The Self Replicating Factory: a work in progress

Michel Lamontagne

Following up his piece, Worldship and self replicating systems, in our last issue, Michel Lamontagne brings us his latest thinking on large scale self-reproduction.

Summary

The self replicating factory has been an ideal pursued by technological society for nearly 100 years. Many of its elements were present in the Ford Rivière Rouge plant in the early 20th century[1]. Its likely form has not changed significantly since the nineteen eighties, in particular the large form factory that Drexler dubbed ‘The clanking self reproductive factory’[2]. Recent progresses is deep learning and automation for vehicles have advanced multi purpose robots to at least the advanced prototype phases.

Fundamental problems remain. On Earth, with the local ecosystem and planetary conditions, humans are significantly better than multi purpose robots for a large number of tasks. “Lights out factories”[3], that operate with minimal human intervention remain marginal, but are progressing. Rigidly designed factories have proven disappointing economically[4]. The existence of specialized production units with Just on Time distribution has mostly superseded the vertical integration of large multipurpose plants.

However, renewed development of low cost to orbit rocket systems are in the process of creating an easier environment for space development. In a few years, it will be possible to land a 100 tonnes equipment package on the Moon for a fraction of the present cost. Combined with some limited human presence and the creation of seed packages that provide the essential elements than the factory is unable to make itself, largely self replicating factories might become available soon. Perhaps less perfect than the original visions, but certainly useful in creating a future in space rather than confined to the Earth.

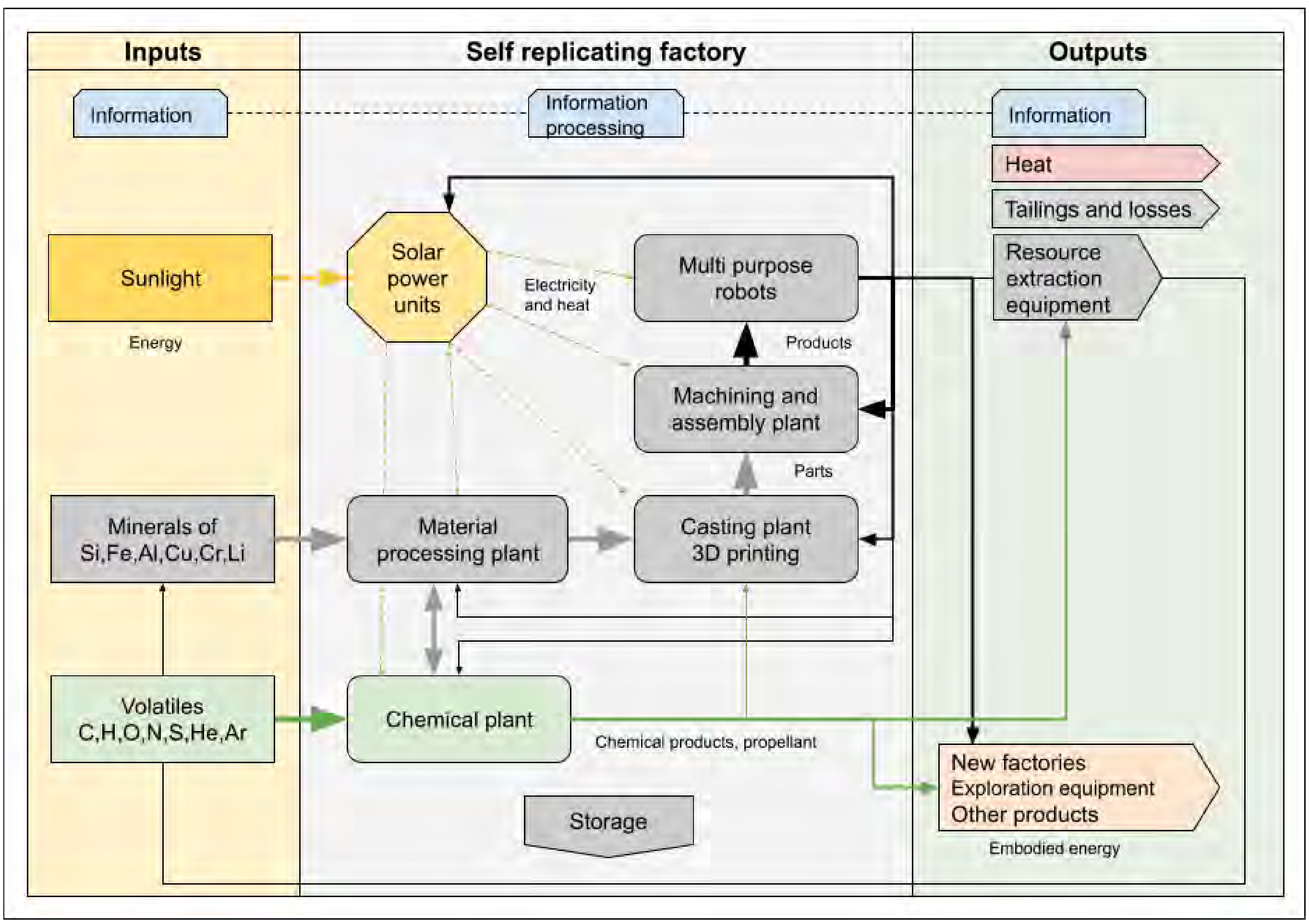


Diagram 1- A self replicating factory. Solid lines represent transportation of materials (all images by the author unless otherwise noted).

General description

At the heart of the diagram, as well as at the heart of a self replicating factory, you will find the multi purpose robot. Meet RG-132, the level 5 self driving car, oups, multi-purpose robot:

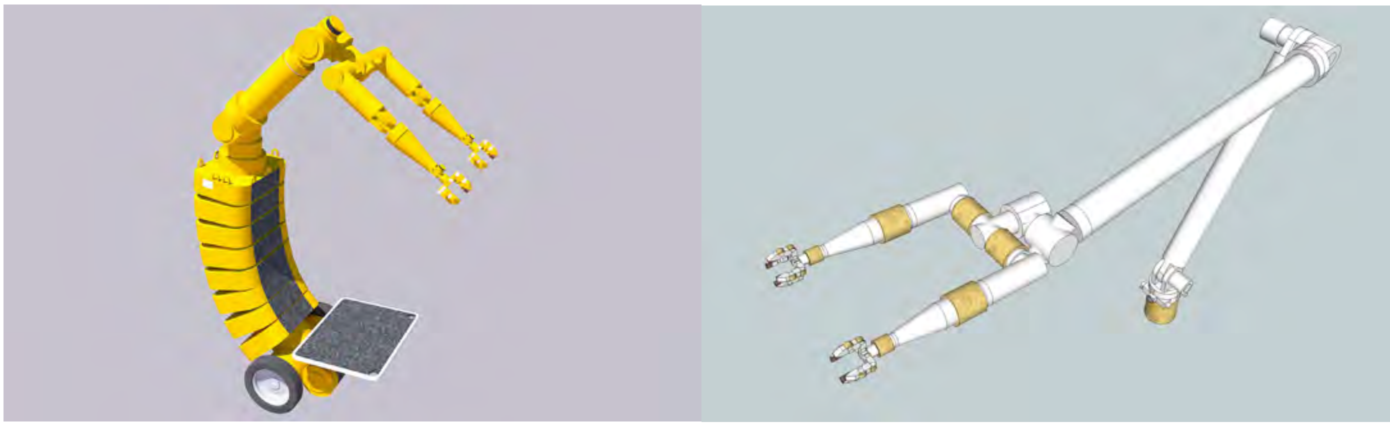


Image 1 - Ground version and zero-G version.

The requirements for a self driving vehicle are essentially the same as those of a multipurpose robot, as regards to its mobility in the environment. However, the robot also needs to be self loading and to be able to do fine manipulations, functions that are not required of cars but that have been available for decades from industrial robots.

As in today's deep learning systems, only part of the intelligence resides in the vehicle/robot. Most of the deep learning takes place in a central server system.

The multi purpose robot morphs naturally into an even closer analog to the self driving vehicle in the self driving truck and its space equivalent, the space tug.

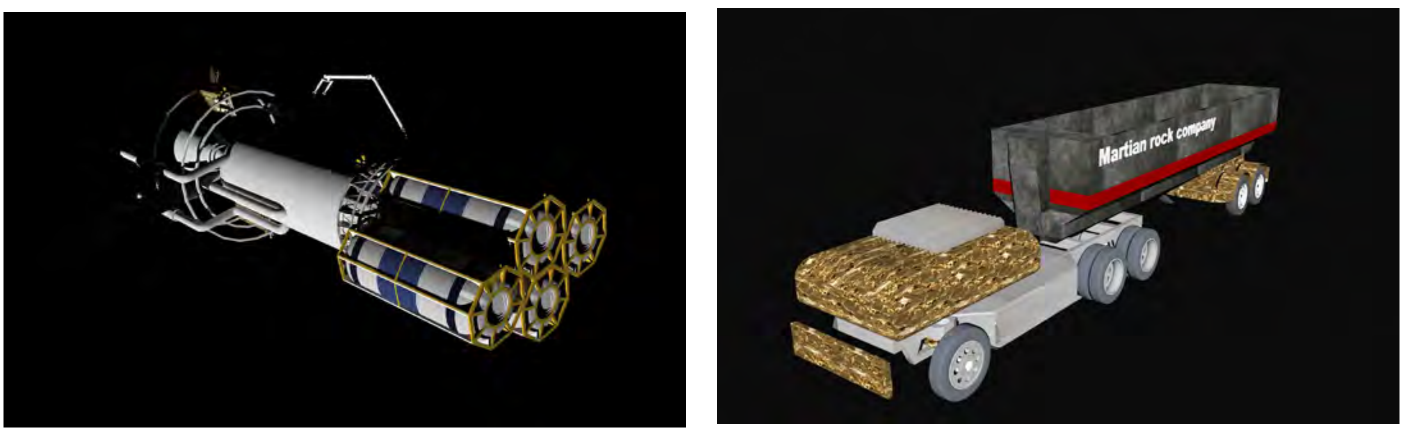


Image 2- Space tug with some ore tanks and autonomous truck with a ore trailer

These find their purpose both in hauling materials and in moving extraction and separation equipment to where the ore is found. To feed the material separation units, at the beginning of the supply chain, are the digging machines, such as these orbital diggers of surface roadheaders.

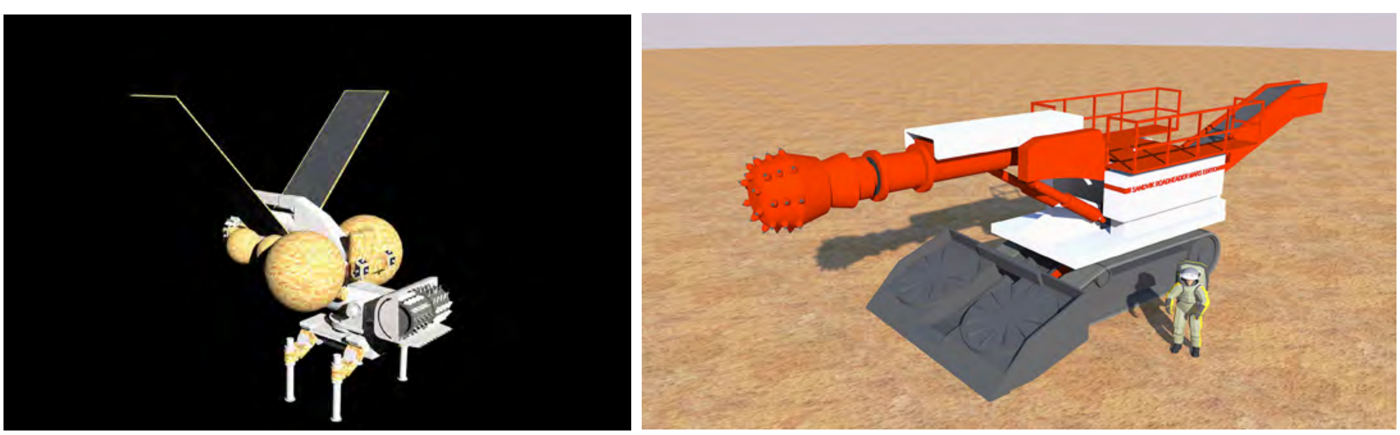


Image 3- An ice extractor for a low gravity moon, and a Martian regolith digging machine.

The first level of mineral extraction is generally to remove steriles from the ore. Ideally this is done on the mining site itself to reduce transportation. Mineral concentration by crushing and separation is commonly done at the mine site as well.

Image 4- Space tug and concentrator and ground version of same.

Finding the best location for the concentrator is the business of the geologist. Either on wheels or as a small autonomous probe. Capable of some on the spot analysis, most of the analysis would be done in a laboratory at the factory, that would double as a process laboratory.

Image 5- Geologist, ground and space versions. Commonality reduces the number of parts required for production. A modern reference would be the NASA MMSEV.

All of these machines are products of the factory. These are complex vehicles, but only represent a small mass of the production from the factory. Except for structural elements and ground preparation, the most common product of the factory will be solar power units.

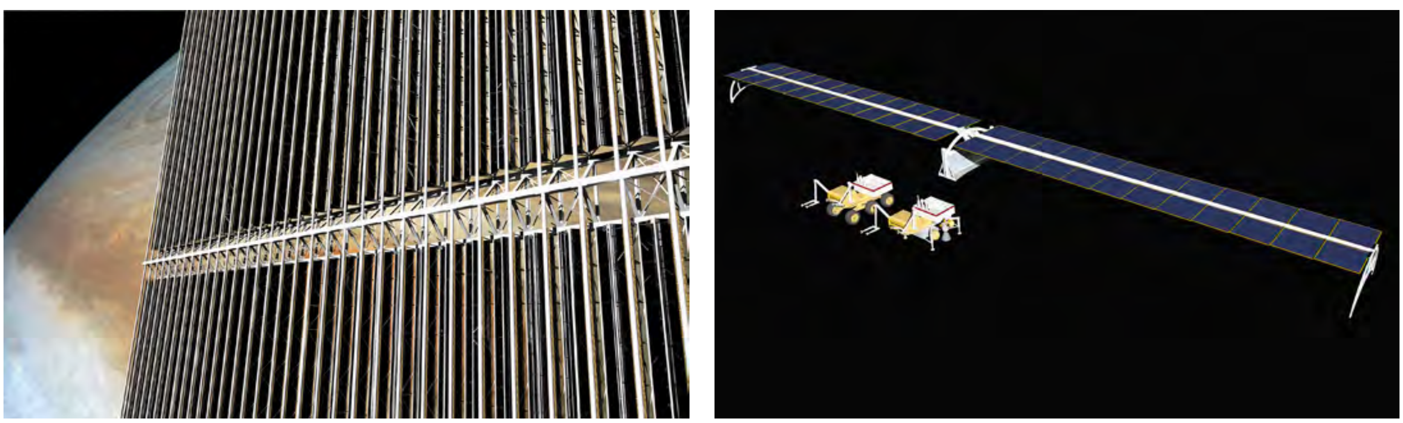


Image 6- A solar array with concentrators for a gas giant orbital installation, and a surface type deployable and orientable array for surface installation

Solar arrays give the possibility of local energy production, reducing the need for a large scale energy distribution infrastructure and of an extensive supporting civilization.

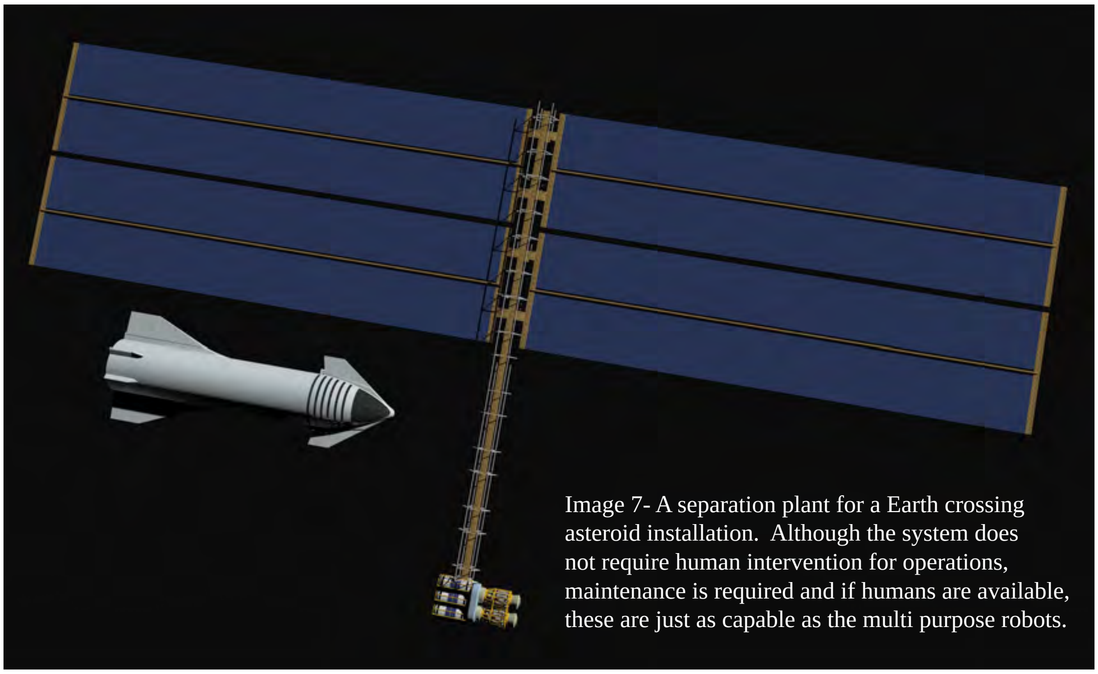


Image 7- A separation plant for a Earth crossing asteroid installation. Although the system does not require human intervention for operations, maintenance is required and if humans are available, these are just as capable as the multi purpose robots.

Trucks also operate on the mining sites, moving steriles to tailing areas and ore to concentrators.

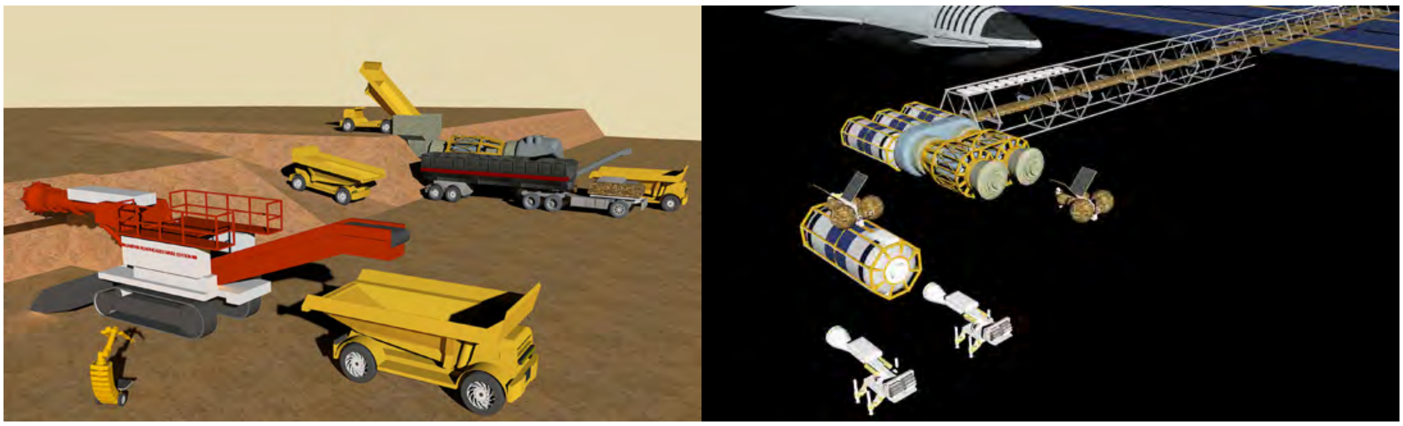


Image 8 - A mining site on Mars. Mining trucks that restrict themselves to the mine site and long haul trucks are shown. Self driving mining trucks already exist[5]. And the space equivalent.

The trucks and tugs feed the factory input areas, where storage silos store the materials required for the first stages of transformation, separation and reduction. Refineries that produce the first grade of products required for the factory.

If Martian settlements take off, Mars may not see self replicating factories, but rather apply the model of the extended production systems and Just in Time existing on Earth. Automation will provide high productivity, and will also be applied on Earth.

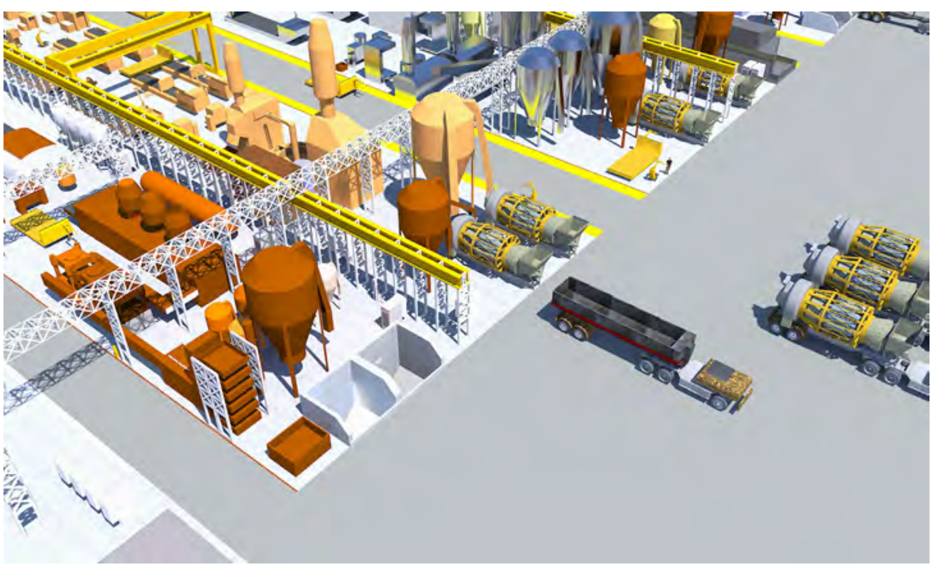


Image 9- View in the materials input area for the Silica, Iron and Aluminum production lines, lunar or martian surface factory. If you search a bit you will find the human to scale.

The silica is crushed and graded to different dimensions, while the iron ore is separated to Fe_2O_3 by centrifugal separation. The Alumina needs to be separated chemically from the ore that contains it in more complex forms, such as clays or olivine.

In the factory material handling takes many forms: autonomous lifts and carriers, automated storage systems and various cranes.

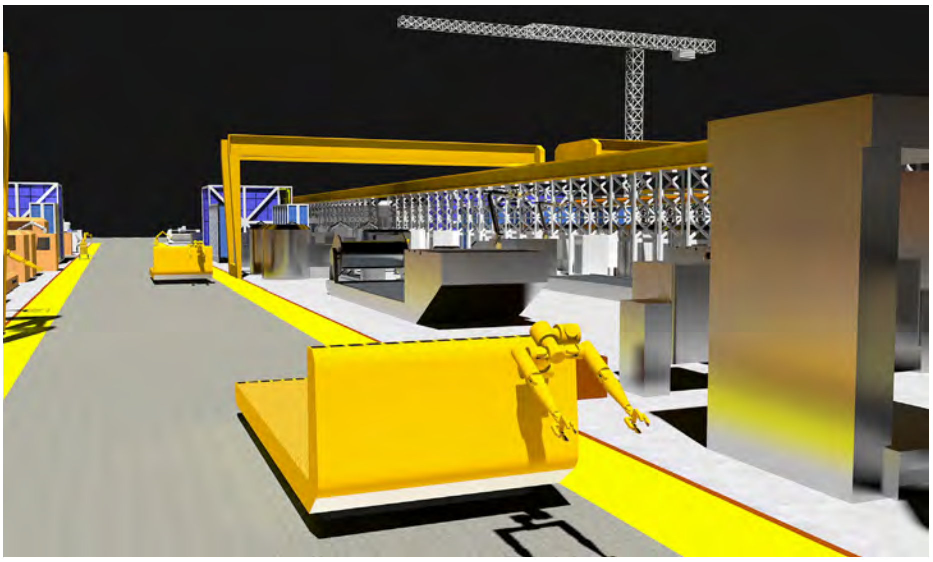


Image 10- An autonomous carrier moves in front of some aluminium shaping equipment and remelting furnaces. Overhead cranes handle large parts, while the tall crane in the background carries out final assembly of the larger equipment.

The single floor plan simplifies the maintenance and operations, and is more compatible with the wheeled robots. A few special multi handed/legged robots would be required in case of work in elevated areas.

Image 11 - A smaller orbital version of the factory. Part of the factory would rotate to facilitate processes and handling

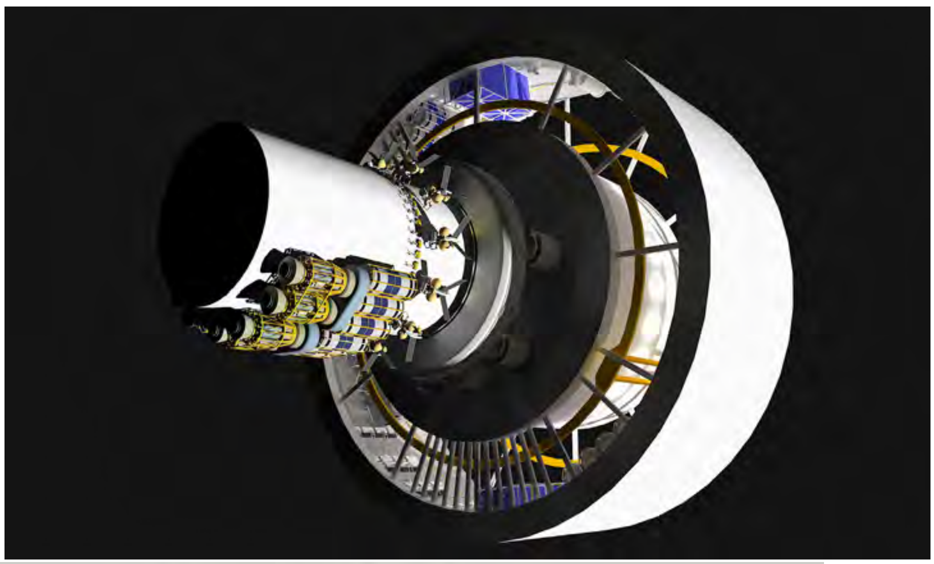
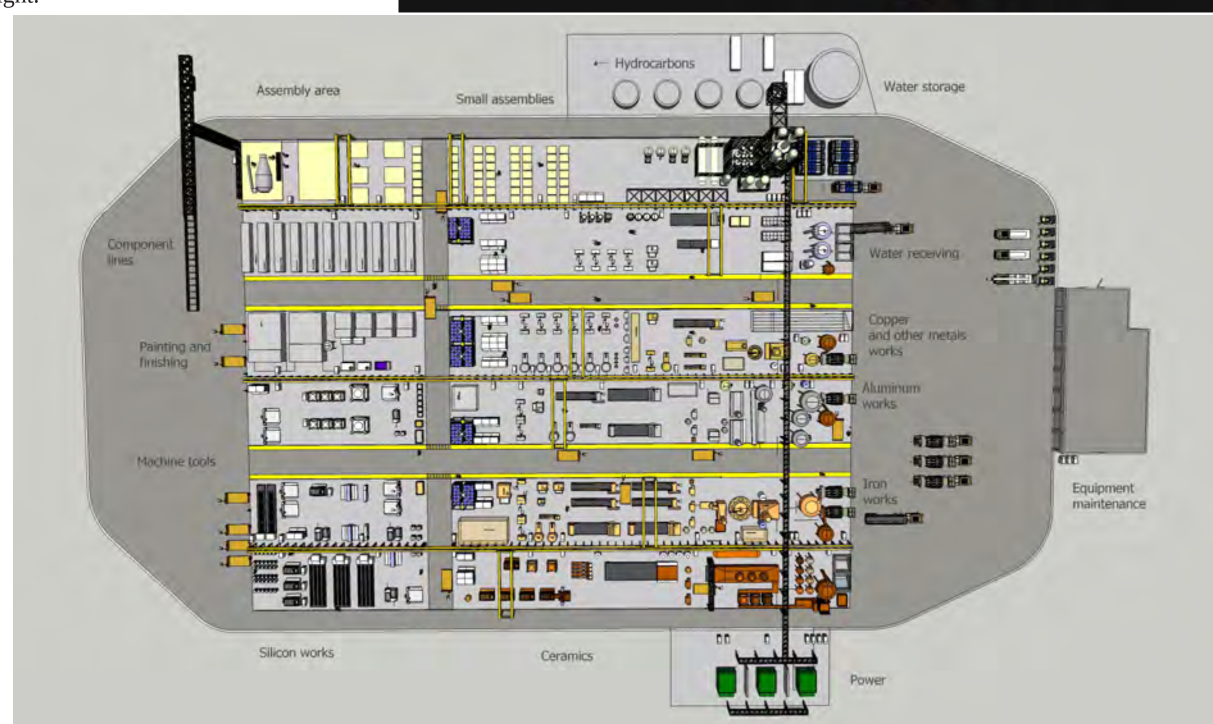


Image 12- Factory plan. A roof carrying solar cells would almost certainly be required, in particular on the Moon. The roof would be closed with insulated panels, for the long lunar night.



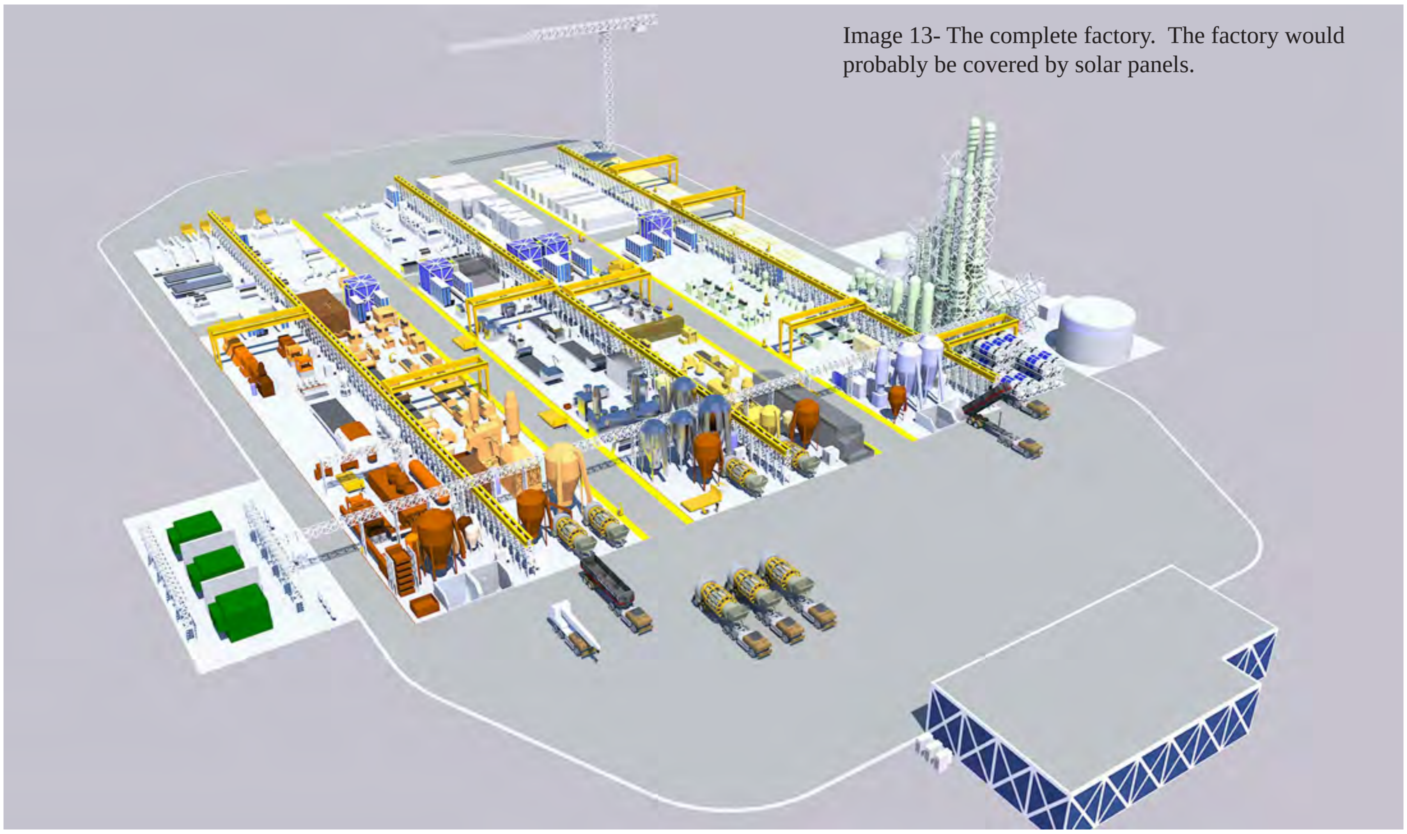


Image 13- The complete factory. The factory would probably be covered by solar panels.

There is nothing new in all this. In fact, the factory shown here is just a different version of the similar work done in the early eighties. But we are a lot closer to building it than we were then.

Image 14- 1980 version of the self replicating moon factory. Credit: NASA

An even earlier vision can be found in the 1941 Ford River Rouge plant. Vertical integration went from raw material supply to a manufactured car on a single site, very close to what is proposed for self replicating factories.

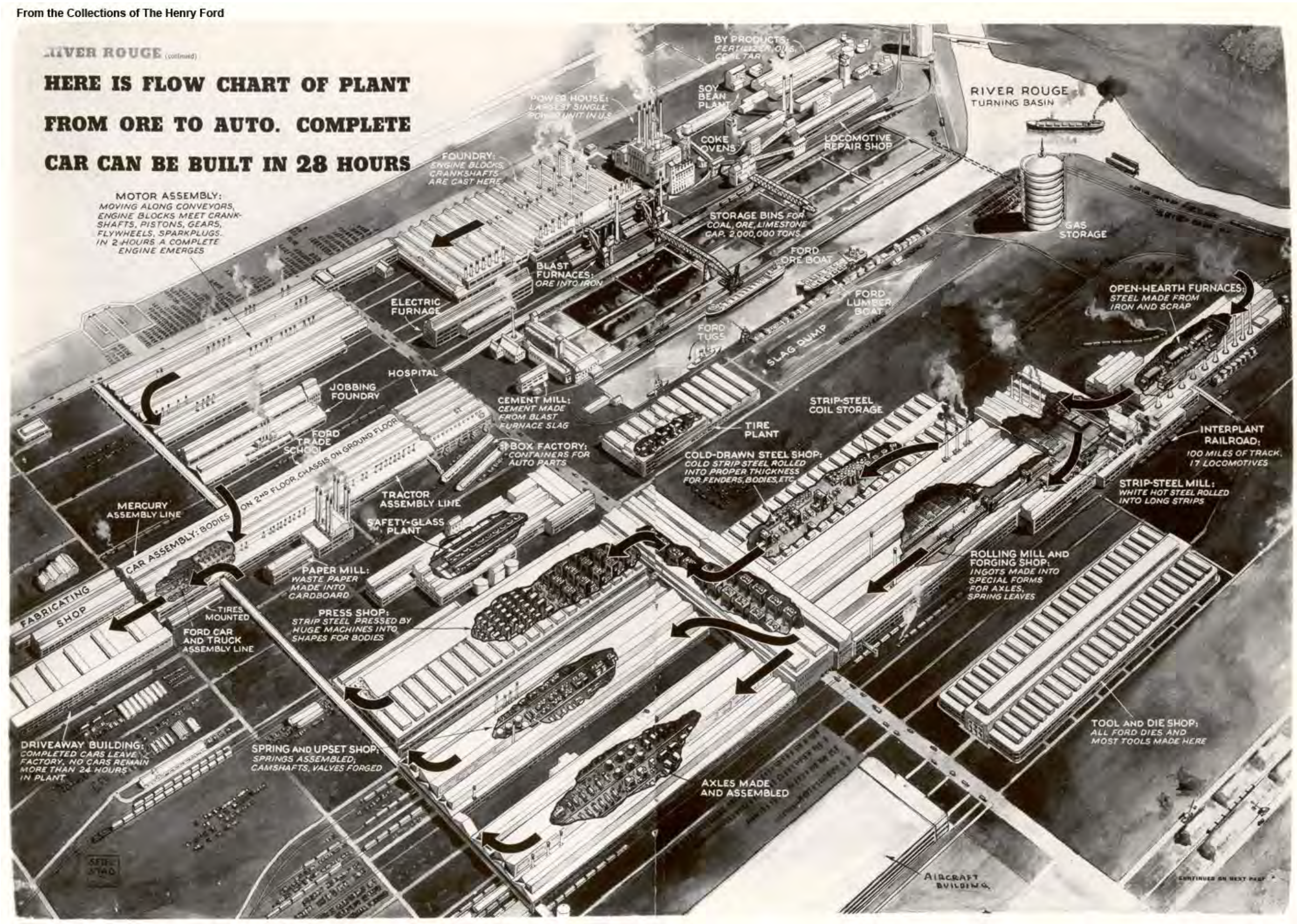


Image 15 - The Ford Rivière rouge plant in 1941.

Perhaps one of the most complete implementation of the vertically integrated factory in history.

Credit: University of Michigan-Dearborn - *Automobile in American Life and Society* www.autolife.umd.umich.edu/
"From the Collection of The Henry Ford. 1) P.833.75060"
www.autolife.umd.umich.edu/Labor/L_Overview/FlowChart_RougePlant_FullSize.htm

Operations

The self reproducing factory illustrated here is based on a production rate of 10,000 tonnes of steel per year, with ratios for other materials drawn from World production numbers for minerals and metals of 2020[6]. These numbers are for a self replicating factory on the Moon.

Self replicating factory	million T/year reference	Tonne per year	t/day	ratio ore to metal	total ore required per year	Ore, t/day	Embodied energy	Power
	Earth	Factory					kWh/t	kW
Water, factor of 6		60,000	200	1	60,000	200	140	1,750
Hydrogen from electrolysis		125	0.4	8	1,000	3	50,400	1,313
Carbon, from CO2		500	2	4	2,000	7	280	29
Slag, factor of 4		40,000	133	1		133	280	2,333
Cement	4,000	13,333	44	1		44	420	1,167
Steel and iron	3,000	10,000	33	4	40,000	133	9,800	20,417
Aluminium (doubled from Earth)	64	427	1.4	12	5,120	17	61,600	5,476
Magnesium	29	96	0.3	12	1,148	4	61,600	1,228
Copper	20	67	0.2	100	6,667	22	39,200	544
Manganese	19	63	0.2	100	6,270	21	39,200	512
Chromium	44	147	0.5	100	14,667	49	33,600	1,027
Silicon for solar cells		140	0	2	280	1	560,000	16,333
Polymers		500	1.7	1		2	22,400	2,333
Other metals/resources	110	363	1.2	150	54,450	182	42,000	3,176
Total		**11,801**	**419**		**191,602**	**818**		**57,638**

Table -1 Production numbers for a 10,000 tonnes of steel per year nominal self replicating factory.

The two most energy intensive productions are structural steel and silicon for solar cells. The power values are for continuous production during a year. Actual power could vary significantly depending on emplacement, resource accessibility and orbital characteristics of the location. The factory could reproduce itself about every two years, and produce about its mass of equivalent equipment in the ratio shown in the table. Added emphasis on solar cells, for example, would reduce mass output as these are high energy, low mass items. The factory is essentially energy limited, but probably also operationally limited as regards to the complexity of the manufactured parts.

It might be possible to optimise this factory to a smaller dimension, ideally to a point where the entire seed material required for a new factory could fit inside a 100 tonnes payload. This might be enough for a factory massing about 2,000 tonnes. At this point the unmounted solar cells might come from Earth, considerably reducing the energy required for the production of power systems.

For a lunar self replicating factory the lack of volatiles, such as water, CO2 and carbon as well as nitrogen might limit the capabilities of the factory considerably, although some volatiles are available from polar sources.

Recent developments

Some recent technological developments are moving industry towards the capability for self reproducing factories, notable elements are:

● Additive manufacturing; flexible production lines, use of simple materials for production for both plastics and metals. Additive manufacturing can also be used to produce dies for extrusion machines and various specialized small runs tooling, making the maintenance and modifications of conventional production machines easier. Extrusion fabrication remains orders of magnitude faster than additive manufacturing for many applications, and the combination of the two may be a winning approach.

● Deep learning; the development of much more independent robotic systems, with real world applications such as self driving cars drives a rapid development of these technologies; human input remains essential for deep learning training, however, and this still prevents the development of fully autonomous systems that might be required for Interstellar exploration.

● Minimal fabs; this is a manufacturing system for producing small runs of microprocessors. The technology is promising but may not survive the fierce competition from multi billion dollar fabs.

● The rapid evolution of cheaper space access, first from SpaceX and next from all of their waking up competition, is poised to deliver now markets than are likely to require in situ resources development, that in turn requires highly autonomous systems for production.

Some other factors that are still obstacles to total autonomy, and in particular make the use of fully automated factories on Earth unlikely, are the following:

● The low cost of human labor, and the high efficiency and flexibility of humans compared to robots.

● The low cost of transportation vs the cost of warehousing.

● The lower cost of large scale specialized factory products.

The first world economy seems to have started divorcing itself from the constant growth of energy production. Quality products take less and less energy to produce and to operate. On the other end of the economic spectrum, the increase in productivity may have started to outstrip the ability to consume the products in certain markets. This might grow into the capability of space production to create materials resources that can be used for entirely new ways of life, such as space settlements.

Image 16 - An early factory, with a number of SpaceX Starships serving as basic construction elements

Evolution of the factory

Starting with a first factory on the Moon, the precursor factories might be a small version of the Ford River Rouge vertically integrated plant. Deep learning could be carried out in simulation on Earth. The space environment of a lunar factory should be much simpler to navigate than a modern city road.

The factory would evolve towards the larger, more autonomous surface version explored in this article, and eventually move to interplanetary space. These factories would then follow humanity to the Stars, after having helped to build the infrastructure required for the occupation of the solar system and for Interstellar travel.

The single unit self replicating machine may remain far in the future, but a self replicating factory, part of a larger technological system, may soon exist. Rather like a plant or a tree is an individual system within the larger framework of an ecosystem.

On Earth, despite the abundance of mineral resources and energy sources, the self replicating factory may never come to be, outcompeted by more specialized elements of technological civilization. And humans are still hard to beat as far as autonomous robots go.

On the Moon, the lack of volatiles may handicap the long term development of the factories. However, factories on the Moon would be very useful for the fabrication of some of the elements for habitats in Earth orbit, as has been known for decades.

Self replicating factories might find wide use on Mars, in particular if the planet turns out to be impossible to settle. The factories could be operated from orbit in a fly-in fly-out type of operation. Mars is the closest large scale source of volatiles to the Earth, and use of in-situ propellant manufacturing may reduce the deltaV cost from the surface to orbit to a very low level.

The asteroid belt may be the ultimate resource for space settlement construction. However, volatile rich asteroids are in the outer limits of the belt, where the solar resource is getting rarer. Fusion power might then supplant solar power, but fusion remains a speculative technology.

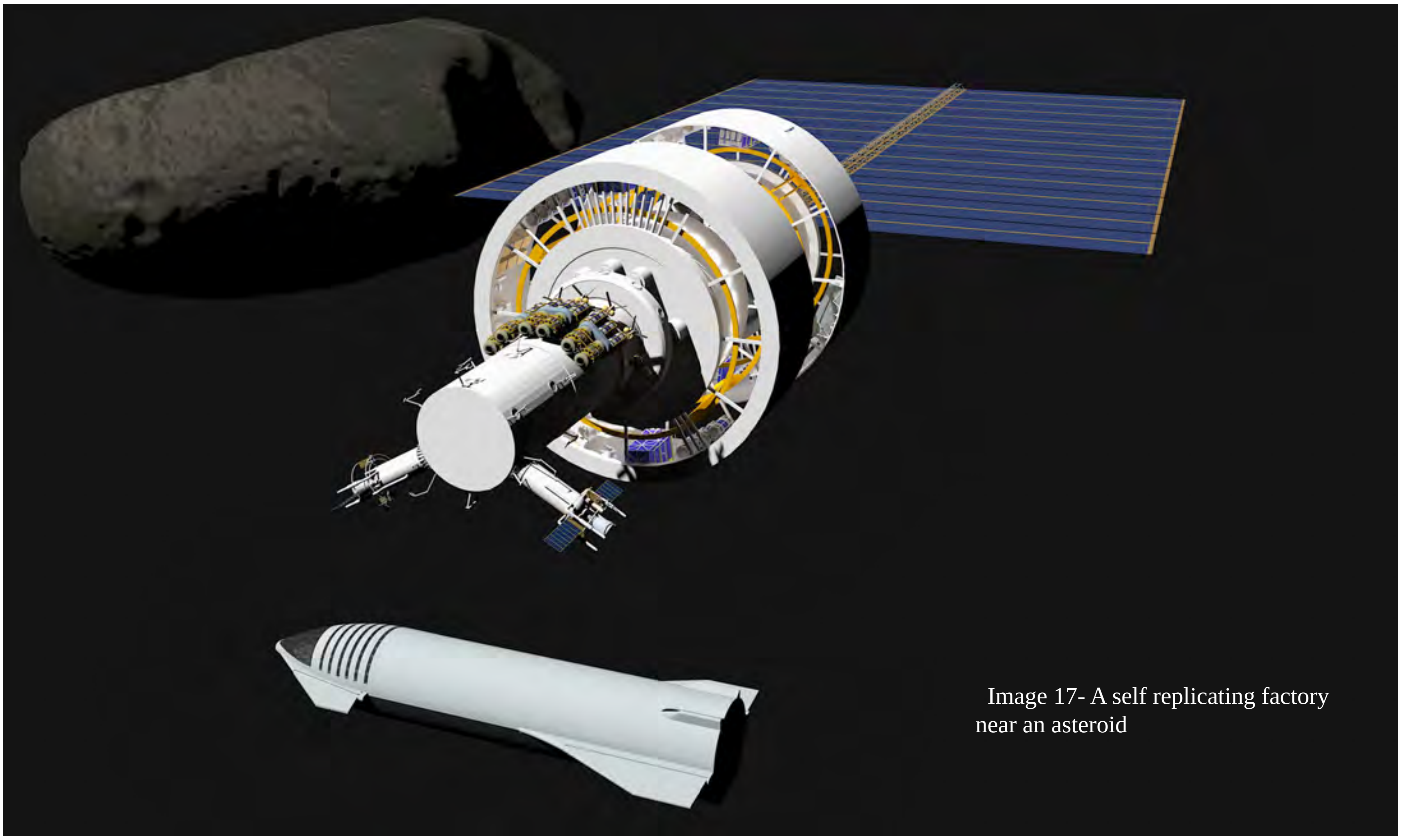


Image 17- A self replicating factory near an asteroid

Interstellar applications

Self replicating factories bypass the paradigm of limited resources often applied in the development of tiny probes and miniature exploration systems. In effect, any self replicating factory can eventually produce systems of any size, it is just a matter of time. Giving the exponential nature of the self replicating factory's output, waiting a few generations allows for much larger equipment. The resources available in the solar system, both in energy and matter, are stupendously large. Even the largest of worldships is an infinitesimal piece of equipment compared to a small moon, not to mention a full planet.

Conclusion

A large increase in the efficiency of autonomous production is likely in the near future. This increase should be applied to the creation of factories for the development of in situ resources for the exploration and development of the solar system. Additive manufacturing and high volume process tooling will combine into factories capable of flexible production runs and multiple outputs with very low modification costs. Combined with exploration and efficient resource acquisition, all the ingredients seem available for the creation of self replicating factories that can open up to solar system to occupation. Even if completely autonomous self replicating factories never come to pass, partially self replicating factories can be used to create habitats for humans in space. The inhabitants of these habitats can then participate in the operations of the factories, blurring the line between a self replicating factory and a self replicating civilization.

References

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About The Author

Michel Lamontagne is one of the two principal developers, with Robert Freeland, of the Firefly interstellar probe design for Project Icarus (see Patrick Mahon's discussion of the basics of its propulstion in *Reaching the Stars in a Century using Fusion Propulsion: A Review Paper based on the 'Firefly Icarus' Design* in Principium 22 August 2018 and at i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/. Michel is a French Canadian engineer living near Montreal. He works in mechanical engineering, mainly in building systems: plumbing and HVAC. As you will see from the illustrations here, and his cover art for P22, P30 and P31, Michel is an artist as well as an engineer. He mostly worked in comic art in his earlier years; you can find examples of this earlier work (up till 2014) on the web site: sites.google.com/site/bdespace /Home - use the side menu for most images. His more recent work is on Deviant Art: www. deviantart.com/michel-lamontagne/gallery/.