B, and difficulty, D, are the same. The hardware block, B, was set to 2, second generation, assuming that the ISS systems have heritage going back to closed chamber crew tests. Recycling physical-chemical technology is not especially difficult space technology. The recycling development difficulty, D, was set to 1, more than average, for a high reliability system.

The sum of the unit design costs for a LiOH canister, oxygen tank, and water tank is 9.0 million 1999 dollars. The sum of the unit design costs for an ISS ECLSS carbon dioxide removal subsystem, carbon dioxide reduction subsystem, oxygen generation subsystem, water processing subsystem, and urine processing subsystem is 726 million 1999 dollars. This number seems in the right order of magnitude according to a previous analysis, which estimated the cost of ISS ECLSS spares for the years 2010 to 2020 at 407 million 2011 dollars. The ISS requires several spares to be on board for back-up, but since many were previously procured, this 10 year spares cost may differ significantly from the actual original procurement cost." (Jones, 2016)

VI. ISS ECLSS Subsystem and Storage Reliability

The ISS ECLSS subsystems include the Oxygen Generation System (OGS), Carbon Dioxide Removal System (CDRA), Urine Processor Assembly (UPA), Water Processor Assembly (WPA), and the Carbon Dioxide Reduction System (CRS), also known as the Sabatier. These subsystems use subsubsystems that are the Orbital Replacement Units (ORUs). Several of each ORU are stored on the ISS to replace failed ORUs. This section uses the subsystem's ORU MTBFs to calculate the overall subsystem failure rates and the MTBFs for the OGS, CDRA, UPA, and WPA. No data was found for the CRS/Sabatier.

A. MTBFs Based on Preflight Data

Table 7 gives the ORU names, MTBFs, and the preflight failure rate estimates for the OGS and CDRA.

Table 7 .The ORU preflight MTBFs and failure rates for the OGS and CDRA.

Oxygen Generation System (OGS)			Carbon Dioxide Removal System (CDRA)		
Subsystem (ORU)	MADS MTBF, hours	Failure rate per hour	Subsystem (ORU)	BVAD MTBF, hours	Failure rate per hour
Hydrogen Pressure dome	29,551	0.000034	Air Pump Two-Stage ORU	156,200	0.000006
Process Controller	75,677	0.000013	Blower	129,700	0.000008
Oxygen Outlet	99,252	0.000010	Check Valves	100,000	0.000010
Pump	189,433	0.000005	Desiccant Beds	77,100	0.000013
Inlet Deionizing Bed	442,487	0.000002	Heat Controller	242,700	0.000004
Nitrogen Purge	140,195	0.000007	Precooler	129,700	0.000008
Power Supply Module	49,202	0.000020	Pump Fan Motor Controller	2,272,000	0.000000
Water	37,885	0.000026	Selector Valves	117,000	0.000009
			Sorbent Beds (Zeolite)	77,100	0.000013
Total failure rate		0.000119	Total failure rate		0.000071
Overall MTBF	8,437		Overall MTBF	14,110	

The OGS does not include the Hydrogen Sensor and ACTEX. The ORU failure rate f is equal to 1/MTBF. For small subsystem failure rates, the overall system failure rate is equal to the sum of the subsystem failure rates. Table 8 gives the ORU names, MTBFs, and failure rates for the UPA and WPA.

Table 8 .The ORU preflight MTBFs and failure rates for the UPA and WPA. (Continues on next page.)

Urine Processor Assembly (UPA)			Water Processor Assembly (WPA)		
Subsystem (ORU)	MADS MTBF, hours	Failure rate per hour	Subsystem (ORU)	MADS MTBF, hours	Failure rate per hour
Wastewater Storage Tank Assembly	82,200	0.000012	Catalytic Reactor	27,077	0.000037
Firmware Controller Assembly	13,453	0.000074	Gas Separator	61,182	0.000016
Separator Plumbing Assembly	88,993	0.000011	Ion Exchange Bed	442,478	0.000002
Pressure Control and Pump Assembly	59,221	0.000017	Microbial Check Valve	178,447	0.000006
Distillation Assembly	41,376	0.000024	Multifiltration Bed #1	349,650	0.000003

Fluids Control and Pump Assembly	22,759	0.000044	Multifiltration Bed #2	349,650	0.000003
			Particulate Filter	560,695	0.000002
			Process Controller	70,745	0.000014
			Pump Separator	39,429	0.000025
			Reactor Health Sensor	134,077	0.000007
			Sensor	184,618	0.000005
			Separator Filter	642,342	0.000002
			Start-up Filter	226,850	0.000004
			Water Delivery	81,797	0.000012
			Waste Water	43,669	0.000023
			Water Storage	40,463	0.000025
			Oxygen Filter	342,548	0.000003
Total failure rate		0.000183	Total failure rate		0.000190
Overall MTBF	5,473		Overall MTBF	5,270	

The OGS, UPA, and WPA MTBFs are from the ISS Maintenance & Analysis Data Set. (MADS, 2015) This data set gives the estimated MTBFs before flight data was acquired. The CDRA MTBFs are from the BVAD, also estimated before flight. (Hanford, 2004). The OGS, CDRA, UPA, and WPA level MTBFs vary from 5,000 to 14,000 hours. Considering only these subsystems, the ISS ECLSS would have at most an MTBF of 1,780 hours, or 0.20 years. The other subsystems and system level integration problems could reduce this estimate based on only four subsystems.

B. MTBFs Based on Flight Data

Bagdigian et al. show the observed MTBFs for the OGS, UPA, and WRS. (Bagdigian et al., 2015) These systems had then operated on ISS for about eight years. Some ORUs have had no failures and some have had several. In cases where all the ISS OGA ORUs have reached their end of life, the estimated MTBF is the average observed lifetime. In cases where one unit has operated without failure for eight years, the MTBF is estimated as eight years, 70,000 hours. If equipment has operated for a time T with no failures, this suggests that the probability of failure was less than one-half for that time. The MTBF can be roughly estimated as T. If the MTBF was much less, there would have been many failures. The MTBF could be much longer, but longer run time is needed to show that. The flight data MTBFs below are not longer than the successful test time, even where the preflight estimated MTBF is longer. (Some preflight MTBFs are used where no flight data is available.) In cases where one unit has failed but its replacement continues to operate, the MTBF is estimated as the average of the two observed lifetimes. This produces a strictly flight data based estimate of the total failure rates and overall MTBFs. Table 9 gives the ORU names, MTBFs, and failure rates for the OGS based on flight data.

Table 9. The ORU flight MTBFs and failure rates for the OGS.

Oxygen Generation System (OGS)		
Subsystem (ORU)	Data MTBF, hours	Failure rate per hour
Hydrogen Pressure dome	35,000	0.000029
Process Controller	70,000	0.000014
Oxygen Outlet	70,000	0.000014
Pump	35,000	0.000029
Inlet Deionizing Bed	70,000	0.000014
Nitrogen Purge	70,000	0.000014
Power Supply Module	49,202	0.000020
ACTEX -Recirculation	11,000	0.000091
ACTEX -By-Pass	20,000	0.000050
Power Supply Module	49,202	0.000026
Water	38,000	0.000020
Total failure rate		0.000322
Overall MTBF	3,104	

The MADS MTBF is used for the Power Supply Module since no flight data was found. The flight MTBFs are significantly shorter for the Inlet Deionizing Bed, the Nitrogen Purge, and the added ACTEX -Recirculation and -By-pass. The overall OGS MTBF is reduced from 8,437 to 3,104 hours, from about one year to about 18 weeks. Bagdigian et al. did not report lifetimes for the CDRA, but it is well known to have reliability problems. (Bagdigian et al., 2015) An investigation of ISS CDRA reliability found that there were 2.0 reported high level failures per year from 2000 to 2012, even though ISS was unoccupied and no failures were reported from 2004 through 2006. (Jones, 2014-075) This corresponds to a CDRA MTBF of 4,380 hours or 0.5 years, and is much less than the preflight CDRA MTBF of 14,110 hours or 1.6 years. Table 10 gives the ORU names, flight MTBFs, and failure rates for the UPA and WPA.

Table 10 .The ORU flight MTBFs and failure rates for the UPA and WPA.

Urine Processor Assembly (UPA)			Water Processor Assembly (WPA)		
Subsystem (ORU)	Data MTBF, hours	Failure rate per hour	Subsystem (ORU)	Data MTBF, hours	Failure rate per hour
Wastewater Storage Tank Assembly	70,000	0.000014	Catalytic Reactor	14,000	0.000071
Firmware Controller Assembly	70,000	0.000014	Gas Separator	70,000	0.000014
Separator Plumbing Assembly	4,000	0.000250	Ion Exchange Bed	442,478	0.000002
Pressure Control and Pump Assembly	3,000	0.000333	Microbial Check Valve	70,000	0.000014
Distillation Assembly	5,500	0.000182	Multifiltration Bed #1	349,650	0.000003
Fluids Control and Pump Assembly	1,000	0.001000	Multifiltration Bed #2	349,650	0.000003
			Particulate Filter	560,695	0.000002
			Process Controller	70,745	0.000014
			Pump Separator	18,000	0.000056
			Reactor Health Sensor	70,000	0.000014
			Sensor	70,000	0.000014
			Separator Filter	642,342	0.000002
			Start-up Filter	226,850	0.000004
			Water Delivery	70,000	0.000014
			Waste Water	70,000	0.000014
			Water Storage	70,000	0.000014
			Oxygen Filter	342,548	0.000003
Total failure rate		0.001794	Total failure rate		0.000260
Overall MTBF	557		Overall MTBF	3,850	

Only flight MTBFs were used for the UPA. Flight MTBFs were used for the WPA where available, otherwise MADS MTBFs were used. The UPA flight MTBFs are significantly shorter for the Separator Plumbing Assembly, the Pressure Control and Pump Assembly, the Distillation Assembly, and the Fluids Control and Pump Assembly. The overall UPA MTBF is reduced from to 5,473 to 557 hours, from 7.5 months to less than 1 month. The WPA flight MTBFs are shorter for the Catalytic Reactor, Microbial Check Valve, Pump Separator, Reactor Health Sensor, recycling and Sensor. The overall WPA MTBF is reduced from to 5,270 to 3,850 hours, from 7.2 months to 5.3 months.

Based on flight data, and considering only the OGS, CDRA, UPA, and WPA subsystems, the ISS ECLSS would have at most an MTBF of 384 hours, or 2.3 weeks. The other subsystems and system level integration problems could reduce this estimate based on four subsystems, if they also contain high probability failure modes. Since the failure

rates of subsystems add, a few or even only one high failure rate problem can dominate the observed overall system failure rate.

C. Storage Tank and Cannister Reliability

Composite overwrapped pressure vessels (COPVs) have been used to store oxygen in most spacecraft for propulsion and for atmosphere in human spacecraft. They have been highly reliable. The analysis of the accelerated life testing on a used NASA shuttle COPV tank found an estimated life of 350 years for the worst used shuttle tank the testers could obtain. This would indicate the oxygen tank failure rate is about 1/350 years = 0.0028 per year. The oxygen tank MTBF of 350 years is about 3 million hours. (Jones, 2017-89) Water tanks can be expected to have better reliability than oxygen tanks since they use simpler technology and are not under pressure. The Apollo 13 experience showed that a LiOH container can actually be built in flight using cardboard and duct tape. It is hard to imagine an unrecoverable LiOH cannister failure. We can consider the preflight MTBFs of oxygen tanks, water tanks, and LiOH cannisters to be roughly similar at about 3 million hours. Since storage systems have not failed in flight, providing the equivalent of flight data for them is not obvious. The ISS has been continually occupied from 2000 to 2020, so tanks have demonstrated 20 years of life, 175,200 hours, which is used as an estimate of their flight proven MTBF. LiOH has been used on all human space missions since 1962, 58 years, but probably no individual cannister has lasted more than the 20 year ISS mission. The estimate of flight proven LiOH MTBF is 175,200 hours, again the same as the tanks. Such very low probabilities of a container failure consider only the intrinsic failure modes. The probability of an accident causing a failure, due to an environmental impact or human error, is probably much larger.

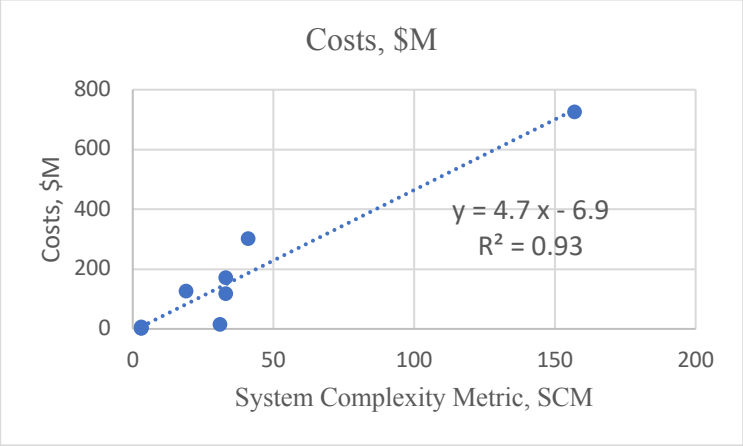
VII. The SCM as a Predictor of Cost and MTBF

Table 11 shows the System Complexity Metric, SCM, Costs, Preflight MTBFs, and Flight MTBFs for the ISS ECLSS and storage systems.

Table 11 The SCMs, Costs, Preflight MTBFs, and Flight MTBFs for ISS ECLSS and storage systems.

Name	System Complexity Metric, SCM	Costs, $M	Preflight MTBFs, hours	Flight MTBFs, hours
Urine Processor Assembly	19	126	5,473	557
Water Processor Assembly	41	300	5,270	3,850
Oxygen Generator Assembly	33	116	8,437	3,104
Carbon Dioxide Removal Assembly	33	170	14,110	4,380
Carbon Dioxide Reduction System	31	13.8		
Total ECLSS subsystems	157	726	1,780	384
LiOH canister	3	0.7	3,066,000	175,200
Oxygen tank	3	2.0	3,066,000	175,200
Water tank	3	6.3	3,066,000	175,200
Total storage subsystems	9		1,022,000	58,400

Figure 4. Costs versus SCM.



The costs are linearly proportional to the SCM over two or three orders of magnitude. The coefficient of determination, R^2, is 0.93. A system with an SCM that is x times higher can be expected to cost x times as much. The costs for the ISS ECLSS subsystems vary widely for SCM 20 to 40, reflecting differences in basic technology. Figure 5 shows ISS ECLSS and storage preflight MTBFs versus SCM. Figure 6 is similar for flight MTBFs versus SCM.

Figure 5. ISS ECLSS and storage preflight MTBFs versus SCM.

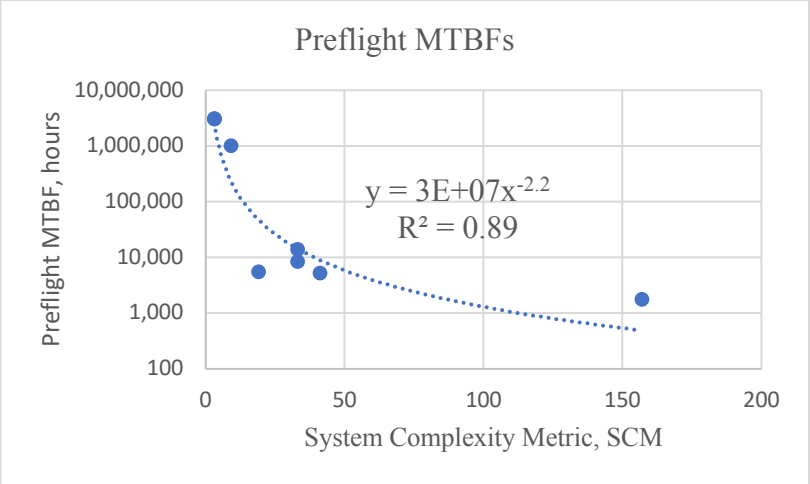
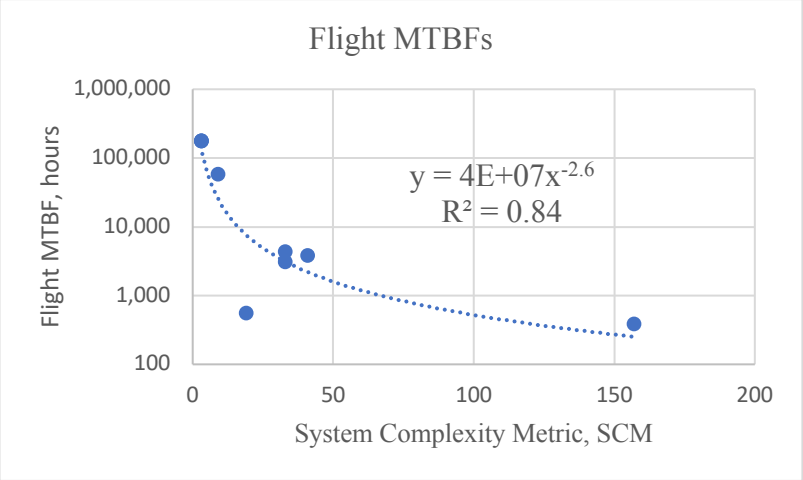


Figure 6. ISS ECLSS and storage flight MTBFs versus SCM



The preflight MTBF is also well correlated with the SCM. MTBF declines exponentially as $SCM^{-2.2}$.

The flight MTBFs behave similarly to the preflight MTBFs Both are well correlated with the SCM and have an exponential decline. For flight, MTBF declines as $SCM^{-2.6}$. This is interesting because the flight MTBFs are much lower, by factors of 25 to 90 percent. The combined ECLSS MTBF including UPA, WPA, OGS, and CRS drops from 1,780 to 384 hours, about 89 percent. The flight MTBFs are harder to predict than the preflight estimated MTBFs.

The estimated MTBFs are based on the component MTBFs and assume that no system level failure modes will be introduced. In actual experience, errors occur in requirements definition, design, and human operation. It is well known that the initial flight failure rate of a system is often about ten times the preflight estimated rate, exactly as we have seen here. (Jones, 2020) However, any unexpected high failure rate modes appear early in test and operations and they can determine the initial MTBF, which can be highly variable.

VIII. Discussion

The SCM (System Complexity Metric) was developed to compare proposed overall system architectures and to help choose between them before detailed design. The SCM is equal to the combined number of parts and their interactions. It is directly measured from higher level system and subsystem block diagrams. The SCM is strongly correlated with cost and MTBF (Mean Time Before Failure).

The SCM could be made more accurate by including more system layers, even all of them down to off-the-shelf unrepairable piece parts. However the intended use of the SCM is initial comparison of top level design architectures, so detailed design information is not expected to be available. And later in design detailed lower level designs should be compared using the extensive information available, not the SCM.

Only large differences in SCM, ratios of 5, 10, or more, should be considered meaningful. Even detailed professional estimates of cost and reliability are notoriously imprecise. Costs predictions often err by a factor of 2 or 3, and reliability predictions can be off by several orders of magnitude.

The SCM is proposed to replace ESM (Equivalent System Mass) which has been used almost exclusively in NASA life support research for decades. ESM includes the mass of the system hardware and the masses required to support the system, such as power and cooling. ESM directly determines launch cost but does not include development and operations costs. ESM was developed by life support management to help advocate recycling systems over storage for life support. ESM is specifically intended to avoid discussion of cost. ESM neglects reliability by assuming that

the systems compared can be designed to have the same reliability, which is not the case. SCM is an engineering metric designed to focus attention on cost and reliability.

By definition, a complex system is a system with a large number of interacting components. Complexity is a function of the number of parts and the number of their interactions. This leads directly to the definition of the SCM as the sum of the parts count and the number of their interactions. Complexity has been measured by parts count alone, but parts count alone cannot reflect the significant complexity reduction due to the usual hierarchical design. Complexity has been measured by the average number of interconnections per part, the interactions per node, but this number is usually in the range of five to seven due to human cognitive limitations and it does not distinguish between larger and smaller systems with higher and lower parts counts. Work using the SCM shows that, especially for larger systems, the number of interconnections is much larger than the number of subsystems or nodes. The interconnection count dominates the SCM, but using the sum of interconnections alone would not save much effort and does not appear to have been suggested. The SCM seems to be intuitively and logically the right metric for complexity.

Appendix: Structural complexity measures

By definition a complex system is a system with a large number of interacting components. Complexity is a function of the number of parts and the number of their interactions. This leads directly to the definition of the SCM as the sum of the parts count and the number of their interactions. Even though complexity is an important general topic in engineering and much work has been done, the SCM is not based on past work but rather directly uses the common sense definition of complexity. This paper developed a simple structural complexity measure using only the number of components and interconnections. More elaborate structural complexity measures are used extensively in software and occasionally in hardware. They are based on graph theory.

A. More elaborate complexity measures use graph theory

A graph with n nodes can be defined by its n x n adjacency matrix, which has a 1 for linked nodes and a 0 for unlinked nodes. It is somewhat similar to the design structure matrix. The n x n adjacency matrix describes the number of nodes and links, but is the basis of other complexity measures. A connectedness metric measures the total or the average number of links between the nodes. Graph energy metrics measure the largest eigenvalue or the sum of the absolute eigenvalues of the matrix. (Efatmaneshnik and Ryan, 2015)

B. Software complexity measures

There has been extensive research in using complexity metrics to monitor and guide engineering. Most of the work pertains to software, which is more easily measured than hardware. One of the foundational papers was by McCabe in 1976. (McCabe, 1976)

McCabe's complexity measure is the cyclomatic number V(G) of a graph G with n vertices, e edges, and p connected components is $V(G) = e - n + p$. This measure is the number of independent loops or control loops in a graph. (McCabe, 1976) The SCM uses a similar simple formula, including the number of nodes (connected components) plus number of directional interfaces (not the same as edges minus vertices).

McCabe's work has been widely accepted, is described in software texts, and was the basis of much further research and application. Google scholar counts 7,436 citations.

A survey of metrics of software complexity found that three, lines of code, the Halstead complexity metric, and McCabe's cyclomatic complexity metric were widely used and considered effective. The Halstead complexity metric counts the number of distinct symbols and logic units and their total number in the software and combines them in a formula. The Halstead complexity metric measures the complexity in the data stream but ignores the complexity of the data flow, which is measured by McCabe's cyclomatic complexity metric. The cyclomatic complexity metric in turn ignores the complexity of the data stream. The bug density and the likelihood of introducing new bugs during repair both increase with complexity. At high complexity one bug may be added for each two removed. Software defect prediction is improved by using all three metrics rather than any one. However, the Halstead complexity metric and the cyclomatic complexity metric are both strongly linearly corelated with lines of code, so that using only lines of code is attractive. (Yu and Zhou, 2010) Empirical evidence shows that the cyclomatic complexity metric is often simply a proxy for the traditional metric of lines of code, and that lines of code gives better results in many cases. (Shepperd, 1988)

Some suggest replacing McCabe's complexity measure with the simpler lines of code, but others think that more information would be beneficial. The underlying dimensionality of a large number of different software complexity metrics was examined. Studies show that software complexity metrics are highly correlated and analysis of previous work suggests they can be reduced to five uncorrelated dimensions. These are control, volume, action, effort, and modularity. Control is similar to McCabe's complexity, while control, volume, and action interact with lines of code, which would seem to diminish their independence. Software complexity can be measured as "a simple function of a small number of variables." (Munson and Khoshgoftaar, 1989)

A widely used list of criteria, Weyuker's criteria, was developed to evaluate software complexity measures. It found that there were substantial differences between McCabe's cyclomatic number, Halstead's programming effort, and lines of code. (Weyuker, 1988)

C. A hardware complexity measure

Sinha developed a hardware structural complexity metric in his Ph.D. dissertation and with his advisor de Weck and others published describing it and its implications for system architecture and design. Google scholar counts 58 citations. Sinha has published about 20 papers in this area. The metric is based on network graph theory and considers the complexity of the components, their interactions, and the architecture. (Sinha, 2014) (Sinha and de Weck, 2013a) (Sinha, Omer, and de Weck, 2013)

There is not much previous work on hardware complexity metrics. Sinha's literature review mentions the use of parts count. Most previous work has been done on software, and Sinha mentions McCabe's metric and Weyuker's criteria. The previous complexity measures he lists are all used in software, the number of components, number of interactions, number of loops, nesting depth, graph planarity, CoBRA complexity, heterogeneity of network, and matrix energy. CoBRA is hybrid method for software cost estimation, benchmarking, and risk assessment. (Sinha, 2014)

The complexity of engineered systems is due to the interconnected architecture of their components. These complex systems can be described using a matrix of their interconnections and their complexity can be quantified by matrix analysis. The proposed structural complexity metric for system architectures consists of three terms representing the complexity of system components, the connections between the components, and topological complexity. (Sinha and de Weck, 2013a) (Sinha and de Weck, 2013b) (Sinha and de Weck, 2012a) (Sinha, Omer, and de Weck, 2013)

The structural complexity function is

$$C = C1 + C2\ C3$$

The first term C1 is the sum of the complexities of the components within the system. "It relates to the component engineering activity within a system development effort and does not involve architectural information." (Sinha and Suh, 2018) (Sinha, Omer, and de Weck, 2013) (Sinha, Suh, and de Weck, 2017) The second term has two components, C2 and C3. C2 measures "the number and complexity of each pair-wise interaction," which relates to interface design and management activity in system development. C3 measures the "effect of architecture design or the arrangement of the interfaces," and reflects the difficulty of system integration. (Sinha and Suh, 2018) (Sinha, Omer, and de Weck, 2013) Matrix energy is used as the measure as of architectural complexity in C3. (Sinha and de Weck, 2016) The combined term, C2 C3, reflects the complexities due to component-to-component interfaces and the overall architectural arrangement of system components in the integrated system. (Sinha and Suh, 2018)

Typically major subsystems have high component complexity while supporting backup and control systems "are the primary contributors to topological complexity and have significant impact on system integration efforts." (Sinha and de Weck, 2012a) Two architectures having the same number of nodes and connections can have different complexity due to their internal structure. Increasing modularity often but not always reduces complexity. (Sinha and de Weck, 2013a) (Sinha and de Weck, 2012a) (Sinha and de Weck, 2012b) (Sinha and de Weck, 2013c) A centralized architecture typical of top-down designed hardware has lower complexity while distributed organically growing architectures have higher complexity. (Sinha and Suh, 2018) (Sinha, Omer, and de Weck, 2013) The complexity measure increases as the architecture becomes increasingly complex, from a centralized bus, to hierarchical layers, and ultimately a distributed any-to-any network. (Sinha, Omer, and de Weck, 2013) In one demonstration, cost increased exponentially with increasing structural complexity, with exponent, 1.69. (Sinha, Omer, and de Weck, 2013)

D. Complexity measures discussion

This review was not included in the original paper because past work was thought not especially relevant and potentially distracting from the practical intent of the paper. The purpose of the paper is to advocate use of the SCM to estimate complexity and so help reduce cost and improve reliability. The academic history of complexity measures seemed unnecessary but it does have useful lessons, such as confirming the relationships between architectural structures and complexity.

Complexity is a directly perceived intuition of mental difficulty. We do not understand, we do not have a way to explain reality, we feel uncertain. It is also clearly seen that complex systems and situations have many distinct objects and a multiplicity of interactions. Higher complexity increases effort in understanding and raises the probability of error, which increase system development cost and reduce reliability. Systems engineers usually strive to simplify systems.

Why then are systems overly complex? The system developers are drawn to innovate, improve performance, and add new capabilities, which all increase complexity. This has occurred in space life support research and in complexity

metric development. Researchers who intended to help reduce complexity have developed overly complex metrics that are difficult to understand and apply. SCM is more solidly founded on the direct perception of complexity.

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