IAC-19-B3.2.12-53461

Investment Decision Model for a Commercially Owned and Operated Space Station in Low Earth Orbit

George C. Lordos[a]*, Matthew T. Moraguez[a], Alejandro E. Trujillo[a], Samuel I. Wald[b], Richard de Neufville[c] and Olivier de Weck[d]

[a] *Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, 33-409, Cambridge, MA 02139, USA*, glordos@mit.edu; moraguez@mit.edu, and alextruj@mit.edu
[b] *Barrios Technology, Houston, TX 77058,* Samuel.i.wald@nasa.gov
[c] *Professor of Engineering Systems, Institute for Data, Systems and Society, Massachusetts Institute of Technology, 77 Massachusetts Avenue, E17-369, Cambridge, MA 02139, USA*, ardent@mit.edu
[d] *Professor of Aerospace Engineering and Engineering Systems, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, 33-412, Cambridge, MA 02139,* deweck@mit.edu
* Corresponding Author

Abstract

NASA and private companies are actively exploring a commercially owned and operated successor to the International Space Station (ISS) upon its retirement. However, cost remains a stumbling block, and state of the art costing methods are still tuned for contractors and government agencies. For private investors interested in commercial human spaceflight, there is a need for new modelling techniques which integrate demand modelling with new cost models to support investment decision making. This is especially critical because important model inputs, such as projections of future launch costs, impact both the demand and supply sides of a commercial space opportunity. The integrated investment decision model presented in this paper was applied to a 2017 NASA/NIA-sponsored study for a private space station: the **MA**naged, **R**econfigurable, **I**n-space **N**odal **A**ssembly (MARINA). MARINA's main activity is space tourism via its anchor tenant, a luxury Earth-facing space hotel. Secondary activities are the rental of serviced berths and interior rack space to companies wishing to provide services to other MARINA tenants and users. The starting point for modelling was to select appropriate anchors and uncertainty ranges for model parameters. These drive an ensemble of interlinked models of demand for space tourism; berth / rack leases; construction costs; operating costs, and launch costs. We simulated exogenous and endogenous events, including agent decisions and interactions among model components. The models drive a 20-year cash flow forecast, condensed to a Net Present Value (NPV) using a conservative 20% discount rate. A Monte Carlo of the NPV's samples the uncertain variables and yields a statistical distribution of Expected NPV (ENPV). Our baseline control case without real options estimated the ENPV range to between -$3 billion to +$3.6 billion, with probability 90%. The real options were then enabled, simulating the decisions of agents to activate pre-emplaced options in response to actual events. The best result with real options was an improved ENPV range from +$0.2 billion to +$3.9 billion with probability 80%, demonstrating commercial viability. This work demonstrates the application of real options to the simultaneous modelling of demand and lifecycle cost drivers for complex space systems while retaining the realism of uncertain input variables and flexible, path-dependent strategies by rational agents. The approach facilitates the concurrent design of business strategies and space system designs by helping the architect to discover, calculate and communicate net present value, ultimately overcoming existing roadblocks and contributing to a "GO" investment decision by a private investor.
Keywords: real options, investment decision model, space hotel, commercial space station, cislunar space economy, space economics

Acronyms/Abbreviations

Expected Net Present Value (ENPV)
Independent, Identically Distributed (IID)
Net Present Value (NPV)
Non-Recurring Engineering (NRE)

1. Introduction

NASA is interested in concepts for a commercially owned and operated habitable space station to replace the International Space Station (ISS) upon its scheduled retirement within the coming decade. Such a space station could save NASA a substantial fraction of the more than $3b per year currently spent on ISS human spaceflight operations while maintaining the existence of a LEO destination which has helped foster the recent growth of the commercial launch market. It would also help accelerate the development and qualification of new space technologies in support of the Artemis program for the return to the Moon and of the path to Mars.

However, such a station will not materialize unless and until the question of its commercial viability has been convincingly addressed. This work proposes a modelling methodology to assist decision-makers in NASA and the private sectors who may be interested in this question.

As the starting point for our work, we have specialized the commercial viability question in a realistic way that would make the contemplated space enterprise more viable, as follows:

1. what are the most attractive markets which could be created in low Earth orbit for the in-space provision and exchange of habitation-related services?
2. how might NASA best support the early emergence of such markets in low Earth orbit, on a strictly temporary and time-limited basis?

Building on earlier works on flexibility and real options by two of the authors [1], [2], [3], this work describes an economic modelling approach which brings together a special, catalytic role for NASA; demand and launch cost forecasts; decisions under uncertainty and real options, to produce a distribution of expected net present value estimates for alternative permutations of technical and economic architectures for a commercially owned and operated LEO space station. This methodology is applied to a case study of the MARINA space station and space hotel concept [4] which was created in 2017 by an interdisciplinary MIT team*.

The objective is to uncover a specific, critical set of technological and economic conditions which would be necessary and sufficient to induce private companies to risk substantial private capital in a large, complex space project such as a commercial space station, with NASA acting as a market-maker and financial catalyst.

The approach presented here can be used to simulate and assess the potential economic viability of various cislunar space economy activities. It can also be generalized to the study of the potential economic viability of terrestrial high-risk, complex projects featuring high fixed costs, long development cycles, uncertainty in key assumptions, path-dependent project evolution depending on agent decisions and, importantly, opportunities to structure and exploit real options before making the “GO” decision.

2. Material and methods

2.1 Summary of the MARINA concept

*MARINA** was inspired by large, multi-tenant projects such as malls, yacht marinas and covered bazaars. Yacht marinas provide a fully-serviced berth to visiting yachts and opportunities to interact with other users and service providers. When these interactions add value to all parties, powerful network effects can make the project enduring: the world’s largest and oldest covered market, Istanbul’s Grand Bazaar (Fig. 1) is almost 555 years old.

Fig. 1. Istanbul’s Grand Bazaar, the world’s largest and oldest covered market, has 61 covered streets and 4,000 shops. It was founded in 1455 and attracts ~325,000 visitors each day. (Image credit: Hurriyet Daily News)

Such multi-tenant, multi-user projects manage size and complexity by relying primarily on modular scalability and standardized interfaces. Overcoming this complexity sets the stage for offering compelling value propositions to tenants and users, making the project commercially viable. Typical value proposition elements include: plug-and-play tenancy; the provision of services which would not otherwise be economically available to the prospective tenant; ready access to customers or service providers under one roof, and, in the case of bazaars and shopping malls, powerful synergistic network effects which fortify and assure the commercial viability over deep time. Accordingly, the MIT MARINA team sought from the outset to infuse MARINA, shown in Fig. 2, with similar characteristics.

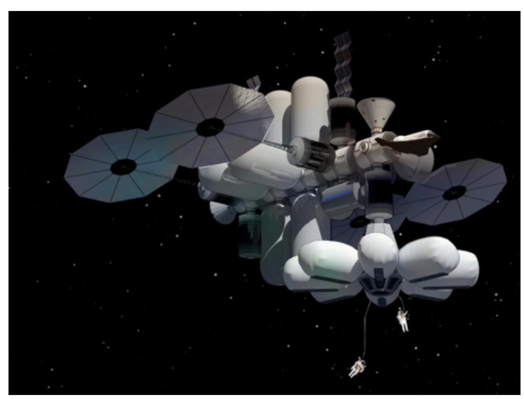

Fig. 2. Artist’s rendering of the MARINA Space Station featuring: 5 node modules; a space hotel with 8 rooms, bar, restaurant and gym, berthed at fore nadir; modules for NASA and commercial tenants; solar panels; and 3 visiting spacecraft. (Image: MIT MARINA team [4])

* MARINA was created by the MIT MARINA team which included four authors of this work among its members. See ‘Acknowledgments’ section for details.

The system architecture that supports the selected business model is based on special node modules which form the linear backbone and public space of MARINA, as shown in Fig. 2. These modules interconnect with other node modules and with tenant-owned modules via International Docking Adapter (IDA) ports featuring an expanded International Docking System Standard (IDSS) bus. Internally, the same expanded IDSS bus distributes data, power, air and fluids from and to internal rack-mounted modules. These rack-mounted modules may in turn also be tenant-owned and operated, replicating the modular scalability and standardized interfaces observed in successful marketplaces. The system architecture is intended to result in a flexible, value-adding space station environment which will attract diverse tenants and users who may then trade with each other.

Thus, just like a mall, covered bazaar or yacht marina, the envisioned MARINA concept involves renting out fully-serviced berths or rack space in a space station which offers a compelling set of value propositions to both tenants and visitors. The tenants pay rent, and it is this rent which must cover the entire economic cost of building, operating, maintaining and profiting from MARINA. Thus, the main economic activity of the station owner is that of the landlord, the main economic activity of MARINA's tenants is expected to be as users and providers of in-space habitability services, and the main economic activity of visitors will be as consumers or users of MARINA products and services.

2.2 MARINA Concept of Operations

Node and customer modules are launched separately and assembled in space starting in 2022. Two node modules, a NASA-rented module and the first four rooms of the space hotel are the minimal configuration to commence operations by 2025. Further launches continue adding modules to the station or transport commercial crew and supplies. A gradual build-up of assets would be in accordance with the flexibility strategy described above.

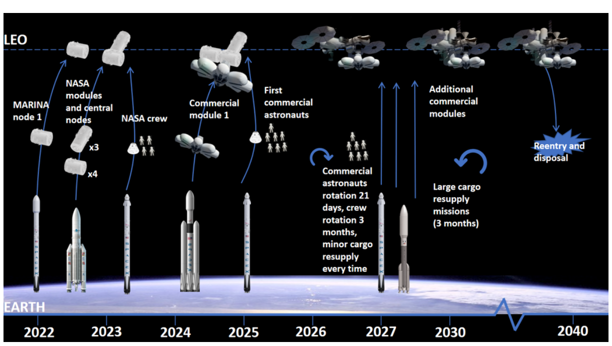

Fig. 3. Concept of Operations for MARINA from initial launch to disposal. (Image: MIT MARINA team [4]) (See also section 'Full Size Tables and Figures' at end)

2.3 Summary of Integrated Modelling Methodology

We used a three-stage process, summarized in Table 1, to develop the integrated model for the assessment of commercial viability of a LEO space station:

Table 1. Stages to Develop an Integrated Model for Assessment of Commercial Viability of a LEO Space Station

Stage 1	Select best human spaceflight opportunity
	Choose 'anchor tenant' for the space station
	Identify secondary economic activities
	Identify cost-reducing technology trends
	Identify drivers of demand, cost; find data
	Create closed-form demand, cost equations
	Reduce all outcomes to cash flow impacts
	Select time horizon and discount rate
	Calculate deterministic project NPV
Stage 2	Determine sensitivity of NPV to variables
	Replace important variables with pdf's
	Wrap cash flow model inside Monte Carlo
	Sample the NPV for 10,000 possible futures
	Calculate pdf of project's Expected NPV
Stage 3	Introduce decision points for rational agents
	What information is available at these points
	Model real options available at some points
	Model the decisions of agents at the points
	Recalculate pdf of project Expected NPV

The three stages correspond broadly to key milestones in the evolution and usefulness of the overall model. The approach we followed and the changes to the model at each stage described in more detail below.

2.3.1 Stage 1 – Initial Deterministic Model

The realization of a privately funded habitable space station is a very difficult technical and economic challenge at this time. To reduce this difficulty, the authors and the MIT MARINA team made certain strategic decisions which guided the development of the system architecture and the business model. For example, we started by reasoning that orbital space tourism, which has unlimited growth potential, has already been demonstrated at prices which are near what is needed for viability [5], and hence we determined that MARINA's anchor tenant ought to be a space hotel. Decisions like this were essential in order to start modelling something concrete which would ultimately have a realistic chance of yielding a positive net present value.

Having decided what we will be building, we followed the remaining steps described in Table 1, Stage 1 and created an overall 20-year cash flow model where each line of cash inflows or outflows was affected by calculations made in one or more of eight sub-models.

We initially anchored each of these sub-models on deterministic data inputs, as shown in Table 2. The resulting cash flows were then summed and discounted to calculate an initial deterministic NPV of the project. Many NPV analyses in most industries will either stop at this stage, or repeat the stage using some variant(s) of "conservative", "expected" and "optimistic" assumptions. Unlike these analyses, the purpose of the initial deterministic model in this work is twofold: to explore the sensitivity of the model output to changes in different input variables, and to confirm that its output should not be used because of the Flaw of Averages [2].

Table 2. Deterministic Data Anchors for Initial Model

Sub-model	Deterministic Data Anchor:
Launch Cost	$62m for a Falcon 9 launch
Launch accidents	Average of F9 & Soyuz history
Holiday demand	Equation using wealth data
IDA port demand	Two modes: very little, too much
Income summary	$5-$10m price for orbital holiday
Operating costs	Estimated SpaceX operating costs
Construction cost	0.8X-2X cost of a B747 per node
NASA payments	Per COTS, prepay for services

2.3.2 *Stage 2 – Model with Uncertain Inputs*

Having created a model which can calculate an initial deterministic NPV, we varied each input variable separately to gauge the sensitivity of the NPV outcome to changes in each input variable. For MARINA, we found that future launch cost, construction cost and demand would have the biggest impact on NPV. Given this result, each of these deterministic variables was replaced with a probability distribution function as shown in Table 3:

Table 3. Treatment of Uncertainty in Stage 2 Model

Sub-model	Treatment of Uncertainty
Launch Cost	Skewed distribution: learning rate ~1% to ~9.5% p.a., mean 1.5%
Accidents	
Holiday demand	Uniform: wealth fraction+willing
IDA port demand	Uniform: across a H/L range
Income summary	*(endogenous / derived)*
Operating costs	*(endogenous / derived)*
Construction cost	Skewed: ~0.8X to ~2X, mean 1X
NASA payments	*(endogenous / derived)*

The specific decisions for the treatment of uncertainty are discussed in section 3 below. The last step in this stage was to wrap a Monte Carlo analysis engine around the overall cash flow model. This allows the sampling of the input pdf's for the above key variables, resulting in the calculation of 2,000 different NPV results, one for each of the 2,000 sampled states of the world. This sample population of NPV's is used to construct a cumulative distribution function which can be queried to extract the probability of the project NPV exceeding, or being less than, any given level (such as $0). The average of the sampled NPV's is the Expected NPV of the project and the standard deviation of the sampled NPV's has meaning similar to the 'beta' measure of risk in finance.

The ENPV is thus an average of the (discounted) sum of the sub-model outputs that feed into the overall project cash flow, compared to the deterministic NPV which is a sum of the functions of the averages. Thus, the ENPV calculated at Stage 2 is a better predictor of the likely commercial viability of the project than the deterministic NPV from Stage 1 because the ENPV does not succumb to the Flaw of Averages.

However, this Stage 2 ENPV is unlikely to be positive for a commercial space station, and/or is likely to come with a very high standard deviation. This riskiness, reflected in the high discount rate, is a result of the high and uncertain one-off development costs and the highly uncertain trajectory of demand and operating costs, both of which are driven largely by the future evolution of launch costs. This means that if the analysis were to stop at Stage 2, the private space station project would likely receive a "NO GO" decision by a private investor. To recover from this condition, the architect must substantially redesign the project to increase the Expected NPV. One such approach to project redesign involves the introduction of Real Options [1], [2].

2.3.3 *Stage 3 – Model with Real Options and Agents*

The key idea with Real Options is to change the design of the project from the outset, potentially at a cost, so as to make it possible to defer certain large cash outflows (which represent investments) to future points in time, whereupon the relevant state of the world will be less uncertain [2], so as to increase the expected return while simultaneously reducing risk.

A Real Option enables the decision maker to simultaneously increase the expected (i.e. average) NPV of a given investment decision and to reduce its contribution to the standard deviation of the NPV. For this work, we first generated and selected a number of real options, and then converted them into IF..THEN...ELSE statements which could be coded into our model. Generating and selecting the Real Options is an activity which requires an understanding of the economics and market dynamics of the enterprise in question. The full list of real options generated for the MARINA model is shown in Appendix A, and one example of a real option is shown in Table 4. This option modifies the business model, from owning/operating the hotel rooms to selling/operating them. Many uncertainties will have resolved themselves by 2022 when the option must be exercised, hence the option has value.

Table 4. Example of a Real Option in the Stage 3 Model.

Definition of Real Option	**Definition of IF statement**
Real Option to sell all the hotel rooms off-plan to high net worth individuals, with an agreement to manage the rooms on their behalf. This will be exercised if, following NRE work, three or more of the following *adverse events* have occurred: High Node costs; High hotel room cost; High 2022 launch costs (counts as 3 events); Signs of low demand; High interest rates (counts as 2 events).	IF [Score of 3 or more on *adverse events*: High Node costs(1); High hotel room cost(1); High 2022 launch cost(3); Signs of low demand(1); High interest rates(2)] THEN **[Sell Rooms]** ELSE **[Borrow Funds and Build Hotel Rooms]**
	IF [Sell] THEN **[Room Expense= Revenue Share% x Room Income]** ELSE **[Room Expense = Int Rate % x Cost of Rooms]**

The addition of Real Options and simulated rational agents who resolve them based on realistic available information are the two critical steps which increase the credibility of the model and the Expected NPV of the project, while also reducing the standard deviation of the sample population of NPVs generated by the Monte Carlo model. With these additions we are ready to apply the model to the MARINA case study.

3. The MARINA Case Study and Model Details

The MARINA concept, as presented at the RASC-AL 2017 forum and competition, incorporated the following competition requirements:

- The station shall be commercially owned and operated
- The station should have a 15-year life in Low Earth Orbit (LEO)
- The first module should be launched by 2022
- NASA will be a rent-paying tenant of the new station for some duration of its lifetime
- The project should give consideration to existing related investments by NASA's partners

In the MARINA concept, a luxury space hotel is the anchor tenant for a period of 15 years and NASA is a tenant for a period of 10 years. Third parties can rent berths (International Docking Adapter (IDA) ports) or spaces in the internal racks. If all of MARINA's tenants can make a profit, then they will be able to sustainably afford the rent and MARINA can be financially self-sustaining. Therefore, validating the commercial viability of the MARINA business model turns on whether we can validate business model of MARINA's anchor tenant, namely orbital space tourism using a space hotel in LEO. Thus, for the purposes of keeping the analysis manageable and simple to communicate to stakeholders and interested parties, the MARINA station and the space hotel were combined into a single project. Such a combined project could take many forms, such as a partnership between a commercial space launch company and a hotel management chain, or a developer subcontracting to the space launch company and to the hotel chain.

3.1 Overview

The MARINA project kicks off in 2018 with commercial agreements between the developer, NASA and a hotel management company. These are accompanied by fundraising and the related design and non-recurring engineering (NRE) work. By 2022, the first node module will be launched, followed soon after by a second node module, a NASA module and the first crew. The hotel will be completed by 2024 and will receive its first guests in 2025, at which point MARINA's configuration will resemble Fig. 4. Additional nodes and customer modules will follow immediately after and the station will be completed by 2026, ready to receive third-party tenant modules.

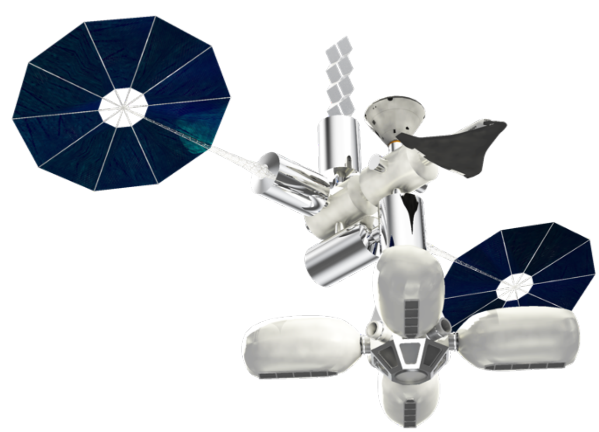

Fig. 4. The MARINA station with two nodes, NASA modules (zenith), space hotel modules (nadir) and two visiting commercial crew spacecraft. (Image: MIT MARINA team [4])

3.2 Operating Cost Sub-model

In both the cases of the hotel and the MARINA station, we note from Table 5 that their operations are characterized by high levels of fixed and semi-fixed costs. That is, even with a very low number of customers for the hotel, at least 2 flights to LEO per year will be required to keep the hotel in operation, and in the case of MARINA, the cost of ground operations, maintenance parts and maintenance and resupply flights will be fixed almost regardless of the number of IDA ports rented. The presence of high fixed costs further increases the riskiness of this highly capital intensive project.

Table 5. Analysis of Orbital Hotel Operating Costs. (For a larger version, see "Full Size Tables" section.)

Analysis of Orbital Hotel Operating Costs
All amounts in $ millions

HOTEL	Amount	Per:	2025	2026	2027	2028	2029
Fixed Costs							
Staff salaries	$0.15	person / yr	$0.60	$0.60	$0.60	$0.60	$0.60
Ground operations - hotel	$2.00	yr	$2.00	$2.00	$2.00	$2.00	$2.00
Maintenance - cost of spare parts	2%	yr	$2.85	$2.85	$2.85	$2.85	$2.85
Upseats required for staff	1	staff member per yr	4	4	4	4	4
Upmass of consumables required	2.00	kg per person per day	14568	12440	2920	2920	2920
Upmass of spare parts required	225	kg/room/yr	1800	1800	1800	1800	1800
Launches for HOTEL staff, parts, consumables	calculated	launch / yr	7	6	3	3	3
Launch cost	varies	per launch	$359.76	$304.26	$150.15	$148.23	$146.35
Insurance cost	varies	% per launch	$18.24	$19.86	$9.89	$9.64	$9.40
Variable Costs							
Purchase cost of consumables	$0.000010	kg	$0.15	$0.12	$0.03	$0.03	$0.03
Total Hotel Operating Costs			**$383.59**	**$329.69**	**$165.52**	**$163.34**	**$161.23**
MARINA (i.e. rest of station)							
Ground operations - MARINA	$24.00		$24.00	$24.00	$24.00	$24.00	$24.00
Maintenance - cost of spare parts	1%	yr	$27.49	$27.49	$27.49	$27.49	$27.49
Upmass of consumables required	2	kg / module / day	5110	5110	5110	5110	5110
Upmass of spare parts required	250	kg / module / year	1750	1750	1750	1750	1750
Purchase cost of consumables	$0.000010	kg	$0.05	$0.05	$0.05	$0.05	$0.05
Launches for MARINA parts, consumables	calculated	launch / yr	5	4	1	1	1
Launch cost	varies	per launch	$256.97	$202.84	$50.05	$49.41	$48.78
Insurance cost	varies	% per launch	$14.15	$14.70	$4.89	$4.78	$4.68
Total MARINA Operating Costs			**$322.65**	**$269.08**	**$106.47**	**$105.73**	**$105.00**

3.3 Income Summary Sub-model

As an illustration of how the flexibility strategy could help mitigate these substantial risks, in the instance portrayed in Table 6 below the number of IDA ports available to rent in the year 2031, which is 7, was equal to the number of IDA ports rented, also 7. That is, there is 100% occupancy of the IDA ports available to rent to other commercial tenants. This increases the requirement for additional nodes by +1 which triggers the construction of another node. The new node is launched in 2032, increasing the number of IDA ports available to rent from 7 to 10, after reserving one additional port for visiting spacecraft. Launches of new node modules expand MARINA's capacity in a modular fashion, as shown in Fig. 5.

Table 6. Hotel Revenue Model and IDA Port Revenue Model. (For a larger version of this table, please see "Full Size Tables and Figures" at the end of this paper.)

MIT STRATEGIC ENGINEERING

HOTEL REVENUE MODEL, 2025 - 2040

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Launch Cost per person	$7.34	$7.24	$7.15	$7.06	$6.97	$6.88	$6.80	$6.71	$6.63	$6.55	$6.47	$6.40
Room Cost per person	$5.00	$5.08	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00
Total Holiday Cost per person	$12.34	$12.32	$12.15	$12.06	$11.97	$11.88	$11.80	$11.71	$11.63	$11.55	$11.47	$11.40
Potential Demand for holidays	740	756	315	334	390	646	797	1053	1181	1348	635	871
Actual Demand for holidays	416	340	0	0	0	0	41	256	128	167	0	0
Rooms in construction	0	0	0	0	0	0	0	0	0	0	0	0
Number of Rooms	8	8	8	8	8	8	8	8	8	8	8	8
Holidays available	416	416	416	416	416	416	416	416	416	416	416	416
Holidays sold	416	340	0	0	0	0	41	256	128	167	0	0
Occupancy	100%	82%	0%	0%	0%	0%	10%	62%	31%	40%	0%	0%
Room Revenue	$2,080	$1,700	$0	$0	$0	$0	$205	$1,280	$640	$835	$0	$0
Dragon launches customers	59	49	0	0	0	0	6	37	18	24	0	0
Launch accident?	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
Number of Station Staff	4	4	4	4	4	4	4	4	4	4	4	4
Less: Operating Costs	$383.6	$329.7	$165.5	$163.3	$161.2	$159.2	$157.2	$254.9	$202.5	$203.3	$152.0	$150.1
Less: Rent share to owners OR In	$83.2	$68.0	$0.0	$0.0	$0.0	$0.0	$8.2	$51.2	$25.6	$33.4	$0.0	$0.0
Net contribution from hotel	$1,613	$1,302	-$166	-$163	-$161	-$159	$40	$974	$412	$598	-$152	-$150

IDA PORT REVENUE MODEL, 2025 - 2040

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Ida ports for NASA modules	3	3	3	3	3	3	3	3	3	3	0	0
Rent paid by NASA	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0		
Potential demand for IDA ports	5	5	5	5	6	6	7	9	12	25	25	25
+ Nodes required, up to max	1	1	1	1	1	1	2	2	3	3	3	3
Nodes under construction	1	0	0	0	0	0	1	0	1	0	0	0
Additional Nodes launched	0	1	0	0	0	0	0	1	0	1	0	0
Cumulative nodes in orbit	2	3	3	3	3	3	3	4	4	5	5	5
IDA ports available to rent	4	7	7	7	7	7	7	10	10	13	16	16
IDA ports rented	4	5	5	5	6	6	7	9	10	13	16	16
IDA ports reserved hotel, craft	3	4	4	4	4	4	4	5	5	6	6	6
Rent income from IDA ports	$240	$300	$300	$300	$360	$360	$420	$540	$600	$780	$960	$960
Less: Operating Costs	$124.0	$131.7	$128.3	$125.3	$146.3	$142.5	$144.6	$158.1	$174.6	$193.1	$189.6	$186.2
Net contrib fm renting IDA ports	$115.99	$168.30	$171.67	$174.74	$213.66	$217.47	$275.37	$381.88	$425.40	$586.90	$770.44	$773.75

Flexibility to expand based on demand

17

In the events portrayed in Table 6 by that specific instance of the simulation, the launch of an additional node in 2032 turned out to have been a good move, as the occupancy of IDA nodes returns back to 100% within two years and the net contribution from the activity of renting IDA ports has increased by 55%, from $275m in 2031 to $425m in 2033. This substantial increase in net contribution came about because the incremental revenue from renting more IDA ports was significantly higher than the incremental costs of operating an additional node, due to the presence of fixed costs which were described in Table 5 above.

Fig. 5. The MARINA station with five nodes, NASA modules (zenith), space hotel modules (fore nadir), tenant modules (berthed) and three visiting commercial crew spacecraft. (Image: MIT MARINA team [4])

3.4 Launch Cost Sub-model

Launch cost is a very significant variable because it influences costs of construction, costs of operation, demand by space tourists and demand for rental of IDA ports by other commercial tenants. Accordingly, we devoted additional effort to anchoring our assumptions.

The long-term reduction in launch cost is expected to materialize within an uncertain range and is expected to be driven by increasing competition, advances in rocket reusability and by the traditional learning (experience) curve. The equation used to represent the total uncertain cost reduction potential is of the form $\log(Y) = a + b.\log(X)$, with a selected so as to anchor the 2017 cost to $62 million per launch, which was the cost for a Falcon 9 rocket launch to LEO at the time. The parameter b embodies the uncertainty, and is assigned random values between 0.05 – 0.45. The resulting curves shown in Fig. 6 correspond to average annual compound learning rates of between 1% to 9.5% over a 20-year period.

We note that airlines, which had used reusable aircraft from day one, exhibit a 1.5% per year trend in reductions in operating costs over the last 85 years. Space launch costs on the other hand are only now making the transition from the expendability to the reusability model; therefore, significantly larger one-off cost reductions cannot be excluded. Thus, a range from 1% to up to 9.5%

per year for future reductions in launch costs was deemed reasonable and incorporated into the sub-model.

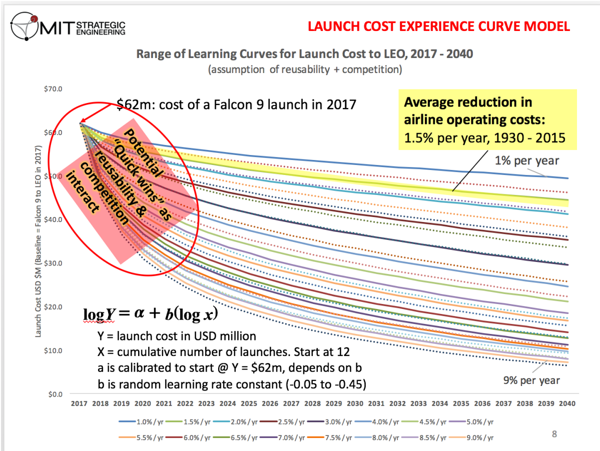

Fig. 6. Potential outcomes of launch cost experience curve sub-model at different long-term learning rates.

3.5 Construction Costs and NRE Sub-model

For the node modules, the construction costs were anchored to the cost of not less than a 747 commercial aircraft, with an uncertainty range of 0.8X undercost to 2.0X overcost. This fully-loaded cost amortizes the Non-Recurring Engineering (NRE) costs over the long term but does not include the costs for the commercially owned, rack-mounted subsystems that would populate the interior of each node module and bestow it with its required functionality, as most of these subsystems would be owned and operated by MARINA customers.

For the much simpler hotel room modules, the cost was modeled such that the baseline would be anchored to the cost of about one 747 and the upper end of 2.5x overcost would also end up being anchored to the approximate cost of about two 747's.

3.6 Demand for IDA Port Rentals Sub-model

Demand by third-party tenants for IDA ports was simulated parametrically to an approximate 1/x constant-price-elasticity demand curve, with launch cost – the main driver of all opportunity costs - serving as the proxy for the price axis. The parameters chosen allow for the possibility of both too low and too high demand for leases of the IDA ports on offer, where "too low" means very little demand (2 ports only) and "too high" means more demand than the station can satisfy. The actual quantity of IDA ports demanded for rent in each year is thus ultimately determined by the uncertain position of this parametrically determined demand curve and by the evolving launch costs that apply in that year.

3.7 Demand for Orbital Holidays Sub-model

Demand for orbital holidays in a space hotel is another critical uncertainty and accordingly a significant amount of effort was invested to model it. The number of wealthy households at different levels of wealth was the first anchor point, using an approach by Kothari & Webber [6] updated with 2016 wealth data from Credit Suisse [7]. A power law trendline curve was fitted to the seven available data points to set up a closed-form equation $y = (4).(10^7).(x^{-1.424})$ to express the number of households y as a function of net worth x, where $x > \$1$ million, as shown in Fig. 7.

The second anchor point were the holidays by Dennis Tito and Mark Shuttleworth, both of whom paid about 10% of their net worth for orbital holidays. From these starting points, the number of households which could afford an orbital holiday is computed using the modelled total cost of the orbital holiday and the modelled uncertain fraction (from 1.5% to 10%) of household net wealth being the maximum amount fraction of net wealth that such a household would spend on an orbital holiday for one person.

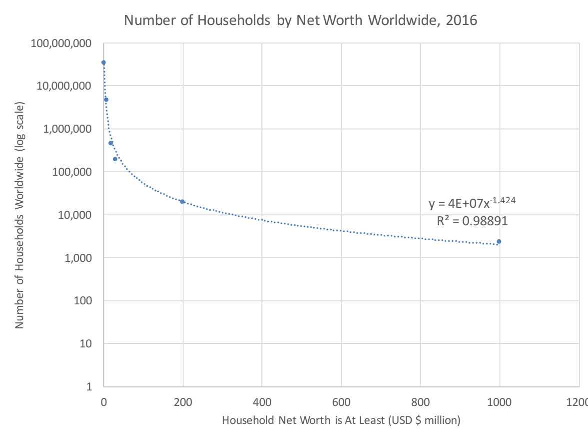

Fig. 7. Modelled number of households by household Wealth, Worldwide (Initial data from Kothari & Webber [6], updated with 2016 data from Credit Suisse [7]).

Each year, the number of households who could afford that year's launch cost plus the hotel room cost represent the size of the maximum potential demand pool. However, especially in the early days, a significant fraction of the individuals who can afford it will not want to go, whether for health or safety reasons, or because they might be waiting for prices to fall further. Hence, the *materialized* demand is modelled as an uncertain fraction of the households which can afford to go. This fraction ranges from 5% to 50%. The starting value of this fraction in 2025, the year when the space hotel commences operations, depends partly on random factors and partly on the total cost of an orbital holiday, with higher holiday costs driving the starting fraction down lower as more people who can afford it nevertheless balk at the high prices and decide to hold out for future lower prices. As time passes without launch accidents, this fraction of people who are willing to go follows a semi-random walk with a random upward bias of +0% to +5% per year, simulating that more people who could go, but who were initially holding back, are gradually joining the pool of people who would go.

Finally, the materialized demand from wealthy households is simply added to a virtual waiting list together with demand from other small sources (corporate travel, winners of a lottery). This virtual waiting list is then depleted each year. When the potential demand level changes, for example because of reductions in launch cost or because of a launch accident, the change impacts the virtual waiting list and from there it may or may not impact the actual demand for orbital holidays.

In a nutshell, the model starts from household wealth data and simulates various uncertain parameters as discussed above to estimate the total number of persons who could and would take a space holiday. It then subtracts those who have already taken an orbital holiday to estimate how much unfulfilled demand materializes each year.

3.8 Risk of Launch Accident Sub-model

Launch accidents are a real and serious risk with various impacts to demand, costs and launch insurance premia and thus have been modelled accordingly.

The starting value of Risk of Launch Accident in 2017 is loosely anchored to the track records of Soyuz and Falcon 9 and is modelled as an uncertain variable ranging from a best case of 1 in 125 to a worst case of 1 in 75. The same learning rate that applies to launch cost reductions then applies to risk reductions as well, on the assumption that the launch provider is learning how to improve the engineering of their rockets as rockets are returned for inspection/refurbishment and the number of cumulative launches increases. Launch accidents can have a very large impact on demand, simulated as a 67% downward shock on the "semi-random upward walk" of the fraction of people who would go followed by a random, one-off large partial recovery about 12 months later and a resumption of the semi-random upward random walk of the fraction who would go.

Launch accidents also drive the launch insurance premium, which starts from 6% in 2017 and then proportionately tracks the reductions to risk, but with premium increases of +25% every time a launch accident occurs in the model.

3.9 Expected NPV Model

The outcomes from all the sub-models come together in the Net Present Value model for MARINA, which is in the form of a cash flow forecast discounted by a 20% discount rate. Every run of the Monte Carlo model yields 2,000 instances of this NPV. The average of these 2,000 NPV's is the Expected NPV (ENPV) of MARINA.

Table 7. The MARINA NPV Model
(For a larger version of this table, please see "Full Size Tables and Figures" at the end of this paper.)

MARINA NPV Model	0	1	2	3	4	5	6	7
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
	2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
Inflows - net contribution hotel				$1,613.2	$1,302.3	-$165.5	-$163.3	-$161.2
Inflows - rent from NASA				$180.0	$180.0	$180.0	$180.0	$180.0
Inflows - milestone payments from NASA	$150.0	$100.0	$100.0	$300.0	$0.0	$0.0	$0.0	$0.0
Inflows - net contribution rent from others				-$202.7	-$149.1	$13.5	$14.3	$15.0
Total Inflows	**$150.0**	**$100.0**	**$100.0**	**$1,890.6**	**$1,333.2**	**$28.0**	**$30.9**	**$33.8**
New nodes construction				$0.0	$0.0	$0.0	$0.0	$0.0
New nodes launch				$0.0	$0.0	$0.0	$0.0	$0.0
Engineering studies	-$257.3							
Construction cost - hotel & gym		-$339.9	-$339.9					
Construction cost - hotel rooms		$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Construction cost - initial nodes	-$392.6	-$392.6						
Launch costs for initial nodes, hotel	-$53.7	-$264.4	-$312.7	$0.0	$0.0	$0.0	$0.0	$0.0
Insurance costs for launches	-$23.2	-$51.0	-$52.7	$0.0	$0.0	$0.0	$0.0	$0.0
Maintenance launches				-$51.4	-$50.7	-$50.1	-$49.4	-$48.8
Total outflows	**-$726.9**	**-$1,048.0**	**-$705.3**	**-$51.4**	**-$50.7**	**-$50.1**	**-$49.4**	**-$48.8**
Net Inflows / Outflows	-$576.9	-$948.0	-$605.3	$1,839.2	$1,282.5	-$22.0	-$18.5	-$15.0
Discounted	-$576.9	-$790.0	-$420.4	$1,064.3	$618.5	-$8.9	-$6.2	-$4.2
NPV	**$181.0**							

It is worth noting from Table 7 that the model 'decided' to sell all hotel rooms off-plan to up to eight high net worth individuals because of various signals (from hard information available to the decision maker in 2022) that the demand for orbital holidays might in fact turn out to be relatively soft. Hence the $0 cost of construction of hotel rooms in Table 7 above, and the $0 rent paid to owners for the years 2027 – 2030 in Table 6 above.

All cash inflows and cash outflows associated with the construction and operation of MARINA and of the space hotel are taken from the sub-models shown in Tables 5 and 6 and summarized in Table 7 above, which shows one possible Net Present Value outcome, based on a single sample of the various uncertain variables which affect the modelled revenues and costs.

3.10 NASA Milestone Payments for foregone real option

The key methodological choice of Real Options and its general application to the MARINA case has been covered in 2.3.3 above. An important detail specific to the development of the MARINA financial model relates to the Milestone Payments flexibility shown in Appendix A: a side study was carried out, holding other things equal and isolating the value of the flexibility to start the entire project up to 10 years later vs. the base case, simulating an entrepreneur waiting for launch costs to fall to a low enough level as to stimulate demand for economic activity in orbit. The increase in expected NPV from this flexibility, which must be foregone because of NASA's clashing requirements to both launch by 2022 and to have a viable commercial business model, was used as the guide for the approximate total delta NPV from the package of milestone payments. The justification is that if NASA wishes to accelerate the transition to a privately owned and operated space station, it should be prepared to replace the lost commercial incentive with a public incentive of equal magnitude. In return NASA would achieve cost reductions and other goals.

4. Results

4.1 Model results with uncertainty, without flexibility

With the model constructed as above and incorporating all the uncertainties described, we conducted a Monte Carlo simulation whereby in each of the 2,000 instances a new sample of the uncertain inputs was picked from normal or uniform IID distributions ranging between the minimum and maximum points shown in Table 3 above. In each instance, these uncertain inputs influence the evolution of demand, revenues and costs which drive cash flows. Net cash flows are then discounted by the 20% discount rate. This resulted in a data set of 2,000 possible values of the expected NPV which were grouped into 49 bins by range of NPV and plotted as shown in Fig. 8:

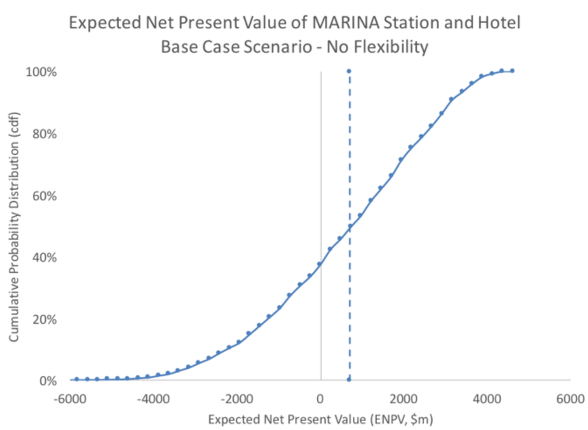

Fig. 8. Expected Net Present Value of MARINA space station and space hotel: base case scenario with uncertainty but without flexibility.

From Fig. 8 and Table 8, we note that the average expected NPV (average ENPV) for the baseline scenario with uncertainty but without flexibility was $694 million, marked by the vertical dotted line. We also find a 90% probability that the ENPV will lie within the range between P_5 = - $3,032 and P_{95} = +$3,635 million, with a 38% probability of a negative NPV.

4.2 Model results with uncertainty and with flexibility

We then enabled all the flexibility options in our model as described in sections 2.3.3, 3.9 and 3.10 above and repeated the Monte Carlo run. In Fig. 9 and in the last column of Table 8, we note that the average expected NPV (average ENPV) for the flexible option plus milestone payments was $2,162 million, an improvement of almost $1.5 billion relative to the baseline run shown in Fig. 8 above. Furthermore, by examining the cumulative probability table used to produce Figure 9, we find a 90% probability that the ENPV of the flexible option plus milestone payments will lie within the range between P_5 = - $455 and P_{95} = +$4,304 million, compared with P5 = - $3,032 and P95 = +$3,635 million for the baseline run without flexibility. Now, it appears that the commercial LEO station may be an attractive business proposition.

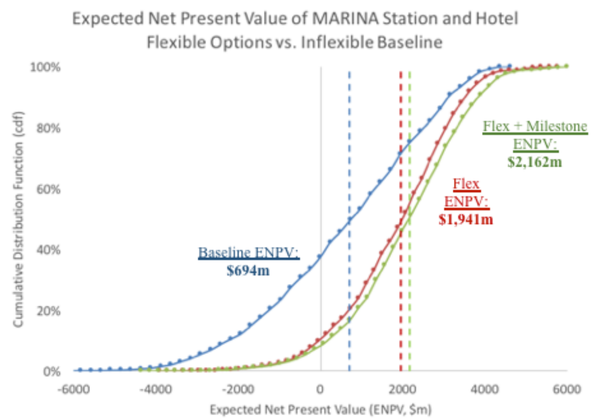

Fig. 9. Expected Net Present Value of MARINA space station and space hotel: two scenaria with uncertainty and with flexibility (red and green) compared to a baseline scenario without flexibility (blue).
(For a larger version of this figure, please see "Full Size Tables and Figures" at the end of this paper.)

4.3 Summary of model results

We summarize the key model results in Table 8. P_5, P_{10}, P_p etc. represent statements that "the NPV will be less than the number shown with probability *p*%". ENPV refers to the average of the 2,000 sampled NPVs resulting from the Monte Carlo simulation and capex refers to the average up-front capital expenditure. The scenario "Flexibility + Milestone Payments" refers to NASA Milestone Payments in exchange for fixing the launch of the first node module regardless of the observed state of the cost of launch variable.

Table 8. Comparative Results of Base Case vs. Flexibility Case

	Base Case	**Flexibility Case**	**Flexibility + Milestone Payments**
P_5	($3,032)	($535)	($455)
P_{10}	($2,183)	($52)	$180
ENPV	$694	$1,941	$2,162
P_{90}	$3,150	$3,525	$3,881
P_{95}	$3,635	$3,912	$4,304
Capex	$6,606	$3,512	$3,515

5. Discussion

From Table 8, we note that the base case, without flexible options, requires a capital investment of \$6.6 billion up to 2025 when MARINA becomes fully operational, not including the cost to NASA and other customers of constructing their modules which will be berthed at MARINA. That level of investment buys a project with an expected NPV of \$694 million, with a 38% probability of a negative NPV and with a 90% probability of a NPV result that may fall anywhere between negative \$3 billion (P_5) to positive \$3.6 billion (P_{95}). The same scenario has a 5% probability of a NPV of less than ***minus*** \$3b. The very high riskiness of this proposition is consistent with the fact that investors have, until now, been reluctant to invest in a commercial space station in low Earth orbit.

By comparison, the flexible case with milestone payments (which also compensates for the enforced 2022 start) comes in at an initial capital investment of only \$3.5 billion, deferring or offloading investment to third parties as necessary depending on events that take place after the commencement of the project, with the result that the expected NPV rises to \$2.2 billion and with a probability of 90% that the NPV will lie between negative \$455 million (P_5) and \$4.3 billion (P_{95}). The probability of a negative NPV in the second flexible scenario is less than 10%, as P_{10} = +\$180 million.

The above indicate that the net present value of the package of flexible options is of the order of \$1.5 billion, being the difference between the base case scenario and the flexible scenaria. Therefore, a rational decision maker should be willing to invest a substantial fraction of this sum up front in order to create and acquire these flexible options which will increase the expected net present value of the entire project.

6. Conclusions

In view of the above, our final recommendation is that the developer of MARINA should adopt a design and a project development strategy incorporating all of the flexibility options described in this report.

Specifically, in order to be in a position to effectively use all the flexibility options over time, the developer of MARINA should diligently structure all key contractual agreements with NASA, with the prospective hotel room owners, with the contractor who will manufacture the node and hotel modules, with the providers of the internal rack-mounted modules and with the launch services provider.

This structuring and other actions will enable the developer to successfully plan in advance how to overcome the substantial obstacles created by the high risk and high uncertainty inherent in a commercial space station project.

By addressing uncertainties in the systematic manner presented in this work, and compensating for them by investing in flexible options, such a plan for a commercially owned and operated LEO space station may have an increased probability of being funded. If funded, the implementation of a flexible strategy such as the strategy outlined in sections 2-4 above would improve the odds of realizing the expected positive net present value from the project.

Acknowledgements

The MARINA concept, including its architecture, space systems engineering design and a brief summary of the financial modelling approach described in this work, was created by the MIT MARINA (2017) team and submitted to the NASA-sponsored Revolutionary Aerospace System Concepts—Academic Linkage (RASC-AL) Forum held at Cocoa Beach in June 2017, where it was awarded first place in the graduate division.

The MIT MARINA (2017) team was led by Matthew Moraguez, Ph.D candidate at MIT's Department of Aeronautics and Astronautics and was advised by Assistant Professor Dr. Caitlin Mueller. The other team members were Dr. Valentina Sumini, graduate students George Lordos, Alejandro Trujillo, Samuel Wald, Johannes Norheim, Meghan Maupin, John Stillman, Alpha Arsano, Anran Li and Mark Tam, and undergraduate student Zoe Lallas. The MARINA images and graphics used in this work were created by the joint work of the following members of the MIT MARINA (2017) team: V. Sumini, G. Lordos, J. Stillman, M. Maupin, A. Li, M. Tam and Z. Lallas.

Appendix A - Real Options

This Appendix lists all Real Options developed for the MARINA commercial viability model.

Definition of Option	Definition of IF statement
Real Option to sell all the hotel rooms off-plan to high net worth individuals, with an agreement to manage the rooms on their behalf. This will be exercised if, following NRE work, three or more of the following *adverse events* have occurred: High Node costs; High hotel room cost; High 2022 launch costs (counts as 3 events); Signs of low demand; High interest rates (counts as 2 events).	IF [Score of 3 or more on *adverse events*: High Node costs(1); High hotel room cost(1); High 2022 launch cost(3); Signs of low demand(1); High interest rates(2)] THEN **[Sell Rooms]** ELSE **[Borrow Funds and Build Hotel Rooms]** IF [Sell] THEN **[Room Expense= Revenue Share% x Room Income]** ELSE **[Room Expense = Int Rate % x Cost of Rooms]**
If demand is strong (based on observations of potential demand, which in turn is driven by [observed] low launch cost) then increase the room price by up to $1m per person per two week holiday, in line with the demand strength estimates.	IF [Potential Demand >> Higher than Holidays Available Per Year] THEN **[Holiday Price = Base Holiday Price + (Demand Strength Indicator [0.0-1.0] * $1m)]** ELSE **[Holiday Price = Base Holiday Price]**
If orbital hotel was fully booked in prior year, then build one more hotel room [unless the rooms were sold to HNWI, in which case this flexibility is irrelevant and MARINA builds all hotel rooms up front]	Start with 3 rooms, or with enough rooms to satisfy first year's waitlist. Then, IF [Last Year Total Holidays Sold = Last Year Total Number of Holidays offered] THEN **[Build 1 More Room, up to Max of 8 Rooms]** ELSE **[Keep same number of rooms]**
If demand for IDA ports is strong, measured by filling at least 75% of all available IDA ports, then increase the number of authorized nodes so as to build and launch one more node module.	IF [Demand for IDA ports reaches existing capacity] THEN [Recalculate # Nodes required] IF [# Nodes required] has increased THEN **[start building a new Node Module]** ELSE **[Do nothing]**
If NASA insists on 2022 start, thereby eliminating flexibility to delay project, then negotiate option with NASA to receive prepayments of future rents tied to MARINA construction milestone payments	IF [Start in 2022 is enforced by NASA] THEN **[Enable 'NASA Milestone Payments Model' worksheet and include in cash flow]**

References

List of references

[1] R. De Neufville, S. Scholtes, and T. Wang, "Real Options by Spreadsheet : Parking Garage Case Example," *J. Infrastruct. Syst.*, vol. 12, no. June, pp. 107–111, 2006.

[2] R. De Neufville and S. Scholtes, *Flexibility in Engineering Design*, Hardcover. Cambridge, MA: MIT Press, 2011.

[3] R. de Neufville, O. L. de Weck, J. Lin, and S. Scholtes, "Identifying Real Options To Improve the Design of Engineering Systems," in *Real Options in Engineering Design, Operations and Management*, no. July, H. Black Nembhard and M. Aktan, Eds. Boca Raton, FL: CRC Press, 2010, pp. 1–37.

[4] M. Moraguez *et al.*, "MARINA: Managed, Reconfigurable, In-space Nodal Assembly," Cocoa Beach, FL, 2017.

[5] R. A. Goehlich, "Space tourism," in *Trends and Issues in Global Tourism 2007*, R. Conrady and M. Buck, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 213–226.

[6] A. P. Kothari and D. Webber, "Potential demand for orbital space tourism opportunities made available via reusable rocket and hypersonic architectures," *AIAA Sp. Conf. Expo. 2010*, no. September, pp. 1–15, 2010.

[7] R. Kersley and A. Koutsoukis, "Credit Suisse Global Wealth Report 2016," 2016.

Full size tables and figures

Table 5. Analysis of Orbital Hotel Operating Costs (one possible instance from a Monte Carlo run).

Analysis of Orbital Hotel Operating Costs

All amounts in $ millions

HOTEL	Amount	Per:	2025	2026	2027	2028	2029
Fixed Costs							
Staff salaries	$0.15	person / yr	$0.60	$0.60	$0.60	$0.60	$0.60
Ground operations - hotel	$2.00	yr	$2.00	$2.00	$2.00	$2.00	$2.00
Maintenance - cost of spare parts	2%	yr	$2.85	$2.85	$2.85	$2.85	$2.85
Upseats required for staff	1	staff member per yr	4	4	4	4	4
Upmass of consumables required	2.00	kg per person per day	14568	12440	2920	2920	2920
Upmass of spare parts required	225	kg/room/yr	1800	1800	1800	1800	1800
Launches for HOTEL staff, parts, consumables	**calculated**	**launch / yr**	**7**	**6**	**3**	**3**	**3**
Launch cost	varies	per launch	$359.76	$304.26	$150.15	$148.23	$146.35
Insurance cost	varies	% per launch	$18.24	$19.86	$9.89	$9.64	$9.40
Variable Costs							
Purchase cost of consumables	$0.000010	kg	$0.15	$0.12	$0.03	$0.03	$0.03
Total Hotel Operating Costs			**$383.59**	**$329.69**	**$165.52**	**$163.34**	**$161.23**

MARINA (i.e. rest of station)	Amount	Per:	2025	2026	2027	2028	2029
Ground operations - MARINA	$24.00		$24.00	$24.00	$24.00	$24.00	$24.00
Maintenance - cost of spare parts	1%	yr	$27.49	$27.49	$27.49	$27.49	$27.49
Upmass of consumables required	2	kg / module / day	5110	5110	5110	5110	5110
Upmass of spare parts required	250	‹g / module / year	1750	1750	1750	1750	1750
Purchase cost of consumables	$0.000010	kg	$0.05	$0.05	$0.05	$0.05	$0.05
Launches for MARINA parts, consumables	**calculated**	**launch / yr**	**5**	**4**	**1**	**1**	**1**
Launch cost	varies	per launch	$256.97	$202.84	$50.05	$49.41	$48.78
Insurance cost	varies	% per launch	$14.15	$14.70	$4.89	$4.78	$4.68
Total MARINA Operating Costs			**$322.65**	**$269.08**	**$106.47**	**$105.73**	**$105.00**

Table 6. Hotel Revenue Model and IDA Port Revenue Model (one possible instance from a Monte Carlo run)

MIT STRATEGIC ENGINEERING

HOTEL REVENUE MODEL, 2025 - 2040

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Launch Cost per person	$7.34	$7.24	$7.15	$7.06	$6.97	$6.88	$6.80	$6.71	$6.63	$6.55	$6.47	$6.40
Room Cost per person	$5.00	$5.08	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00
Total Holiday Cost per person	$12.34	$12.32	$12.15	$12.06	$11.97	$11.88	$11.80	$11.71	$11.63	$11.55	$11.47	$11.40
Potential Demand for holidays	740	756	315	334	390	646	797	1053	1181	1348	635	871
Actual Demand for holidays	416	340	0	0	0	0	41	256	128	167	0	0
Rooms in construction	0	0	0	0	0	0	0	0	0	0	0	0
Number of Rooms	8	8	8	8	8	8	8	8	8	8	8	8
Holidays available	416	416	416	416	416	416	416	416	416	416	416	416
Holidays sold	416	340	0	0	0	0	41	256	128	167	0	0
Occupancy	100%	82%	0%	0%	0%	0%	10%	62%	31%	40%	0%	0%
Room Revenue	$2,080	$1,700	$0	$0	$0	$0	$205	$1,280	$640	$835	$0	$0
Dragon launches customers	59	49	0	0	0	0	6	37	18	24	0	0
Launch accident?	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
Number of Station Staff	4	4	4	4	4	4	4	4	4	4	4	4
Less: Operating Costs	$383.6	$329.7	$165.5	$163.3	$161.2	$159.2	$157.2	$254.9	$202.5	$203.3	$152.0	$150.1
Less: Rent share to owners OR In	$83.2	$68.0	$0.0	$0.0	$0.0	$0.0	$8.2	$51.2	$25.6	$33.4	$0.0	$0.0
Net contribution from hotel	$1,613	$1,302	-$166	-$163	-$161	-$159	$40	$974	$412	$598	-$152	-$150

IDA PORT REVENUE MODEL, 2025 - 2040

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Ida ports for NASA modules	3	3	3	3	3	3	3	3	3	3	0	0
Rent paid by NASA	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0	$180.0		
Potential demand for IDA ports	5	5	5	5	6	6	7	9	12	25	25	25
+ Nodes required, up to max	1	1	1	1	1	1	2	2	3	3	3	3
Nodes under construction	1	0	0	0	0	0	1	0	1	0	0	0
Additional Nodes launched	0	1	0	[illegible]	[illegible]	0	0	1	0	1	0	0
Cumulative nodes in orbit	2	3	3	3	3	3	3	4	4	5	5	5
IDA ports available to rent	4	7	7	[illegible]	7	7	7	10	10	13	16	16
IDA ports rented	4	5	5	5	6	6	7	9	10	13	16	16
IDA ports reserved hotel, craft	3	4	4	4	4	4	4	5	5	6	6	6
Rent income from IDA ports	$240	$300	$300	$300	$360	$360	$420	$540	$600	$780	$960	$960
Less: Operating Costs	$124.0	$131.7	$128.3	$125.3	$146.3	$142.5	$144.6	$158.1	$174.6	$193.1	$189.6	$186.2
Net contrib fm renting IDA ports	$115.99	$168.30	$171.67	$174.74	$213.66	$217.47	$275.37	$381.88	$425.40	$586.90	$770.44	$773.75

Flexibility to expand based on demand

17

Table 7. The MARINA NPV Model (one possible instance from a Monte Carlo run)

MARINA NPV Model	0	1	2	3	4	5	6	7
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
	2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
Inflows - net contribution hotel				$1,613.2	$1,302.3	-$165.5	-$163.3	-$161.2
Inflows - rent from NASA				$180.0	$180.0	$180.0	$180.0	$180.0
Inflows - milestone payments from NASA	$150.0	$100.0	$100.0	$300.0	$0.0	$0.0	$0.0	$0.0
Inflows - net contribution rent from others				-$202.7	-$149.1	$13.5	$14.3	$15.0
Total Inflows	**$150.0**	**$100.0**	**$100.0**	**$1,890.6**	**$1,333.2**	**$28.0**	**$30.9**	**$33.8**
New nodes construction				$0.0	$0.0	$0.0	$0.0	$0.0
New nodes launch				$0.0	$0.0	$0.0	$0.0	$0.0
Engineering studies	-$257.3							
Construction cost - hotel & gym		-$339.9	-$339.9					
Construction cost - hotel rooms		$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Construction cost - initial nodes	-$392.6	-$392.6						
Launch costs for initial nodes, hotel	-$53.7	-$264.4	-$312.7	$0.0	$0.0	$0.0	$0.0	$0.0
Insurance costs for launches	-$23.2	-$51.0	-$52.7	$0.0	$0.0	$0.0	$0.0	$0.0
Maintenance launches				-$51.4	-$50.7	-$50.1	-$49.4	-$48.8
Total outflows	**-$726.9**	**-$1,048.0**	**-$705.3**	**-$51.4**	**-$50.7**	**-$50.1**	**-$49.4**	**-$48.8**
Net Inflows / Outflows	-$576.9	-$948.0	-$605.3	$1,839.2	$1,282.5	-$22.0	-$18.5	-$15.0
Discounted	-$576.9	-$790.0	-$420.4	$1,064.3	$618.5	-$8.9	-$6.2	-$4.2
NPV	**$181.0**							

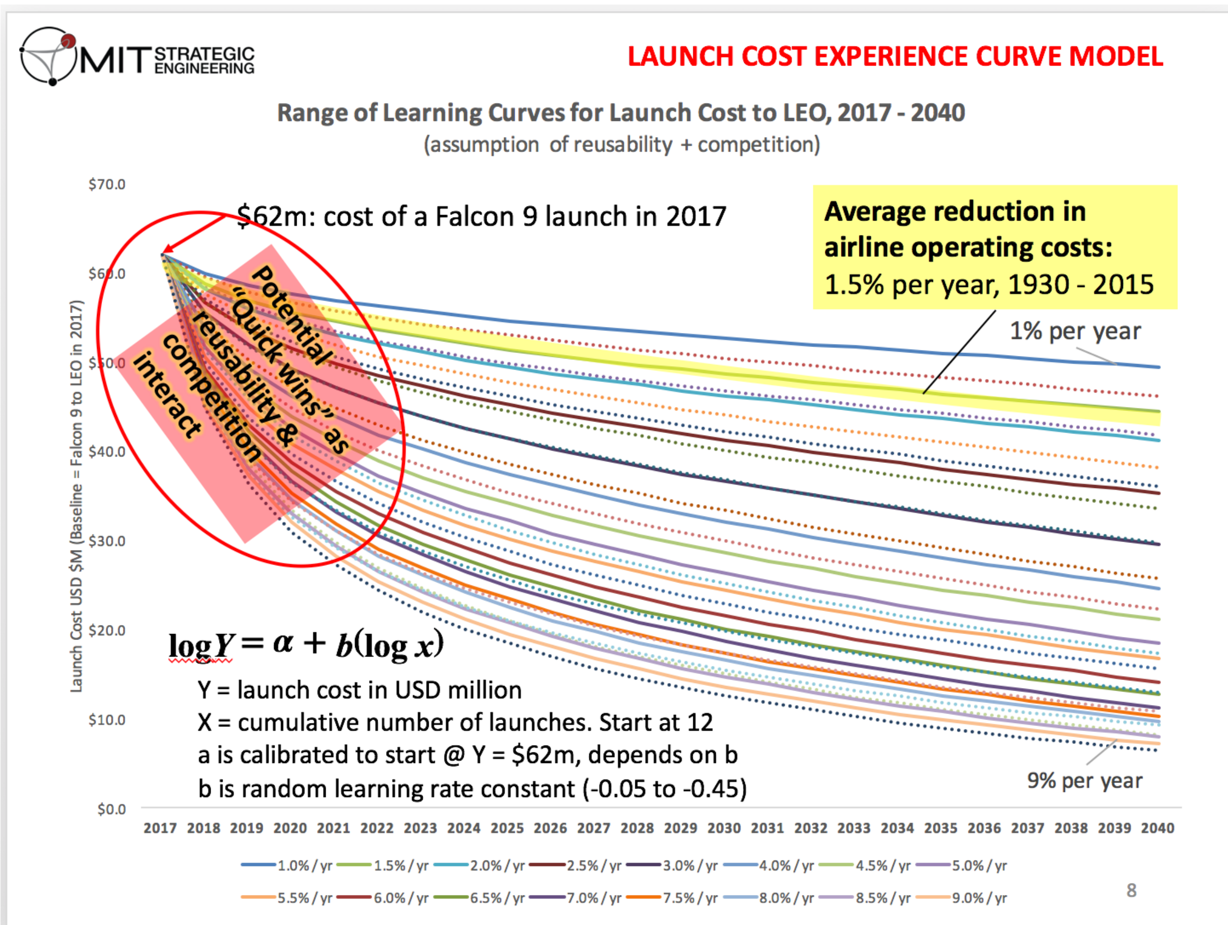

Fig. 6. Potential outcomes of launch cost experience curve sub-model

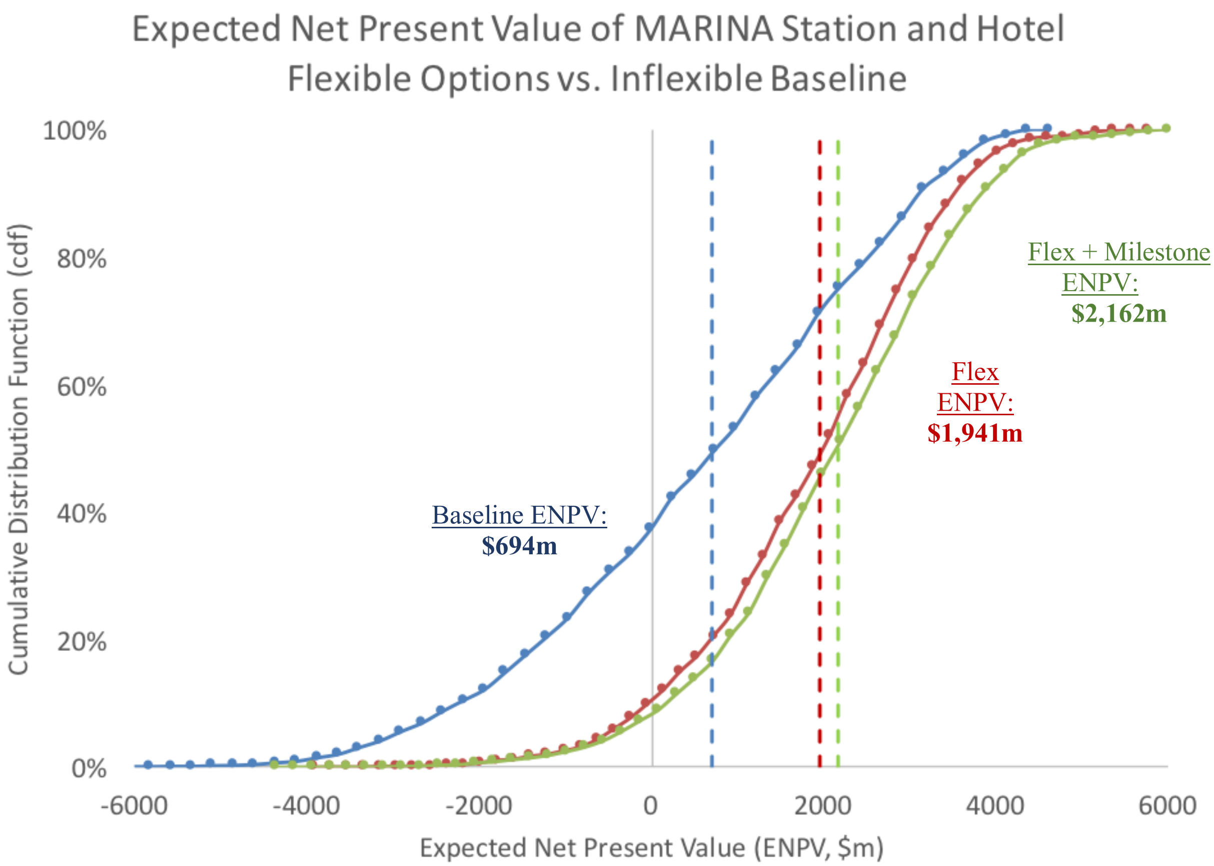

Fig. 9. Expected Net Present Value of MARINA space station and space hotel: two scenaria with uncertainty and with flexibility (red and green lines) vs. the baseline scenario without flexibility (blue line).

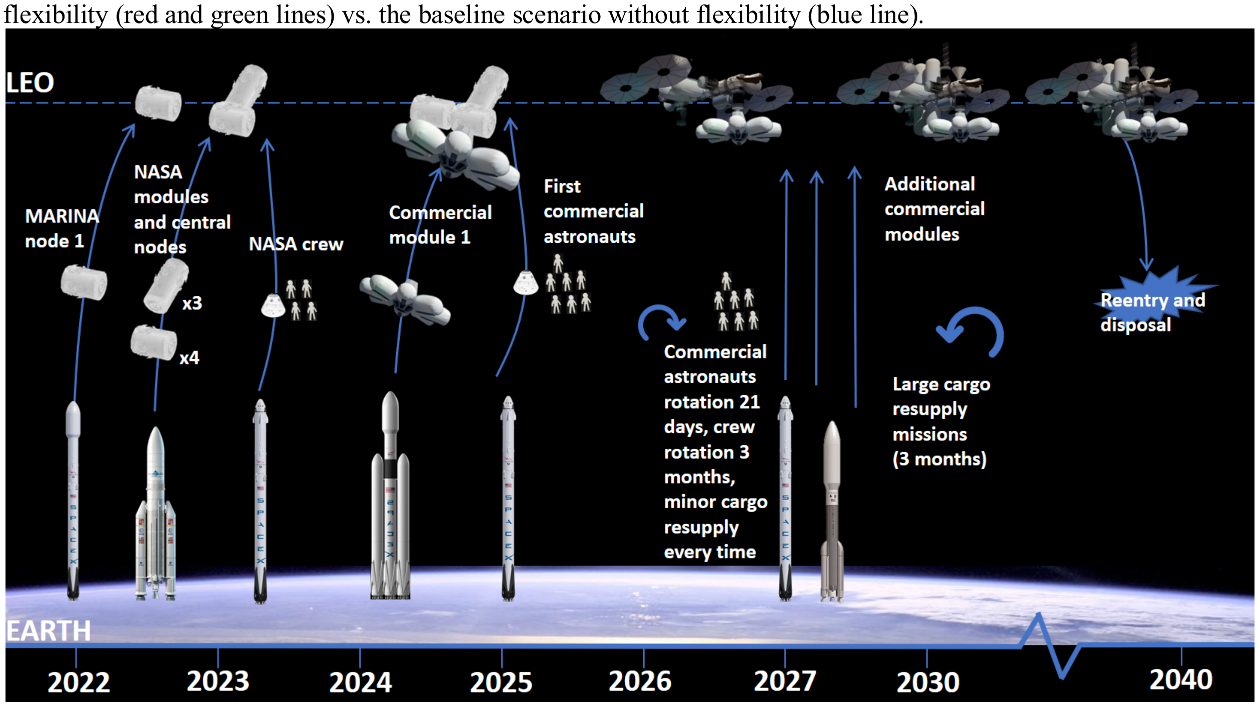

Fig. 3. Concept of Operations for MARINA from initial launch to disposal. (Image: MIT MARINA team [4])