The Rise of Long-lived Complex Systems

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This paper traces the trend of the creation and employment of more and more complex systems from the First Industrial Revolution through the second half of the 20th century and predicts how commercial LEO in the last half of this century will play out. In the second half of the last century, the discipline of systems engineering arose and was perfected to deal with system design complexity. Around 1980, another parallel trend became apparent. Complex systems were living longer and longer lives. A better method of sustaining complex systems arose at this time. This method needs to be widely used and perfected for sustainment of the long-lived complex systems that will be employed in commercial low earth orbit (LEO).

I. Introduction

Section II of this paper describes how the First and Second Industrial Revolutions gave rise to the ability to create self-contained factories using significant power sources that could produce more and more products at higher and higher rates. Section III explains how systems engineering was born in the mid 20th century to deal with the increasing complexity of design and production. Extreme complexity appears first in mid-20th century with high national priority nuclear weapons delivery systems. As these weapons were kept employed over decades, a threshold was passed in the late 20th century that demanded a better way to sustain these ever longer-lived and more complex systems. Specifically, section III explains how ICBM sustainers, out of need and ability, came up with the complex system sustainment management model to ensure continued mission support out of longer and longer lived complex systems.

The trend will reach beyond our current times. Starting near the dawn of the 21st century and over the next several decades, emerging fabrication technologies threaten to upend all of what we think we know about factories. But factories and manufacturing technologies have been evolving since the dawn of the First Industrial Revolution. These new methods will do nothing to slow down, and will likely increase, the trend of more and more complex systems being fielded for longer and longer life-times.

Even the extensive use of machine intelligence as part of manufacturing and fabrication will do nothing but improve our ability to create ever more complex systems. As discussed in section IV, this is because of the relationship of the mission to the complex system it serves. The need for longer and longer lived complex systems is tied to each systems' respective mission. Now, and into the next few decades, only mankind will possess the vision to establish missions. On the other hand, over the next half century various types and uses of machine intelligence will multiply and diversify. Manufacturing and fabrication will continue to be revolutionized in support of future needs.

The trend for longer-lived complex systems will continue and expand beyond weapon systems to systems we all use in all facets of our lives. In section V, fabrication in LEO is discussed as a good example of what this trend looks like in the year 2062. This is because the continuing expense of lifting mass into orbit makes many of these new techniques mandatory. For instance, various machine intelligences will focus on fuel deliveries, vehicle movements, debris surveillance, materials recycling and more because of the cost of lifting humans and their life support. LEO factories will be stingy with raw materials and they will eventually accept almost any in-orbit materials for eventual recycle. The new fabrication techniques such as minimal structures for load, weaving by robots, and, of course, additive manufacturing will support this mission.

Meanwhile, over the next decade, the innovators who created and perfected the complex system sustainment management model and the weapon systems that inspired it are both fading into history. To be ready later, right now sustainers need to learn the better way to sustain long-lived complex systems. That way is summarized in section VI, "Conclusions".

II. A Confluence of Events

Complex systems are composed of machines, methods, and people organized to fulfill a mission. The First Industrial Revolution spanned the years 1760 to 1830 and was characterized by machines taking over what was a lot of work previously completed by hand. When people, such as Evans, came up with, for instance, pulleys and other machines to improve his production of flour, an early "factory system" was created. See figure 1.

Evans had a need, a mission. And he found the technology that helped him do it better.

From 1840 to 1870, the Second Industrial Revolution, we see bigger factories and more efficient power, such as steam, used to power them. We found ways to move items efficiently inside of factories. Steam was also incorporated into transportation, giving us more efficient locomotives and boats to transport our goods.

The Second Industrial Revolution greatly influenced the American Civil War, the first industrialized war. No one understands the concept of mission like the military. In the Civil War, more and more complex machines, even systems, appeared as weapons. For instance, there were the aforementioned railroads with all their tracks, stations, trestles, and water stops. Another example was the first use of military balloons as supported by rail cars, hydrogen generators, and pilots, as recon to see behind enemy lines.

The American Civil War should have been a warning that industrialized killing would reach an alarming crescendo in WWI, based on what was previously accomplished with machine guns, gas, and long range ballistic projectiles. But most military leaders were focused on lightning fast movements of troops and did not sufficiently envision the possibility of trench warfare. WWI was followed by the extremely brutal use of aerial bombing by the Germans in the Spanish Civil War. This was, of course, a lead-in to the German Blitzkrieg of WWII and the Allies use of strategic bombing in both Germany and Japan. The Allies' concept of Strategic Aerial Bombardment as a military doctrine sprung from lessons of the Civil War and the Great War, WWI. In short, the doctrine stated that the nation's industrial capability should be struck so that their ability to wage a modern industrial war would suffer.

This doctrine emerged because many were frustrated by the Civil War generals' lack of understanding of air power. This was not greatly improved in WWI. It was the American Army Signal Aviation Section (perhaps feeling the frustration the most) between the World Wars that created the air doctrine that informed warriors like Curtis LeMay to perfect aerial strategic bombardment during WWII. Generally, the Allies were focused on destroying the Axis nations' industries in order to eliminate their ability to wage war. This worked to facilitate the D-Day invasion of Europe with very few Dresden-like results[1]. But as industry was embedded in large urban centers constructed of wood in Japan, this led to Dresden-like loss of civilian lives there on a massive scale even before the use of atomic bombs.

Post WWII, there was plenty of evidence that the US would not be safe from aerial bombardment just because we lay on the other side of the world from our industrialized enemies. And any feeling that such a massive undertaking was simply too large a program for any potential enemies was wiped out by Sputnik passing overhead in low Earth orbit. Russia was a large country that still possessed some industrial capability post war and was focused on mustering more. It they could put an atomic bomb on the rocket that launched Sputnik, we would be completely vulnerable.

So, driven by the performance of complex weapon systems, we invented even more complex weapon systems to provide deterrence: Intercontinental Ballistic Missiles (ICBMs).

Backing up to the Second Industrial Revolution but on the non-military side, complexity led to great improvements in civilian life such as water, sewage, transportation, and Bell Labs' telephone systems. Mid last century, Bell Labs also developed, or help develop, radar, fire control, acoustics communications, air defense, underwater systems, command and control, and many other special projects[2]. Bell Labs' struggle with all this technology led to the invention of the discipline of systems engineering in the 1940's. The Navy and the Air Force took this discipline and perfected it. This was a necessity, as they strove to create sea launched and ground based nuclear-armed ballistic missiles.

The University of Southern California, realizing the complexity of the 20th Century systems, started training graduate students in the art of systems management. Although it taught about managing systems in general, this program was focused on Air Force officers seeking their USAF-required masters' degrees. Thus, weapon system management, including USAF Space Systems, benefited. When these masters of systems management started managing ICBMs, they applied the systems engineering and systems management principles they had learned to the task of sustaining our deployed ICBM forces. Space systems, by the way, were still focused on development and single missions. Space systems sustainment is only arriving now, with the dawn of commercial space.

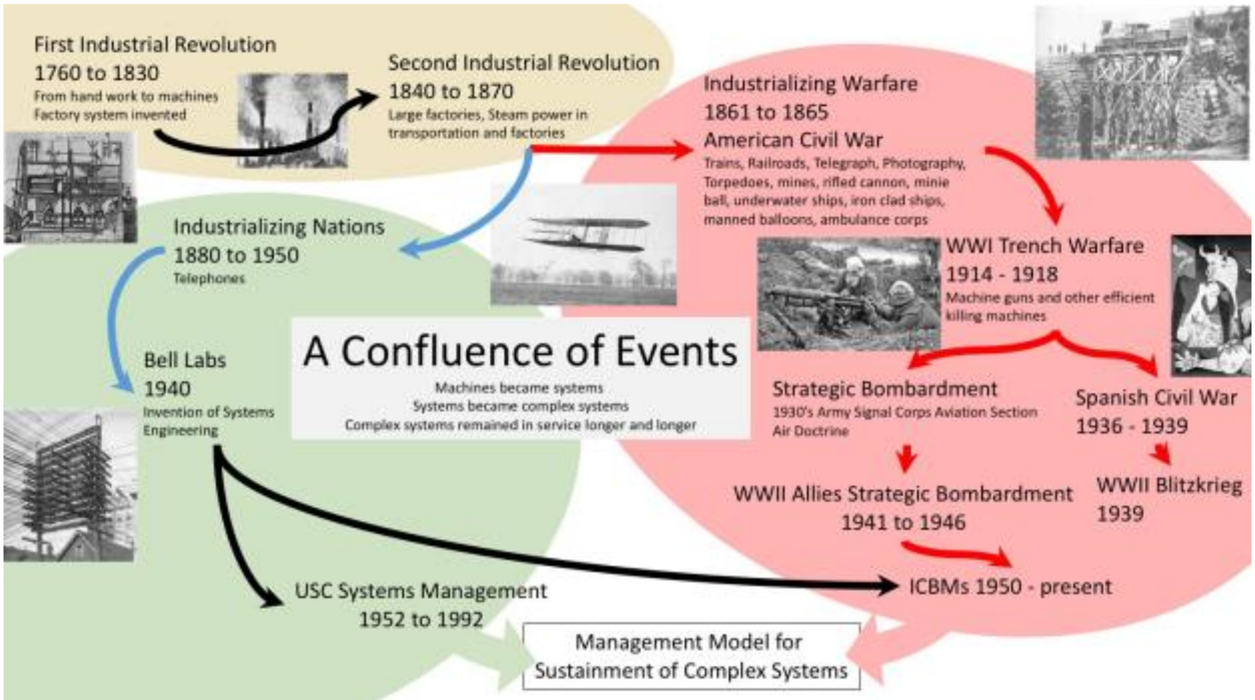

Figure 1: A Confluence of Events

III. A Confluence of Needs and Talent

The ICBM "mafia" was remarkably united. It was more than just a team. It was a tribe3 fully dedicated to the ICBM mission. I was a member of this tribe from 1985 to 2014. My position previous to 1985 was as an engineer in the USAF Space Program at LA Air Force Station.

We ICBM'ers were a family apart from the greater society. We missileers included various communities such as ICBM combat crews, military acquisition experts, suppliers, major defense contractors, civil servants, & etc., all linked by mission. We had a common culture and dialect and recognized leaders. We even had many processes and methods different than the airplane Air Force.

We had strict rules of morality, integrity, truth, and honesty. We expected ourselves and our fellow tribe members to set aside ego and lose ourselves in the mission. To succeed, we had to win, even loot and plunder other weapon systems' funds if we could. We had to take every advantage.

Like barbarians, outsiders might actually disparage us or disparage our mission, but we wore the head of the wolf proudly.

Nuclear weapons are a serious business. Uniformed USAF members of Strategic Air Command who did not operate at a level of perfection were corrected on the spot. SAC members with repeated issues were fired. General Curtis LeMay famously said: "I have neither the time nor the inclination to differentiate between the incompetent and the merely unfortunate". This level of performance tended to influence the other members of the tribe as well.

This dedicated, focused, mission-oriented team had a huge problem to deal with.

ICBMs were deterrence machines. For protection, they were isolated across thousands of square miles and buried in underground highly secure vaults. They were mostly dormant, awaiting a message to launch within seconds.

Despite the lack of data flowing from the solid rockets or liquid rocket or other dormant or semi-dormant systems, we were charged with ensuring they were capable. That is, they must be available, reliable, accurate, hard against attack, and also safe, and sure.

To say this was a difficult task is an understatement.

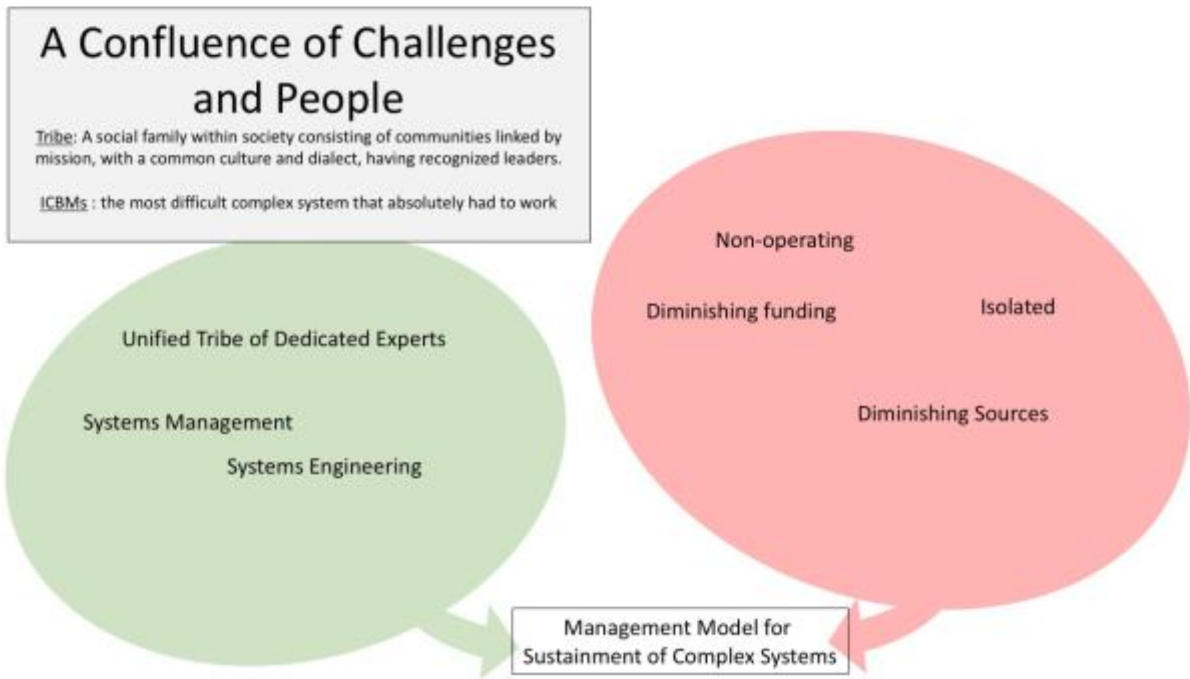

Figure 2: A Confluence of Impossible Challenges and Extraordinary People

Any suspected degradation must be spotted with years of lead time in order to ensure fixes were in place before the mission was compromised. And any fix must work seamlessly within an incredibly complex missile, missile silo, launch command complex, logistics system, repair depots, & etc. Designs were not modular; one small change could have unforeseen consequences. The original engineering documentation could be missing. All this occurred over a period of time where priorities and funding for ICBMs was diminishing, unique contractors were closing shop, and some parts and components were no longer available.

We had the perfect caldron for a dedicated team of experts to rise to the most difficult of sustainment challenges. See Figure 2. The result of this confluence was the complex system sustainment management model. See Figure 3.

As first introduced by me[4], the model is “observe, identify, and fix”. The activities in the “Fix System” box include long-range planning, short term planning, deployment planning, requesting funding, and flowing funding to programs and projects. Decision-makers need this information to grant funding. The raw data needed to do this work comes from identifying risks to the weapon system mission with sufficient lead time to get them fixed. Risk are written against the readiness factors such as reliability or accuracy. Risks cannot be identified unless the weapon system is sufficiently observed so that data and analysis can point to future degradations of the weapon system. For instance, monitoring batteries in the ground launch system can predict when replacement will be needed with more precision than a manufacturer’s stated life. Warfighter requirements, such as probability of target destruction, drive the readiness factors (accuracy, reliability) which directly impact how sustainment risks are written. The model is useful as a common language and a means to create and improve formal processes.

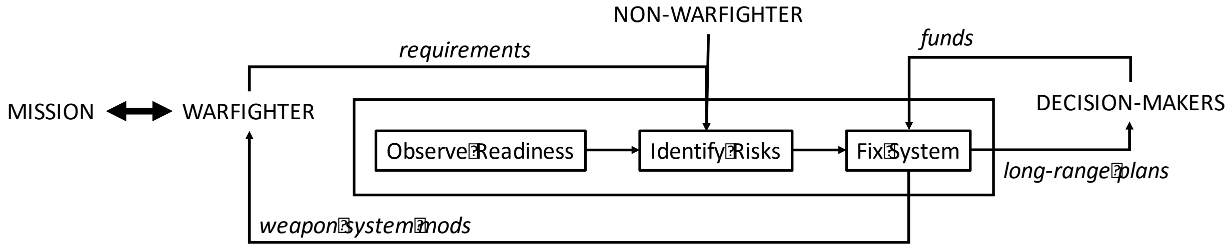

Figure 3: The Weapon System Sustainment Management Model

IV. Where We Are Today

We are on the cusp of losing our understanding of the complex system sustainment management model. The Minuteman III ICBM is about to be retired and replaced with a new system. That is, the focus is shifting from sustainment to development. Those who created and improved it over the years are retiring and many have already expired. The USC Systems Management Master's Program that supported its creation was eliminated decades ago. Even the Strategic Air Command is distant history.

New manufacturing and fabrication techniques are encouraging more and more complexity. As more people learn these skills, they will use them to meet their missions. If the complex system they are contemplating requires the incorporation of other complex systems, such as GPS, internet of things, neural net control systems, or *whatever*, they will simply incorporate them without fear.

As long as the mission exists, people will create a system to support it.

Consider the evolution of missions and weapon systems. See figure 4.

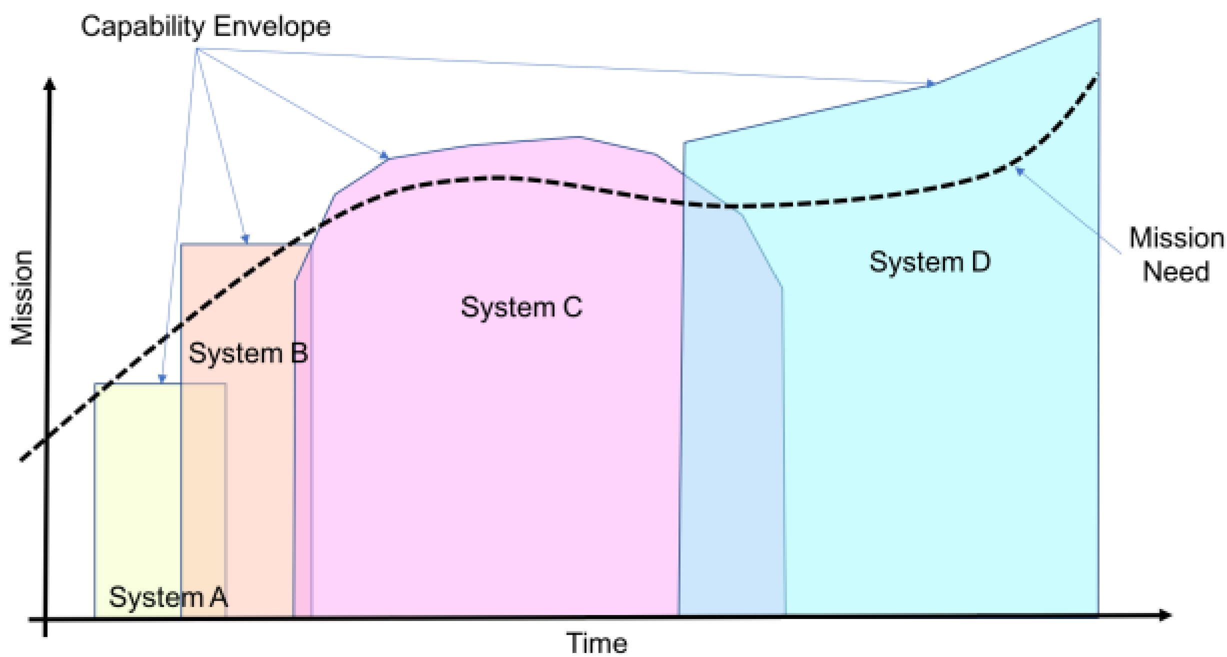

Figure 4: The Deployed System Rises to Support the Evolving Mission

To keep it simple, consider one mission need that remains essentially the same, but becomes more demanding over time. Along with this, consider how various weapon systems are realized and employed to keep up with this mission.

The evolution of the weapon systems occur as early models are fielded and fall short of the mission needs. This creates incentive to design and deploy more models. As the weapon systems live longer, they also are finding ways to self-modify to attempt to reach the mission needs. Areas where the system is taller than the mission line represent margin beyond the need. For example, the fielded system might be more reliable and survivable than required by the mission.

This is a two-dimensional notional graph which is attempting to convey a relationship between mission and system that is highly multi-dimensional. The capabilities boundary on a system is not just a wavy line on top of a box, but many wavy lines being compared to many mission parameters. A slightly more complex version of this graph could use readiness factors like reliability and availability. But each readiness factor is also a multidimensional need and each sortie of the weapon system can have multiple modes. For instance, bombing accuracy doesn't count for a recon mission.

The evolution of the mission occurs as the warfighters realize the boundaries of the technology they are using (either better or worse than they expected), better understanding of the mission they are performing, and a better understanding of the adversary's expected reaction to their weapon system.

These are real world pressures that can add to "requirements creep", but this is not creep per the standard definition. Real requirements creep occurs when an agreed-to contract is buffeted by uncontrolled changes that skyrocket final costs. One of the reasons program managers must keep requirements creep under control is to provide cost, schedule, technical, and political margin to deal with evolutionary changes that top decision-makers agree must occur.

This notional chart is meant to convey the claim that any sufficiently singular mission with evolving weapon systems solutions will tend to longer and longer-lived weapon systems until a final version, like a B-52 or Minuteman III, is a very nearly perfect fit for a mission that has slowed its evolution. Development and production resources are then turned to other more urgent missions. The last solution lives as long as the mission and sustainment allows.

There is nothing inherently military about this. We should expect to see this trend in non-weapon system complex systems as they rise to support civilian (non-warfighter) missions.

Exceptions occur when the mission changes in fundamental ways, a disruptive technology is born, or poor decisions are made allocating resources.[5] The trend is reinforced when sustainment can handle a slowly evolving mission much more cheaply than acquisition.

V. The Year 2062 and LEO Capitalism

Starting around the turn of the last century and continuing to today, various new manufacturing and fabrication methods are emerging as contenders for disrupting the design of factories of the mid 21st century.

Unlike Evan's flour mill, the power will be now distributed. For instance, sunlight across the "factory floor" of LEO will create energy using solar cells. This energy will be used in part to take raw materials and create gas, liquid, or solid fuels to expand the energy options. Nuclear energy sources will be used very seldom to avoid the launch risks. But a viable non-solar option could be energy "beamed up" from stations on the Earth if one of the goals of the enterprise is to radiate excess energy away from the Earth.

Second Industrial Revolution features such as massive factories with complicated conveyor systems, overhead cranes, racking systems, & etc. look very different when the factory is in LEO, where orbital mechanics and swarm security protocols completely reinvent "internal factory" movements.

Today's computer power is already being used routinely to minimize the amount of materials needed in structures like beams and brackets[6]. Universities are studying the minimal set of tiny components needed to create any structure. They have also demonstrated how swarms of robots can be combined and recombined to form the structures themselves. Wall climbing robots and drones have demonstrated their ability to weave structures along walls or suspended.[7] But as of today, these examples are all Earth-bound tech.

Today, Made In Space, Inc. (MIS) is routinely using additive manufacturing aboard the International Space Station[8]. NASA has funded the creation of a device that can recycle materials to create raw material to go into their space-based 3D Printers[9].

MIS is also working with NanoRacks on the "Stash And Deploy" service[10] where CubeSats are assembled on-orbit from electronics kits and custom structures printed on-orbit, loaded into a CubeSat deployer, and launched from the International Space Station (ISS).

Similarly, and for the first time ever, in the year 2017, MIS also demonstrated extended structure manufacturing in thermal vacuum conditions. This technology enables MIS to fabricate space-optimized structures of indefinite size and configuration on-orbit. The only limit is how much feedstock the manufacturing system can carry with it. Where traditional satellite structures lose efficiency due to packing requirements, MIS can manufacture gossamer structures with near-ideal mass-to-volume efficiency by using space itself as the build volume[11]. This MIS program is a NASA's, but commercial agreements between MIS and Axiom Space (commercial space station) are already in place.[12]

Mentally combining swarm intelligence with the MIS extended structure manufacturing capability allows us to envision a future where space platforms can be built with little-to-no regard for terrestrial or launch constraints and remain fully reconfigurable over their service lives, with only mission-level inputs from human controllers and operators. Many useful types of machine intelligence are possible without having to predict a sophisticated artificial intelligence to rival humans. Some are here now, such as self-driving cars; some achievable in the next few decades such as real-time optimal LEO satellite, tug, and warehouse movements; and some that (I predict) will never be achieved by machines such as envisioning military missions in the national self-interest.

See figure 5. Longer range plans call for recycling centers on orbit to grab and reclaim mass that cost so much to be launched, recycled and reused by orbiting factories. Movement between orbits will be facilitated by robots. Our future on-orbit garbage collectors will most certainly be robots. Even today, MIS is leading a team, including industry veterans from Moog CSA Engineering, Harris Corporation, and Oceaneering Space Systems, to develop an innovative capability that rapidly deconstructs launch hardware and reassembles the components into a robust support structure for science instruments[13].

Energy will not only be solar or nuclear, but fuel depots will circle the Earth in near space and LEO with tanker satellites to deliver fuel as needed to those bodies unable to arrive for self-service.

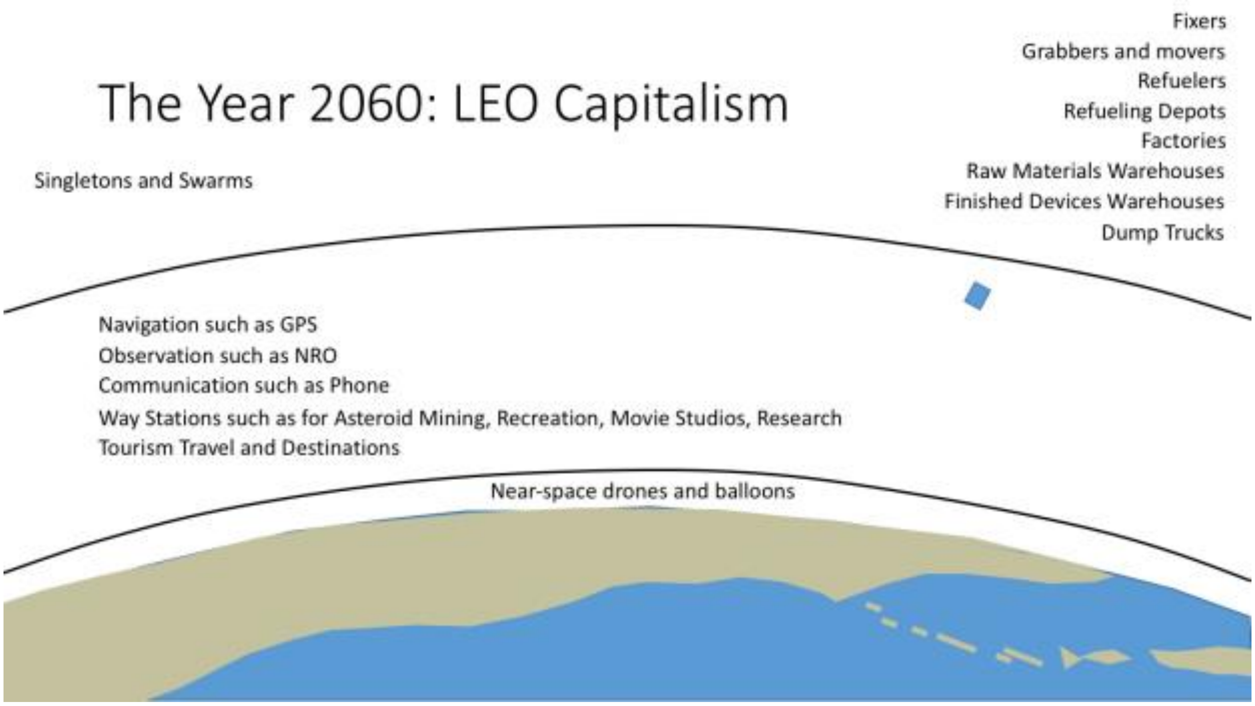

Figure 5: Low Earth Orbit Capitalism

Some orbiting bodies will be swarm clouds while others will be single structures. Some will support space tourism others will support asteroid mining.

With life-support so expensive, any job that can be done via robot instead of a human will be. This includes the minute to minute capital exchange decisions concerning orbital location; timing; and purchase of fuel, repairs, and manufactured items. The long-awaited fourth-party consumer advocates predicted by Doc Searls[14] and others will become a reality. This will spawn yet another form of machine intelligence.

VI. Conclusions

If the descriptions in the last section seem too "Buck Rogers" then consider:

- Planetary Resources is investing their future in asteroid mining[15]
- Amazon has a patent for flying warehouses[16]
- Or you can google "project loon" to see Google's near space internet relays

Also consider that this year, MIS is sending to the ISS the first facility for manufacturing exotic optical fiber in microgravity and returning the finished product for terrestrial sale and use[17].

These examples, and many more, point to trends that tend to reinforce the idea that systems will become more, not less, complex. Because of the pressures of this unique environment, system component parts will get recycled in orbit to become more useful components -- without revisiting Earth and re-launching from that expensive gravity well.

Sustainment enters the space age.

With the increasing retirements and deaths of the individuals who created the complex system sustainment model, now is the time to promote, promulgate, and refine the complex system sustainment management model so that, as the future hits, we are ready.

VII. Acknowledgements

Thanks to Justin Kugler of Made in Space for his review and inputs to this paper.

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[1] Dresden was famously bombed 4 times in February of 1945 by British and American bombers. Some claim the city was a legitimate target for rail and communications. Others point to the resulting firestorms and say it was clearly intended solely as an attack on civilian populations in an attempt to demoralize the enemy.

[2] M.D. Fagen (editor), A History of Engineering and Science in the Bell System: National Service in War and Peace (1925-1975), 1978 Bell Telephone Laboratories, Inc.

[3] In the sense of Jack Donovan's books The Way of Men (2012) and Becoming a Barbarian (2016), both published by Dissonant Hum.

[4] Charles Vono, "Fundamentals of Weapon System Sustainment", AIAA SciTech 2016, San Diego, California 4 – 8 January 2016. Available at the AIAA ARC on-line library.

[5] What is a poor decision? This can be debated for years. Is it a poor decision to field the Joint Strike Fighter or could the funds have been used more productively doled out to military-component unique solutions? Should a business strive to reach Mars when near, or even mid-term, profits cannot be projected?

[6] For instance, see http://www.altairproductdesign.com

[7] Many examples available at this MIT website for instance, http://cba.mit.edu/projects/index.html

[8] See http://madeinspace.us/projects/amf/

[9] See https://3dprint.com/140110/tethers-unlimited-refabricator/

[10] See http://3dfabprint.com/made-in-space-partners-nanoracks-for-on-orbit-satellite-manufacturing-assembly-and-deployment-using-am/

[11] See http://spacenews.com/nasa-made-in-space-think-big-with-archinaut-a-robotic-3d-printing-demo-bound-for-iss/

[12] See http://www.prnewswire.com/news-releases/made-in-space-and-axiom-space-announce-joint-agreement-for-manufacturing-in-low-earth-orbit-300392404.html

[13] See http://madeinspace.us/eagle

[14] Doc Searls, The Intention Economy: When Customers Take Charge, Harvard Business Review Press, 2012. You may also want to read Rick Levine, Christopher Locke, Doc Searls, David Weinberger, The Cluetrain Manifesto: The End of Business as Usual, 10th Anniversary Edition is 2011, Basic Books.

[15] See http://www.parabolicarc.com/2017/06/14/planetary-resources-pivots/

[16] See https://www.cnbc.com/2016/12/29/amazon-flying-warehouse-deploy-delivery-drones-patent.html

[17] See http://madeinspace.us/mis-fiber/