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Economics and Food Provision Options for Luxury Food in an Orbiting Space Hotel

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The near term increase in space access, combined with the technological development of habitat technologies, will result in a market for vacations to space hotels. Like air travel in the last century, costs to orbit will initially allow only the wealthy to travel to orbiting, likely partially inflatable, habitats for short stays. These initial space hotel tourists will provide revenue for later, more broad efforts. Such customers will not be happy with protein bars and reconstitutes. They will expect menus of fresh foods, preferably high quality diverse menus, with a wide variety of options. As a result, a series of trade-offs between supply of foods to orbit, versus supply from orbiting farms, versus grown on site, will need to be made. In order to determine trade-offs, menus, will have to be decomposed into elements that can be sourced in orbit from other habitats, in the hotel's own gardens/farms/machinery, and from Earth. Machinery may include synthesis using yeasts or accumulative manufacture, but it is core to this paper that most elements and entrees will be grown and harvested, then provided fresh, frozen, or dried and processed. Further food considerations include what can be eaten in micro-gravity, versus in artificial gravity environments. Five stages in space hotel development are discussed. Initial analysis indicates many ingredients will in the beginning brought from Earth, as will the labor to cook and serve the food. Given a hotel at a similar orbit as the International Space Station, and farms orbiting nearby, this paper will describe the trade-off analysis for such tourists, including decomposition and the costs of components given the options for supply, and how these menus, trades, and costs will change given changes in costs to Low Earth Orbit per kilogram.

Nomenclature

Core Variables

C = cost in 2016 dollars
m = mass in kg
O = overhead ratio
T = labor time in person*hours
v = volume in cubic meters
P = percentage
SR = span ratio of management labor to total non-management labor
RR = rotation rate in hours, also called tour length. The time an employee is at the restaurant for work
WR = worked ratio a percentage of a tour that is worked, 30% is roughly an 8 hour day, few days off

As Used:

C_t = total cost for time period (a set of guest*days) at the restaurant
C_{fixed} = fixed costs for a set of guest*days, including rent, taxes, etc.
C_d = total cost for all the recipes consumed by one guest for one day
C_r = total cost of one serving of a recipe
C_i = total cost of one unit of an ingredient
$m_{i,r}$ = mass of an ingredient used in a recipe for 1 serving
$m_{i,unit}$ = mass in kg for one unit of an ingredient
$C_{L,(prep, serve, or adm)}$ = hourly wage per labor*hr for any of Severs, Administration, Preparation
$T_{L,(prep, serve, or adm)}$ = time in labor*hrs per recipe for any of Severs, Administration, Preparation
$T_{L,prep}$ = time in labor*hrs per recipe for Preparation

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$C_{L,prep}$ = hourly wage per labor*hr for Preparation (i.e. Chefs,cooks, and other culinary skill etc.) labor
$T_{L,serve}$ = time in labor*hrs per recipe for Servers
$C_{L,serve}$ = hourly wage per labor*hr for Server (i.e. wait staff, runners, dish washers, etc.) labor
$T_{L,adm}$ = time in labor*hrs per recipe for Administration
$C_{L,adm}$ = hourly wage per labor*hr for Administration (management) labor
$C_{L,amort}$ = costs applied to labor amortized over the length of a tour in $/labor*hr
$C_{L,travel}$ = cost to bring a working person to the restaurant from Earth or a colony.
P_{load} = percentage added to wages for all loaded costs that multiple against the hourly wage
P_{B} = percentage added to hourly wages for benefits, taxes, and fees
m_{pea} = mass per person's food, drink or material allowance per hour of a tour (i.e. rotation)
C_{EtoL} = cost per kg to ship an item from Earth to Low Earth Orbit
C_{LtoS} = cost per kg to ship an item from an orbital position in Low Earth Orbit to the restaurant
$O_{i,m}$ = mass dependent overhead ratio for an ingredient
$O_{alive,m}$ = mass dependent overhead ratio for a live ingredient
$O_{vib,m}$ = mass dependent overhead ratio for a vibration or acceleration sensitive ingredient
$O_{env,m}$ = mass dependent overhead ratio for an environmentally (temperature, pressure) sensitive ingredient
$O_{i,v}$ = volume dependent overhead ratio for an ingredient
$O_{alive,v}$ = volume dependent overhead ratio for for a live ingredient
$O_{vib,v}$ = volume dependent overhead ratio for a vibration or acceleration sensitive ingredient
$O_{env,v}$ = volume dependent overhead ratio for an environmentally (temperature, pressure) sensitive ingredient
$v_{i,unit}$ = volume in cubic meters per unit of an ingredient
$C_{store,Earth}$ = cost to store a unit of ingredient pre launch on Earth in $$/unit (volume)
$C_{store,Rest}$ = cost to store a unit of ingredient at the restaurant in $$/unit (volume)
$T_{prep,i}$ = time to prepare an ingredient for storage at the restaurant for later use, in hrs/unit
C_{buy} = cost to purchase the ingredient off the shelf in $$/unit
C_{gndshp} = cost to ship an ingredient from point of purchase to the Launch Site in $$/unit
$C_{repack,E}$ = cost to repack an ingredient to launch from Earth (or other planet) to Low Earth Orbit in $$/unit
$C_{repack,LEO}$ = cost to repack an ingredient in Low Earth Orbit for transfer to the restaurant in $$/unit
$C_{unpack,Rest}$ = cost to unpack a unit of an ingredient at the restaurant (after shipping) in $$/unit
C_{hvst} = cost to harvest/produce a unit of an ingredient at the restaurant/resort/colony in $$/unit

I. Introduction

The concept of space hotels is not new. Rather space luxury lodging and eating has been a topic of science fiction and speculation for nearly a century. Space outposts to date are Spartan affairs, with limited privacy, limited menus, and little non-essential. The International Space Station (ISS) is no exception, being a base camp for scientists, who live with very limited privacy, and make do with limited ingredients and menu options, usually preparing their own meals. It will not remain always so. Eventually those who are willing to pay to travel to Low Earth Orbit (LEO) and beyond will insist on meal choices and foods commensurate with the very high cost of travel to space lodging. These tourists will fund future efforts to improve the luxury and options for staying in orbit, and will also drive economies to support such travel.

While the costs a restaurant pays to rent and operate a facility in orbit or on a planetary body will be very substantial, they are not the only big costs for a space dinning facility. The rent and utilities will be a fixed amount per time period, and these will be allocated to every serving as a constant. The more interesting costs that will change as the space economy evolves will be labor and materials.

Labor to support tourists is also important. It will be a specialized business to cook, serve, and work in a space hotel. For example cooking in zero g will require specialties. To date, all cooking and eating in space has been in micro-gravity. Early missions had foods of pastes, much like baby food, and drinks in bags and bottles, like the fruit juice packs kids use now. This is not entirely accidental, as spin offs often find their way into daily life. Some foods were, and are, shipped as freeze dried or dehydrated concentrates, then re-hydrated before consumption. Like the military Meal-Ready-to-Eat, taste was secondary, nutrition primary. On the ISS, fresh fruits, meats, and vegetables have been brought up with resupply, and very simple recipes have been made using plastic bags and the limited ingredients[1]. This limited food structure is not luxurious to say the least. More complicated cooking will be required to reach more luxurious experiences. Mixing is problematic because there is nothing to hold liquids or solids together, so mixing is done currently in bags, leading to less than perfect mixes. Cooking is similarly problematic. Gravity on Earth allows liquids to boil bottom-up, allowing evaporation and concentration, as in rues.

Boiling in space is a three-dimensional affair, and gasses and liquids mix and pop in many directions, making it difficult to extract steam/evaporates. Further, the closed environment poses challenges for smoke and steam heavy cooking as in frying. I call this the 'cook-pot problem'. One way to overcome the cook-pot problem would be to use centrifugal force to substitute for gravity, leading to a ring shaped cook pot, with gas valves and injectors in the center, and heating elements attached to the outside, and agitators at various points. Spinning the ring pot allows gases to be extracted to concentrate the remainder for rues, and the gases can then be recaptured and recycled. A similar technique at lower temperatures would allow cleaner fermentation of yeasts to make beers and wines. Steaming, as for rice and other foods, is also problematic, but solvable. Steam will have to emanate from either the center or an edge, and forced using pressure and vacuum through the food. There are also advantages. Vacuum allows freeze drying. Zero g should allow near perfect bubbling in rising breads. A perfectly round roll, with near-equal bubbles should be possible, using a poll to hold each roll in a special oven (radiates from all sides, as opposed to bottom as in kitchen ovens on Earth). Add to the challenges cited before, cooks must handle the technologies for printing foods and using recycled foods for the crew.

As a result of the challenges and opportunities, space cooks and servers, as noted above, are labor specialists, that will have to not only deal with the oddities of cooking and serving in space, but will have some of the same limitations for crews working in remote areas, with long rotations between trips down to Earth or to other colonies. Travel leaving gravity wells like Earth is expensive for now, and the crew and their support costs pose significant expenses. Medical limitations for micro-gravity accommodations will limit rotations to under a year, though once gravity can be had in orbit or for colonies on the Moon or planetary bodies, tour lengths can increase and possibly include dependents. Once entire colonies exist near the restaurant, labor may not include rotation costs.

Getting the mass to orbit for the tourists to eat is also a cost. Assuming food comes from Earth, food needs to be shipped from point of purchase to the launch location, then stored until launch, repacked for space travel, loaded into the launch vehicle, launched into orbit, transferred in orbit to the restaurant, then offloaded and stored on site.

Summing all the conditions above illustrates the costs for running a restaurant in space. These high level costs are shown in the figure below:

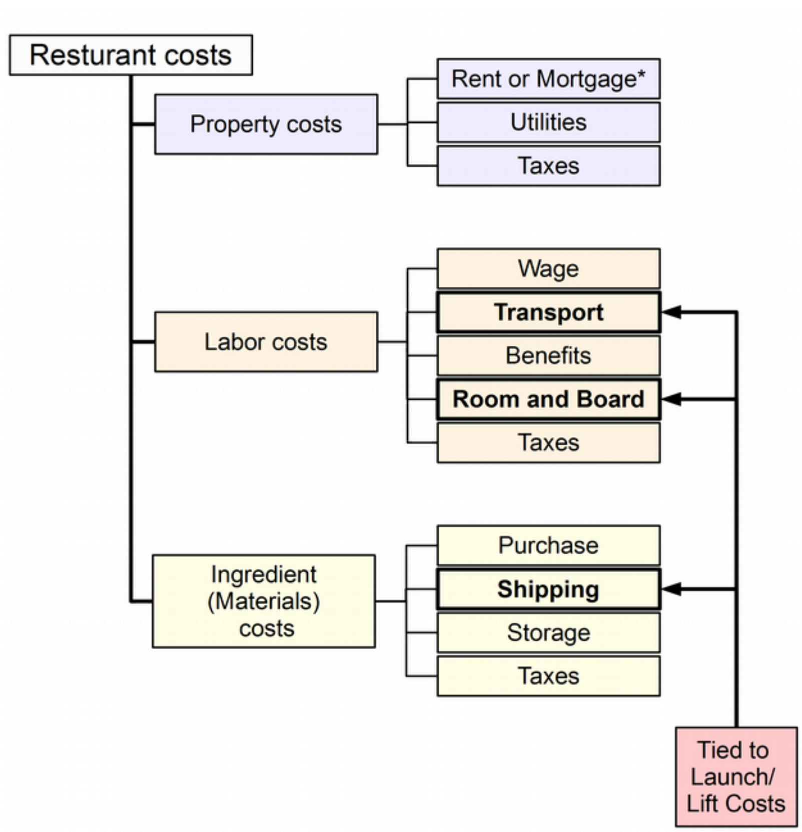

Figure 1. High level restaurant costs

Growing food closer to the point of consumption, and dealing with crew rotation (i.e. getting labor to the location for work), will eventually become keys, due to the costs of launch and lift as noted in Fig. 1. Several stages of lodging and restaurant options will occur as the space economy evolves as summarized in Table 1. below:

Table 1. Spectrum of space restaurants in space resorts/outposts/settlements.

Stage	Space Equiv	Earth Analog	Characteristics
0	ISS as of 2016, All space outposts to 2016.	Everest Base Camp	1) All food/drink is imported (from Earth). 2)Food/drink is nutrition oriented in lieu of taste. Mostly pre-prepared, dehydrated, or frozen. A little fresh fruit or or veggies. Some 3d printed. Experients in growth. 2) Cook your own (microwave, toaster oven) very rudimentary recipies at most. 3) all 0 g 4) No Luxuries, No Privacy beyond dividers.
1	Inflatable or Basic Orbital Unit/Hotel	Oil Rig, Antarctica Bases.	1)Essentially all food/drink is imported (from Earth). 2)Food/drink is targeted to customer taste, though balanced with shipping needs.Some pre-prepared, dehydrated. Many fresh foods, some frozen. Many staples (canned/dry goods). Very limited ingredient variety. Very limited local produce, some 3d printed. 3) Staff cooked, as an additional task. Simple recipies. 4) all 0 g 5) Some degree of privacy with enhanced dividers or seperate modules.
2	Beginning Space Resort	Bare bones Cruise Ship (i.e. Small boat).	1) Most food/drink is imported (from Earth). Some may be locally produced (vegitables, yeasts, spices). 2)Food/drink is targeted to customer taste, though balanced with shipping needs. Some pre-prepared, some canned or dry shipped. Many fresh foods. Good variety of ingredients. 3) Dedicated cook, served by cook or support staff. More complex recipies. 4) all 0g. 5) Guests have their own module/room. Shared Bathrooms.
3	Next Level Space Resort	Major Hotel or Luxury Cruise Ship	1) Most food/drink is imported (from Earth ***or other stations***). Many fresh foods locally produced (vegitables, fruits, yeasts, spices, legumes). Many ingredients availalble. 2)Food/drink is targeted to customer taste, though balanced with shipping needs. Some pre-prepared. Some canned/dry goods. Many fresh foods. High variety of ingredients. 3) ***Dedicated team of cooks, servers, admin.*** Complex reciepies. 4) all 0g, though maybe some very limited gravity. 5) Guests have their own module/room.Shared or seperate bathrooms.
4	Full Space Resort as part of a small settlement.	All inclusive luxury resort as part of a community. Ex; Crocodile bay CR	1) ***Food/drink is from a mix of sources, Earth, Orbital Stations, and Grown on site. Only special items from Earth.*** 2) Food/drink is targeted to customer taste. Wide variety of possible menus, ingredients. 3) Dedicated cooking staff with a master chef, dedicated service staff, and administration. Very Complex, state of the art, recipies and techniques. **Most or all staff are local.** 4) ***Some 0 g and some with partial g to 1 g.*** This may include kitchen and resturant. Multiple dining options. 5) Guests have their own module/room and bathrooms.

In order to determine trade-offs for the costs to operate a restaurant, by guest, for each stage, a menu will have to be decomposed into elements that can be sourced from in orbit from other habitats, in the hotel's own gardens/farms/machinery, and from Earth. Machinery may include synthesis using yeasts or accumulative manufacture, but it is core to this paper that most elements and entrees will be grown and harvested, then provided fresh, frozen, or dried and processed. Other work[2] indicates that while some seafood and many vegetables can be grown in orbit, meats such as fillet mignon, and spices like cinnamon, will likely be brought from Earth.

Give a hotel at a similar orbit as the International Space Station[3], or renting space on an ISS replacement[4], and farms orbiting near the same orbit, this paper will describe the costs for feeding such tourists, decomposition to source components, the costs of components given the options for supply, and examination of how costs will change given changes in costs to Low Earth Orbit (LEO) per kilogram.

II. Method

A. Assumptions

The focus of analysis here are costs affected by launch and lift as in Fig. 1, and stage as defined in Table 1. Assume taxes, insurance, electricity and other utilities, start up, and licensing fees are stable items that can be assessed as a simple percentage of costs or as a fixed cost. Analysis here also ignores real estate costs (i.e. property costs) of rent. The machinery to recycle water, and create electricity will be built into the station where the restaurant resides. Therefore, assume water and air costs are recycled in the restaurant, except as accounted for in wet mass for ingredient costs. These fixed costs are ignored because they are capital costs, and assumed largely invariant with regard to cost to orbit when compared to materials and labor, since once built the fixed costs will be amortized over long periods of time, and this paper is focusing on the costs that vary with launch and lift. Assume profit is likewise assessed as a percentage of costs, though ignored for this paper since it can be arbitrarily set based on market forces. Further biomass from guests and workers may or may not be recycled into food for labor or ingredients for recipes, and it is assumed if this recycled biomass is used, it will be fed to the crew or crops, not guests. Guests always get high quality food.

B. Equations

Modeling the costs associated with a restaurant in space is similar to modeling the costs of a restaurant on Earth. In a typical restaurant, aside from facility costs (i.e. rent, utilities), and legally required costs, all of which are represented here as C_{fixed}, core items are costs for labor, and cost for ingredients as stated before in Fig.1. These costs can be allocated to every recipe produced by the restaurant, the recipe here a serving of food for the guests, and the recipe the core element of production. Recipes in this model may or may not be grouped into meals, but meals are not used as a costing element here. Rather each guests food for the day is composed of recipes, from every cup of coffee to every snack, to every course in a meal. Therefore pricing of recipe determines the cost of food for each guest per day, and thus the costs of the restaurant are echoed in the recipe's costs. Due to the assumptions above, I will defer costs for energy to examine the remaining two recipe costs: labor and ingredient. To examine these core items, it can be said that the costs for any period of days, given a fixed number of guests, regardless of meals, is the sum of the consumption of the guest each day in recipes. Each recipe (one serving) has its own component of labor to cook and serve, and each unit of labor has some level of administrative labor. This structure is seen in Fig. 2 below.

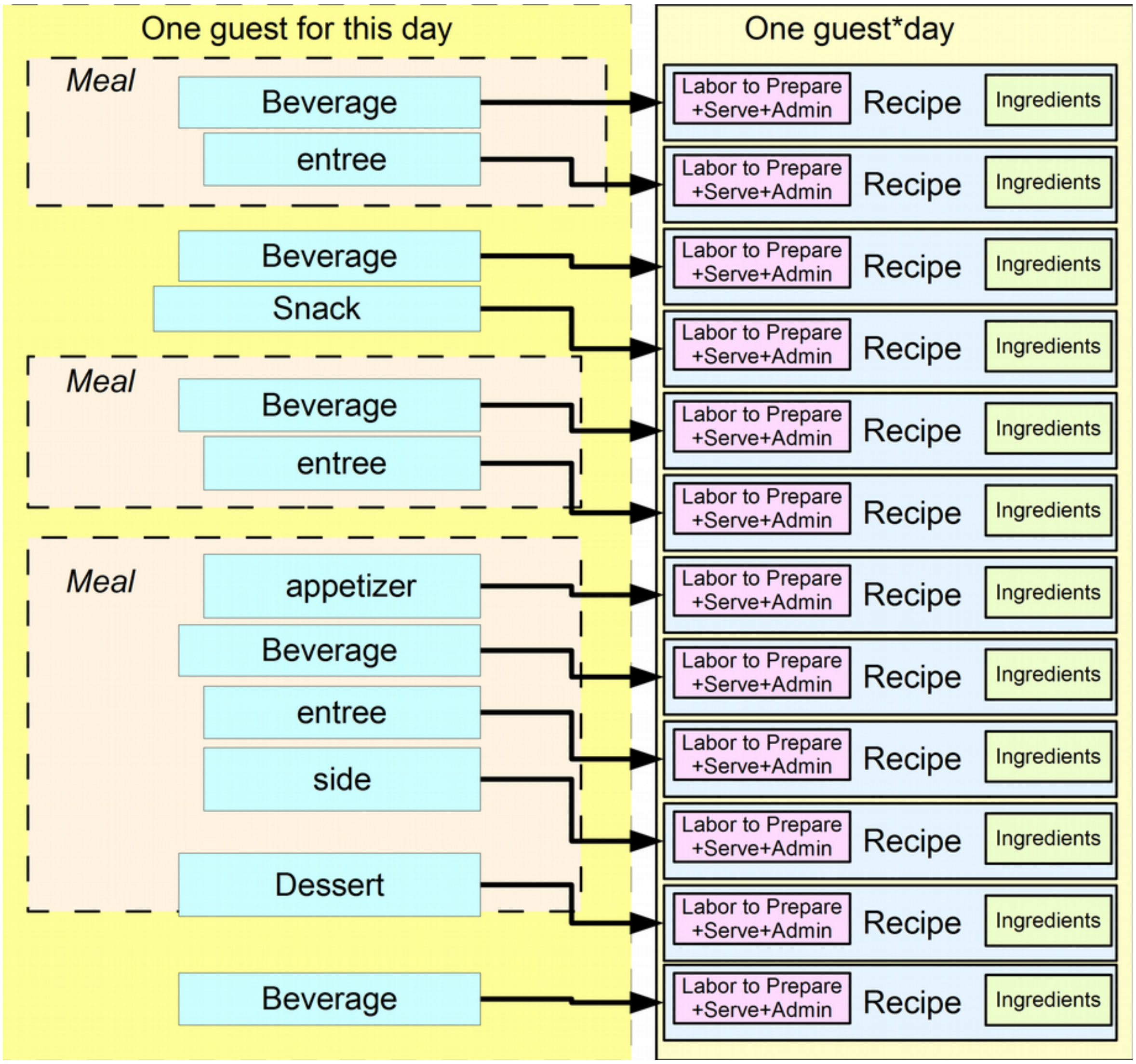

Figure 2. Recipes per guest per day.

If C_t is the cost for the time period (a set of guest*days), and C_d is the cost for each guest for each day, the sum is Eq. 1.

$$C_t = C_{fixed} + \sum_{d=1}^{\text{days in stay}} C_d \tag{1}$$

Costs for each guest for each day, C_d, is itself a sum of the costs for each recipe, C_r, consumed for that guest for that day, as in Eq. 2.

$$C_d = \sum_{r=1}^{\#\text{ recipes}} C_r \tag{2}$$

Eq. 1 can be re-expressed, using Eq. 2, to get Eq. 3:

$$C_t = C_{fixed} + \sum_{d=1}^{\#\text{ days}} \sum_{r=1}^{\#\text{ recipes}} C_r \tag{3}$$

The cost for a recipe (C_r) is sum of the cost of labor to prepare and serve the recipe, and the costs of ingredients to make the recipe. To arrive at the recipe costs, each term will need to be broken down, as in Fig. 3.

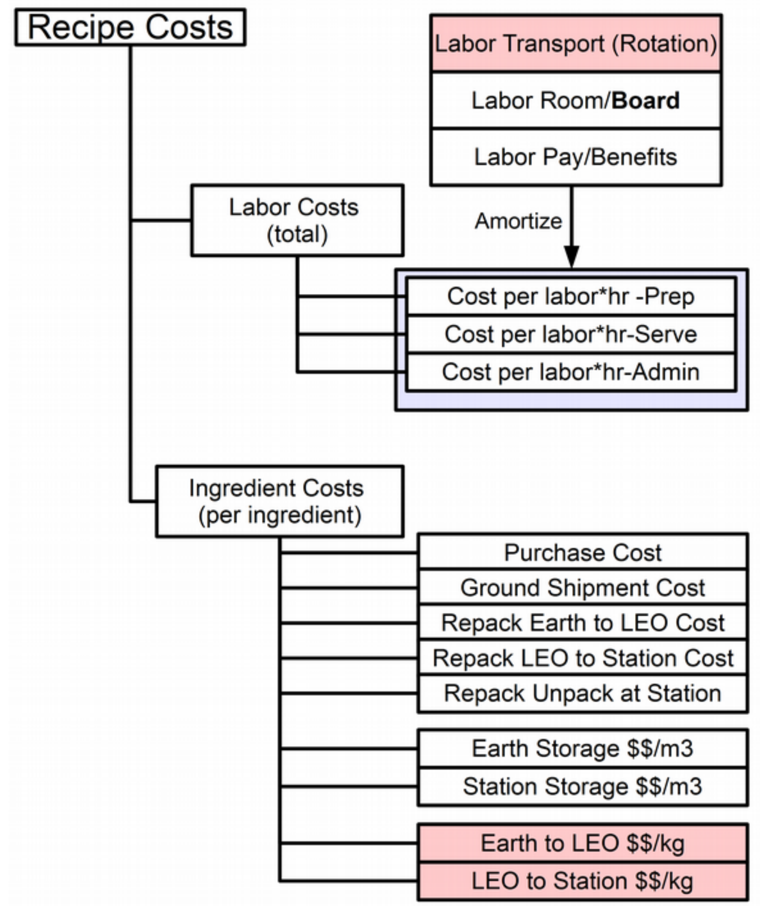

Figure 3. Components of recipe costs.

First, the labor costs term, includes the labor of cooks to prepare the recipe and servers to deliver the recipe, but also includes a portion of the costs to manage the cooks and servers. Labor cost for each type is the labor units used (in person*hours) times the cost for that type of labor (in $$ per person*hour). For preparation, serving, and management (administration), the labor cost for a recipe is:

$$\text{Labor Term} = T_{L,prep}*C_{L,prep} + T_{L,serve}*C_{L,serve} + T_{L,adm}*C_{L,adm}. \quad (4)$$

Note that in some stages, fully loaded labor cost per labor*hour may include the cost for room and board of the worker, and eventually the possible cost of dependents (in stage 4). Administration labor*hours can be assumed to be the result of summing preparation and serving labor then multiplying by a span ratio, SR, for Eq. 5:

$$T_{L,adm} = SR*(T_{L,serve} + T_{L,prep}) \quad (5)$$

Labor for each of $C_{L,prep}$, $C_{L,serve}$, $C_{L,adm}$, includes not just the wage of the employee, $C_{L,w,(prep,serve,\ or\ adm)}$ but also costs amortized ($C_{L,amort}$) over the length of the tour of the employee, and loading costs as a percentage of wages (P_{load}) , for benefits _and in some scenarios below, and room and board.

The amortized costs include: the costs to bring the employee and possibly dependents (see stage 4 in Table 1), to the restaurant and return; the costs of room and board; and the costs for benefits and other fees. All apply regardless of labor type. We need to calculate the amortized portions of labor cost, i.e. $C_{L,amort}$, by spreading out the amortizable costs over the working time of the employee. If tour length, or rotation rate, RR, is the length of time the employee will work at the restaurant, and WR is the work rate, or percentage of time that the employee is working during the tour, then costs are incurred if the employee then has to be transported to and from the restaurant, at restaurant owners expense, are also spread over the tour. Then $C_{L,amort}$ becomes the cost of travel per person to and from the restaurant from Earth or another station or colony, $C_{L,travel}$, divided by working time or (WR* RR), for Eq. 6 below:

$$C_{L,amort} = C_{L,travel}/(WR^* RR) \quad (6)$$

For adding in time-dependent costs, assume benefits and fees add a percentage, $P_{B,}$to the wage cost. Also assume since air and water are recycled, that some food mass, and very small personal mass allowance, are the only large expenses for room and board. Cost of room and board could be tied to two methods: a percentage of the sum of (cost to launch to Low Earth Orbit, C_{EtoL}, and the cost to move to a position in orbit, given Low Earth orbit, C_{LtoS}) known as launch and lift costs in this paper, or a percentage of wage. It is common on cruise ships for the cook to make an extra portion of the guest menu for the crew, and supplement this with lower cost food and drink. It might also be the case that the crew eat recycled mass from bioreactors (both guests and crew produce waste biomass), that is printed into tasteful foods. The cost for room and board is therefore somewhere between the cost of a guest, and a minimal cost of operation.

In both cases, I assume sleeping space and recreation space are very efficient for the crew, and part of the rent for the restaurant, wrapped into the real estate costs noted before.

In a best case, the cost for room and board is roughly a doubling of the wage, where the employee is consuming normally wasted excesses of ingredients or meals for the guests, supplemented with a small mass of dry foods and locally grown foods expressed as $P_{load}=1+P_B$.

Given Eqs. 5 and 6, we arrive at the loaded costs of labor of each type, a best case, in Eqs. 7a-c:

$$C_{L,prep}= C_{L,amort} + C_{L,w,prep} *(1+P_{load}) = (C_{L,travel}/(WR^* RR)) + C_{L,w,prep} * (2+ P_B) \quad (7a)$$
$$C_{L,serve}= C_{L,amort} + C_{L,w,serve} *(1+P_{load}) = (C_{L,travel}/(WR^* RR)) + C_{L,w,serve} * (2+ P_B) \quad (7b)$$
$$C_{L,adm}= C_{L,amort} + C_{L,w,adm} *(1+P_{load}) = (C_{L,travel}/(WR^* RR)) + C_{L,w,adm} *(2+ P_B) \quad (7c)$$

A worse case method is to assume each employee gets roughly 0.80 kg per meal[5] * 3 meals per day = 2.4 kg per day, or 0.1kg/hour per day per employee, in kg*tour hour, m_{pea} , as a personal food or accessory allowance, coming up with the employee. For a 180 day tour, 180 days*2.4 kg/day = 432 kg. Given water on site, this can be assumed to be a lower, partially dry, mass, of around 2kg. Given the mass of safety gear, and other gear to get a person to the station, and the mass of a person, we could assume for a worse case this doubles the travel cost per employee, so $C_{L,amort}$ =(2* $C_{L,travel}$/(WR* RR)), though this assumption works only for tours less than 180 days. As a result for tours up to 180 days, Eqs. 7d-f are applicable:

$$C_{L,prep}= C_{L,amort} + C_{L,w,prep} *(1+P_{load}) = (2^*C_{L,travel}/(WR^* RR)) + C_{L,w,prep} * (1+ P_B) \quad (7d)$$
$$C_{L,serve}= C_{L,amort} + C_{L,w,serve} *(1+P_{load}) = (2^*C_{L,travel}/(WR^* RR)) + C_{L,w,serve} * (1+ P_B) \quad (7e)$$
$$C_{L,adm}= C_{L,amort} + C_{L,w,adm} *(1+P_{load}) = (2^*C_{L,travel}/(WR^* RR)) + C_{L,w,adm} *(1+ P_B) \quad (7f)$$

The Eqs.7d-f to 180 day estimate is costly for high launch and lift costs (as represented in $C_{L,travel}$), where Eq. 7a-c case is better for low to negligent launch and lift costs. Neither is likely to be fully accurate, though both provide a basis for some estimates.

A third case includes the 2.4 kg/24hr (= m_{pea}) per employee per hour estimate, as a multiple of launch and lift costs, (C_{EtoL}+ C_{LtoS}), multiplied by RR for the tour length, then allocated across the tour working hours by dividing by WR to get Eq. 6a, which in turn this lead to more accurate, any tour length, Eqs. 7g-i.

$$C_{L,amort} = (C_{L,travel}/(WR^* RR)) + m_{pea}^*[C_{EtoL}+ C_{LtoS}]/WR \quad (6a)$$

$$C_{L,prep}= C_{L,amort} + C_{L,w,prep} *(1+P_{load}) = (C_{L,travel}/(WR^* RR)) + m_{pea}^*[C_{EtoL}+ C_{LtoS}]/WR + C_{L,w,prep} * (1+ P_B) \quad (7g)$$
$$C_{L,serve}= C_{L,amort} + C_{L,w,serve} *(1+P_{load}) = (C_{L,travel}/(WR^* RR)) + m_{pea}^*[C_{EtoL}+ C_{LtoS}]/WR + C_{L,w,serve} * (1+ P_B) \quad (7h)$$
$$C_{L,adm}= C_{L,amort} + C_{L,w,adm} *(1+P_{load}) = (C_{L,travel}/(WR^* RR)) + m_{pea}^*[C_{EtoL}+ C_{LtoS}]/WR + C_{L,w,adm} *(1+ P_B) \quad (7i)$$

Note that in Eqs. 7g-i, the m_{pea} changes as a colony becomes self sufficient, or as stage from Table 1 increases, approaching simple hourly wages for a restaurant at a permanent, self sufficient colony as stage 4.

A further method, not fully explored in this paper, would be to assume a ratio of employees to guests for the purposes of room and board, ex; 4 employees consume and live in the amount of 1 guest. This would move a term to

Eq. 2 as a multiplier, but require employees to eat whatever recipients or ingredients the guests wanted, which may not agree with their own needs.

Now for the ingredient costs. Ingredients in a recipe are typically bought in units, for example a dozen eggs. A portion of the purchased unit is used in each recipe (example, the portion may be one egg). The ingredient term, is therefore ingredient cost for a unit, C_i, multiplied by the mass used in the recipe, $m_{i,r}$, divided by the mass of the ingredient unit, $m_{i,unit}$. For all ingredients in the recipe, the ingredient term is the sum of the cost all ingredients in the recipe:

$$\text{Ingredient Term} = \sum_{i=1}^{\#\,\text{ingredients}} C_i*(m_{i,r}/m_{i,unit}) \quad (8)$$

For each ingredient unit, which has both a unit mass, $m_{i,unit}$, and a unit volume, $v_{i,unit}$, there is a multiplier for overhead cost associated with packing and shipping sensitive ingredients. Each total overhead, for mass, $O_{i,m}$, or volume,$O_{i,v}$, is the maximum of the overheads associated with the ingredient. If the ingredient is alive, and needs to be protected from temperature, pressure, radiation, and vibration (examples are a dozen fresh eggs, or a fresh banana) it will have mass overhead of $O_{alive,m}$, and a volume overhead of $O_{alive,v}$. For an ingredient with vibration or force sensitivity alone, it will have a mass overhead of $O_{vib,m}$, and a volume overhead of $O_{vib,v.}$ If it is just sensitive to temperature or radiation environmental sensitivity , it will have a mass overhead of $O_{env,m}$ and a volume overhead of $O_{env,v}$. For mass overhead, this results in Eq. 9, and for volume, Eq. 10:

$$O_{i,m} = MAX(O_{alive,m},O_{vib,m},O_{env,m}) \quad (9)$$

$$O_{i,v} = MAX(O_{alive,v},O_{vib,v},O_{env,v}) \quad (10)$$

These overheads feed the cost of a unit of an ingredient, C_i. Mass is tied to launch and lift cost, ($C_{EtoL}+ C_{LtoS}$). Volume based costs here are assumed to be tied to storage and packing costs. The cost to store an ingredient unit on Earth at the launch site until launch is $C_{store,Earth}$ and the possibly substantial cost to store an ingredient unit at the restaurant is $C_{store,Rest}$. There is also possibly a cost to prepare the ingredient for later use, which is the labor*hours times the Cost per labor*hour for cook/preparation people to ready the ingredient for later use, $T_{prep,i}*C_{L,prep}$. Added to these costs are costs by ingredient unit to: buy the ingredient at point of purchase,C_{buy}, shipping and handling of the ingredient on the ground (or via aircraft or ship) from point of purchase to launch site,C_{gndshp}, cost to repack the ingredient for launch from Earth,$C_{repack,E}$, cost to repack the ingredient unit in orbit to transfer to the restaurant, $C_{repack,LEO}$, the cost to unpack the ingredient at the restaurant once the transport is docked, $C_{unpack,Rest}$, and finally, if the ingredient is grown at the restaurant's colony or station, the cost to harvest the ingredient, C_{hvst}. Given all these costs for the unit of an ingredient, we arrive at Eq. 11.

$$C_i = m_{i,unit} * (C_{EtoL}+ C_{ltoS}) *O_{i,m} + v_{i,unit}*[C_{store,Earth}+C_{store,Rest}]*O_{i,v} + T_{prep,i}*C_{L,prep} + C_{buy} + C_{gndshp} + C_{repack,E} + C_{repack,LEO} + C_{unpack,Rest} + C_{hvst} \quad (11)$$

To calculate costs, summing from the low level ingredient unit all the way back to the cost per guest per day for all guest*days will yield cost for any period of time.

Note that where an ingredient comes from can be affect launch and lift costs. Low costs can reflect the sourcing of ingredients near the restaurant, i.e. farmed on site, or by co-orbiting farms. For example if C_{LtoS} costs 10% of the cost to LEO (C_{EtoL}) to ship food between a co-orbiting station, and 50% of the ingredients are co-orbiting station sourced, the averaged launch and lift costs. i.e. ($C_{EtoL}+ C_{LtoS}$) are 55% of C_{EtoL}. This term, ($C_{EtoL}+ C_{LtoS}$), the launch and lift costs, is the key to understanding the dynamics of costs for both labor and ingredients. Adding the labor terms in Eq. 4, and the ingredient term in Eq. 8, yields Eq. 12:

$$C_r = [T_{L,prep}*C_{L,prep}+T_{L,serve}*C_{L,serve}+T_{L,adm}*C_{L,adm}] + [\sum_{i=1}^{\#\,\text{ingredients}} C_i*(m_{i,r}/m_{i,unit})] \quad (12)$$

expanding for Span Ratio for administration:

$$C_r = [T_{L,prep}*C_{L,prep}+T_{L,serve}*C_{L,serve}+ SR*(T_{L,serve} + T_{L,prep}) *C_{L,adm}] + [\sum_{i=1}^{\#\,\text{ingredients}} C_i*(m_{i,r}/m_{i,unit})] \quad (12a)$$

Even given just Eq. 12, the cost of the recipe is a sum of cost per mass used for all ingredients (ingredient term) and the cost of labor. Given the expansions of the labor costs $C_{L,prep}$, $C_{L,serve}$, $C_{L,adm}$, in Eqs. 7, and the ingredient costs, C_i, in Eq. 11, the lift and launch costs are reflected in every recipe, resulting in a need to examine where trade-offs occur, especially in labor versus ingredient costs, as stages increase resulting in lower launch and lift costs. Assumptions, equations, and graphs were therefore used to obtain a series of estimates to examine the labor versus ingredient trade-offs for ($C_{EtoL} + C_{LtoS}$).

C. Calculations and Analysis

One high level coarse estimate, from the top level, can be made by using Eqn. 2, and Eqn. 6a above, broadly setting variables, and iterating for a sum of launch and lift costs, ($C_{etoL}+C_{LtoS}$). In all scenarios, it is assumed that the guest has declared their dining wishes ahead of time, so that ingredients go to the restaurant exactly as needed.

First, a series assumptions are needed to estimate all scenarios. Ignoring fixed costs (i.e. $C_{fixed}= 0$), and setting a 4 kg average guest*day total ingredient consumption (including packing and media), assuming a purchase cost for all ingredients of \$40/kg, with 1 kg units, and setting the sum of all non-mass costs in an ingredient to \$1, and overheads to 1. Next, assume a 4 person*hrs for labor to prep and serve the guest for that day for 8 recipes of 1 ingredient (i.e. $T_{L,prep}+T_{L,serve}=0.5$ person*hrs/recipe), with an hourly rate of $C_{L,w,(prep,\ serve,admin)}$ =\$150 per person*hr. Let the percentage of benefits be 50% (i.e. P_B). Set WR=30% (roughly an 8 hr work day). Set span ratio to one administration hour per eight serve+preparation hours (i.e. SR=1/8).

Further, all scenarios need a per person travel cost as a multiple of launch and lift costs, $C_{L,travel}$. We can get a rough estimate of ($C_{EtoL}+C_{LtoS}$) by looking at the published pricing for the Falcon 9[6], of \$62M for 22,800kg to LEO[7], and 8,300kg to GTO[6]. Assume the lift to the restaurant is roughly 18,000 kg, not counting vehicle mass (and no-crew module). If the delivery vehicle is a CRS Dragon w/trunk, a payload mass of 6,000 kg[6]. The travel cost can be estimated to be \$20M per seat in the near future, by a quote from SpaceX in 2014[8]. Assume a pilot and co-pilot/staff, so five restaurant crew are lifted per trip. If the 7 total people replace 3000 kg, i.e. 429kg/crew, and 5/7 of the crew is restaurant staff, then the travel cost per kg equivalent of the staff is 7*429/5 = 600 kg/person, which is m_{TtoC}. Assuming return is free, we can get this equation:

$$C_{L,travel} = m_{TtoC} * (C_{EtoL}+C_{LtoS}) \tag{13}$$

Using Eq. 13, $C_{L,travel}$ = 600 kg/person * ($C_{etoL}+C_{LtoS}$) for all scenarios.

For Scenario 1, use RR=180 days. Using Eqs. 7d-f, we express $C_{L,(prep,serve,adm)}$= (2*$C_{L,travel}$ /(WR* RR)) + $C_{L,w,(prep,serve,adm)}$ * (1+ P_B) = (2*600* ($C_{EtoL}+C_{LtoS}$) / (30%* 180*24)) + \$150* (1+ 50%) = (1200*($C_{EtoL}+C_{LtoS}$) / 1296)+225. The labor term in Eq. 6a, knowing the rates for all staff types are the same, then becomes like so: [$T_{L,prep}$*$C_{L,prep}$+$T_{L,serve}$*$C_{L,serve}$+ SR*($T_{L,serve}$ + $T_{L,prep}$) *$C_{L,adm}$] = [($T_{L,prep}$+$T_{L,serve}$+ SR*($T_{L,serve}$ + $T_{L,prep}$)) *$C_{L,w,(prep,serve,adm)}$]= [(0.5 person*hrs/recipe+ 1/8*(0.5 person*hrs/recipe)) *$C_{L,w,(prep,serve,adm)}$] = 0.56 * $C_{L,w,(prep,serve,adm)}$= 0.56 * (1200*($C_{EtoL}+C_{LtoS}$) /1296)+225. To account for the ingredient term, as in Eq. 8, a series of assumptions and conversions are rolled in. Next, we will ignore any per ingredient prep time,and given 4kg for 8 recipes, each recipe's ingredient mass is 0.5kg. Using Eq. 11, and givens: C_i = $m_{i,unit}$ *[C_{EtoL}+ C_{LtoS}] *$O_{i,m}$+$v_{i,unit}$*[$C_{store,Earth}$+$C_{store,Rest}$]*$O_{i,v}$+$T_{prep,i}$*$C_{L,prep}$+ C_{buy}+ C_{gndshp} +$C_{repack,E}$ + $C_{repack,LEO}$ + $C_{unpack,Rest}$ + C_{hvst} . All non mass terms other than purchase are assumed to be \$1, so C_i = 1*[C_{EtoL}+ C_{LtoS}]*1+\$1+\$40 . Combined, the ingredient term becomes: 1* C_i*($m_{i,r}$/$m_{i,unit}$) = ([C_{EtoL}+ C_{LtoS}]+41)*0.5kg. All these reductions lead to Equation 12a of C_r = [0.56 * (1200*($C_{EtoL}+C_{LtoS}$) /1296)+225] + ([C_{EtoL}+ C_{LtoS}]+41)*0.5kg. C_d, cost per guest per day, then becomes for one day, 8 recipes: C_d = 8*{[0.56 * (1200*($C_{EtoL}+C_{LtoS}$) /1296)+225] + [([C_{EtoL}+ C_{LtoS}]+41)*0.5]}.

In a spreadsheet, iterating for ($C_{etoL}+C_{LtoS}$) (i.e. launch and lift costs) we get the following graph of costs per guest per day for Scenario 1:

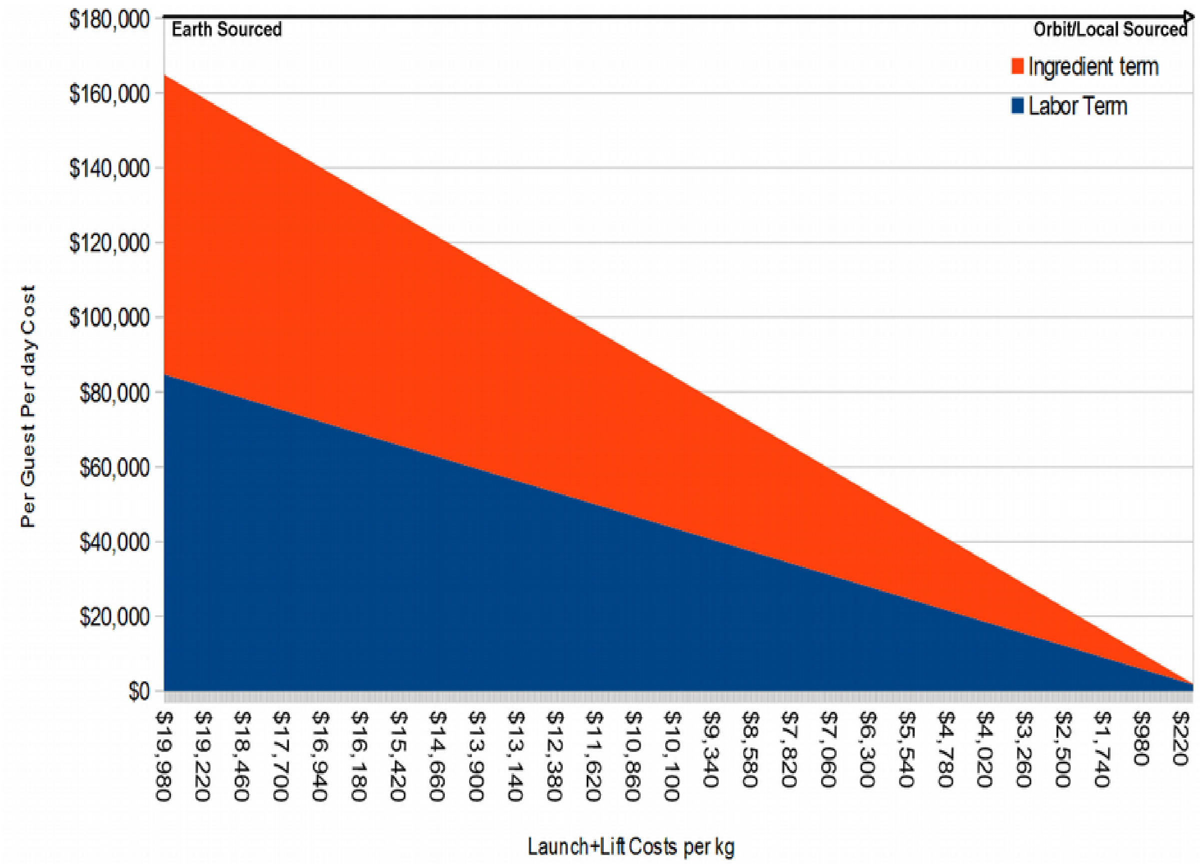

Figure 4. Scenario 1: 180 day rotation, using Eqs. 7d-f.

The ingredient portion starts as nearly equal to the labor term , but as $C_{EtoL}+C_{LtoS}$ approaches 0, the labor term becomes a majority of the costs.

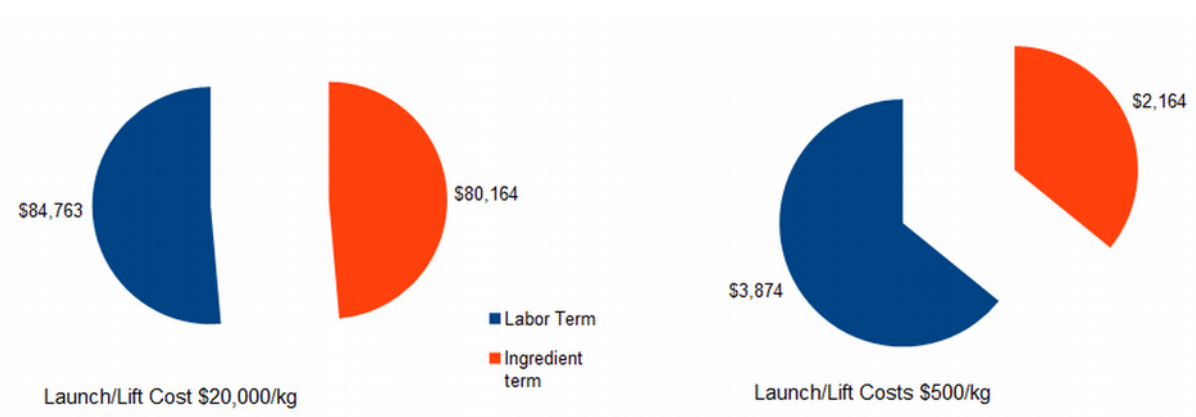

Figure 5. Scenario 1: 180 day rotation, Eqs. 7d-f, labor vs ingredient costs.

Clearly, rotation strategy of employees becomes very important to amortize travel costs over as long as period as possible. It ia also important to feed employees foods from on site to limit the mass that must be brought with the employees. Since Eqs. 7d-f is limited to 180 days, we need to use other equations for longer terms.

A second scenario uses Eqs. 7g-i, the same givens as above, and setting m_{pea} = 0.1 kg/hr. Set the tour length to a year, i.e. RR=365*24. As above, $C_{L,travel}$ = 600 kg/person * ($C_{EtoL}+C_{LtoS}$) $/kg. Again as above the ingredient term = ([C_{EtoL}+ C_{LtoS}]+41)*0.5kg. Using Eq. 6a, $C_{L,amort}$ = ($C_{L,travel}$ /(WR* RR)) + m_{pea}*[C_{EtoL}+ C_{ltoS}] / WR = (600*($C_{EtoL}+C_{LtoS}$) /(30%* 365*24)) + (0.1)*(C_{EtoL}+ C_{LtoS})/30% = (600 /(30%* 365*24))+(0.1/30%))*($C_{EtoL}+C_{LtoS}$) =

$0.56*(C_{EtoL}+C_{LtoS})$. Next, $C_{L,(prep,serve,adm)} = C_{L,amort} + C_{L,w,(pre,serve,adm)} *(1+P_{load}) = 0.56*(C_{EtoL}+C_{LtoS}) +150*(1+50\%) = 0.56*(C_{EtoL}+C_{LtoS}) +225$. This leads to the Labor term in Eq. 6a to be $[(T_{L,prep}+T_{L,serve}+ SR*(T_{L,serve} + T_{L,prep}))* C_{L,w,(prep,serve,adm)}]= [1.125*(0.5) *(0.56*(C_{EtoL}+C_{LtoS}) +225)] = [0.56*(0.56*(C_{EtoL}+C_{LtoS}) +225)]$. Combining labor and ingredient terms: $C_r = ((C_{EtoL}+ C_{LtoS})+41)*0.5 +(0.56*(0.56*(C_{EtoL}+C_{LtoS}) +225))$ again this is linear with respect to launch and lift costs. As above, $C_d = 8*((C_{EtoL}+ C_{LtoS})+41)*0.5 +(0.56*(0.56*(C_{EtoL}+C_{LtoS}) +225))$.

Graphing as above:

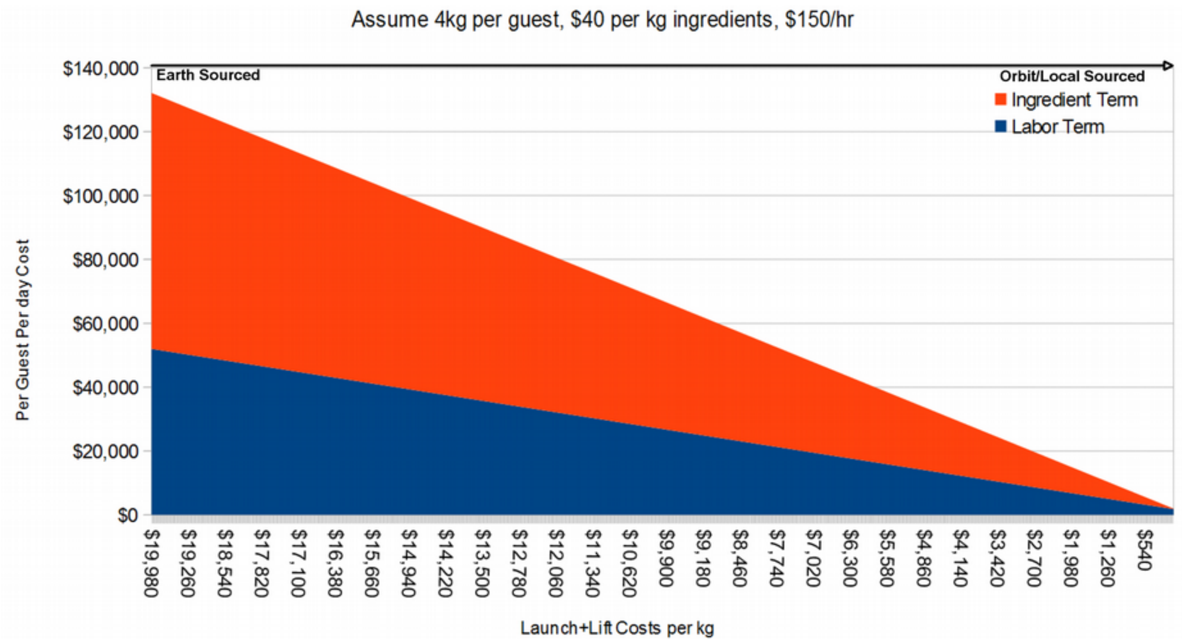

Figure 6. Scenario 2: 365 day rotation rate, using Eqs. 7g-i.

Given the longer rotation rate of 365 days, but given the accounting of Eqs. 7g-i, the costs are similar, though labor is less then in scenario 1 which uses Equations 7d-f, and has a 180 rotation.

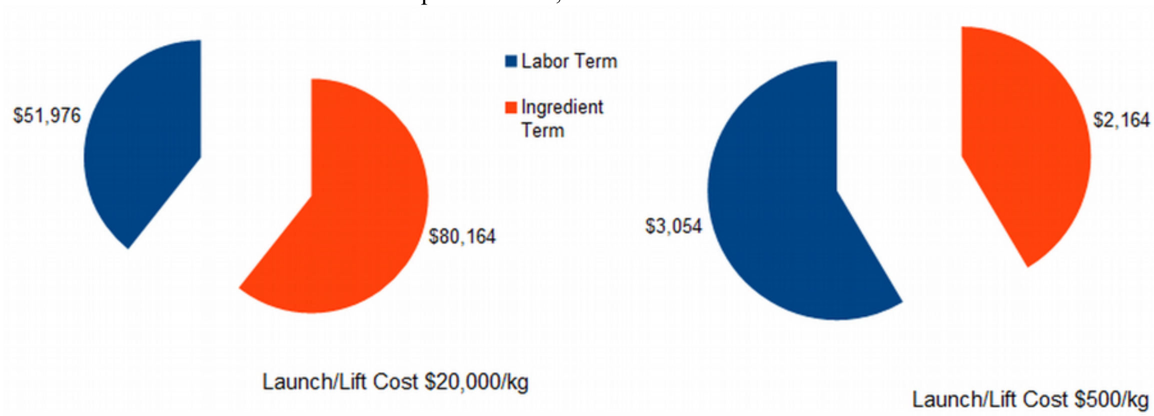

Figure 7. Scenario 2: 365 day rotation, labor vs. ingredient costs.

Modeling for dependents is another scenario, Scenario 3. Assume two dependents, the same one year tour, each dependent gets the same allowance in m_{pea} but do not work in the restaurant. This changes m_{pea} to 0.3kg/hr. Calculating an in scenario 2, Using Eq. 6a, $C_{L,amort} = (C_{L,travel} /(WR* RR)) + m_{pea}*[C_{EtoL}+ C_{LtoS}]/WR =$ $(600*(C_{EtoL}+C_{LtoS}) /(30\%* 365*24)) + (0.3)*(C_{EtoL}+ C_{LtoS})/30\% = (600 /(30\%* 365*24))+(0.3/30\%))*(C_{EtoL}+C_{LtoS}) = 1.23*(C_{EtoL}+C_{LtoS})$. Next, $C_{L,(prep,serve,adm)} = C_{L,amort} + C_{L,w,(pre,serve,adm)} *(1+P_{load}) = 1.23*(C_{EtoL}+C_{LtoS}) +150*(1+50\%) = 1.23*(C_{EtoL}+C_{LtoS}) +225$. This leads to the Labor term in equation 7a to be $[(T_{L,prep}+T_{L,serve}+ SR*(T_{L,serve} + T_{L,prep}))* C_{L,w,(prep,serve,adm)}]= [1.125*(0.5) *(1.23*(C_{EtoL}+C_{LtoS}) +225)] = [0.56*(1.23*(C_{EtoL}+C_{LtoS}) +225)]$. Combining labor and ingredient terms: $C_r = ((C_{EtoL}+ C_{LtoS})+41)*0.5 +(0.56*(1.23*(C_{EtoL}+C_{LtoS}) +225))$ again this is linear with

respect to launch and lift costs. As above, $C_d = 8*((C_{EtoL}+ C_{LtoS})+41)*0.5 +(0.56*(1.23*(C_{EtoL}+C_{LtoS}) +225))$.
Graphing as above:

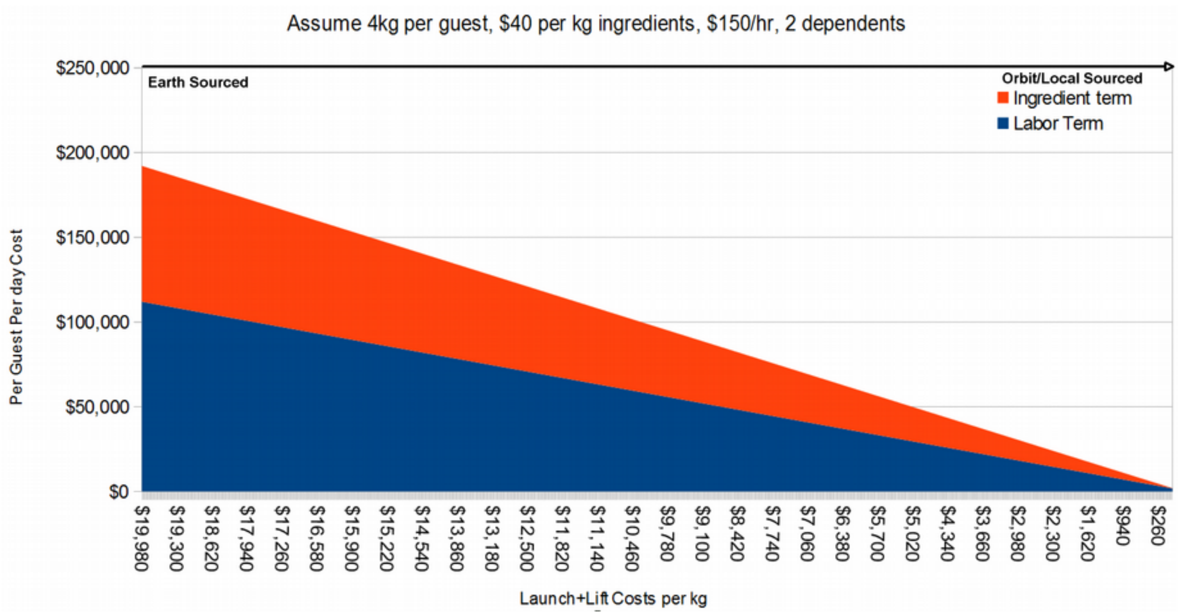

Figure 8. Scenario 3: 365 day rotation with 2 dependents, Eqs. 7g-i.

The extra mass allocation in m_{pea} for the dependents almost doubles the cost of labor, but long tours will require accompaniment to retain senior cooks, servers, and administrators, given a colony that supports the restaurant and has gravity. That said, Scenario 3 will likely only occur when launch and lift costs are lower than current.

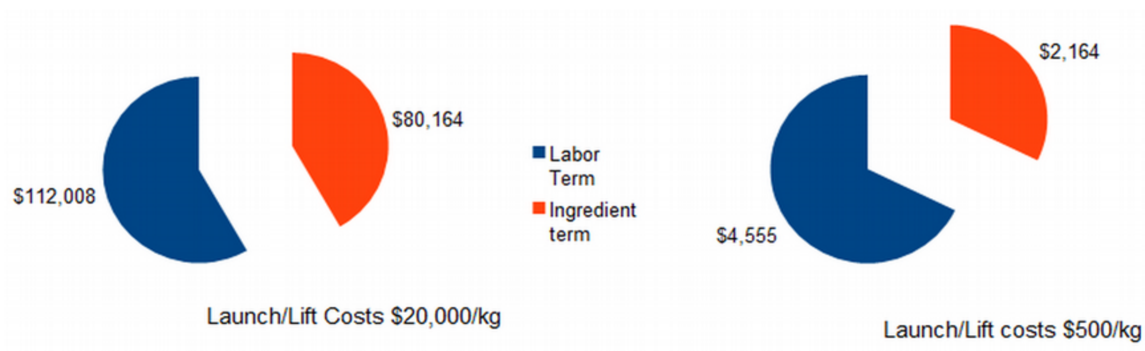

Figure 9. Scenario 3: 365 day rotation, 2 dependents, labor vs. ingredient costs.

A further implication is that as long as launch and lift costs are fairly high relative to the demand for space hotels and restaurants, it would be far cheaper to prepare food on Earth then ship it packaged with the guests to the hotel, to avoid labor costs, or to use robots to cook and serve to limit labor on station. Preparing food before shipment, if the food mass is the same as the ingredient mass, drops the labor term to a trivial level compared to the ingredient costs, as can be seen in the graph below:

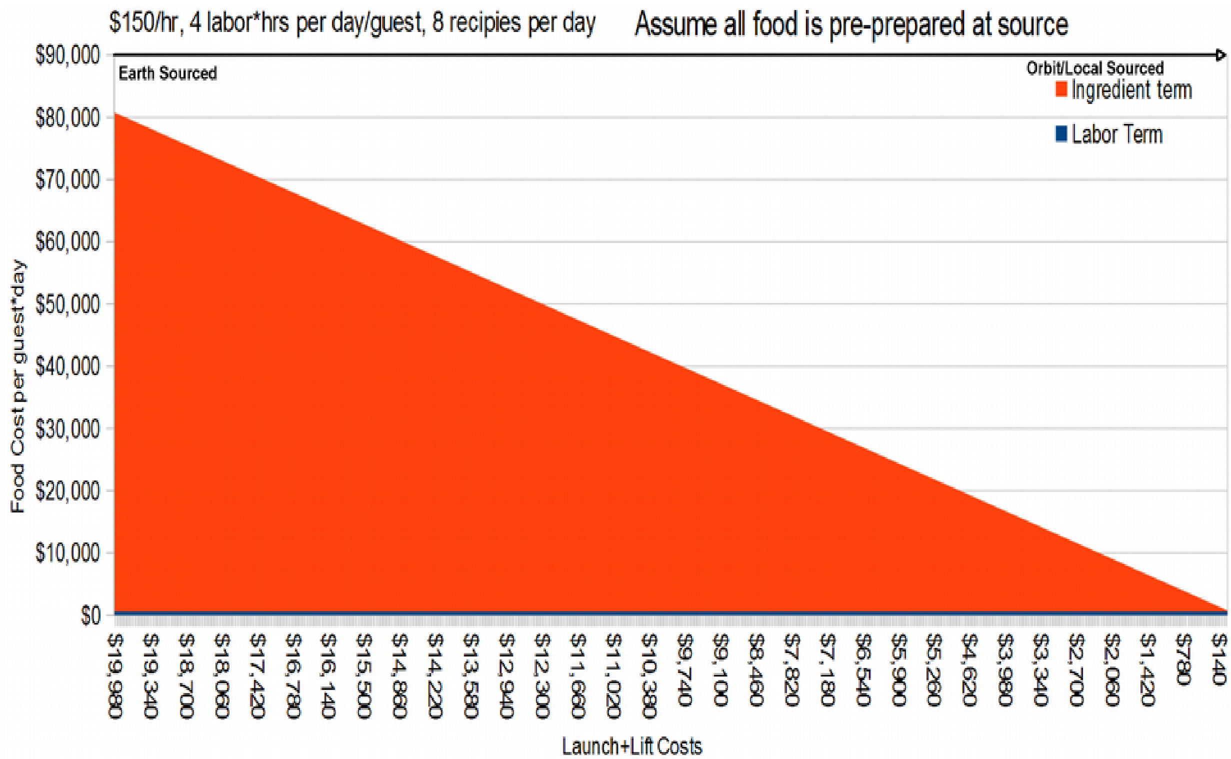

Figure 10. Scenario 4: Assuming all food is prepared at source then shipped to the station packed.

Even doubling the wage for Earth-based labor, the labor term is still trivial compared to launch and lift costs for the food mass until launch costs drop well below $1000/kg.

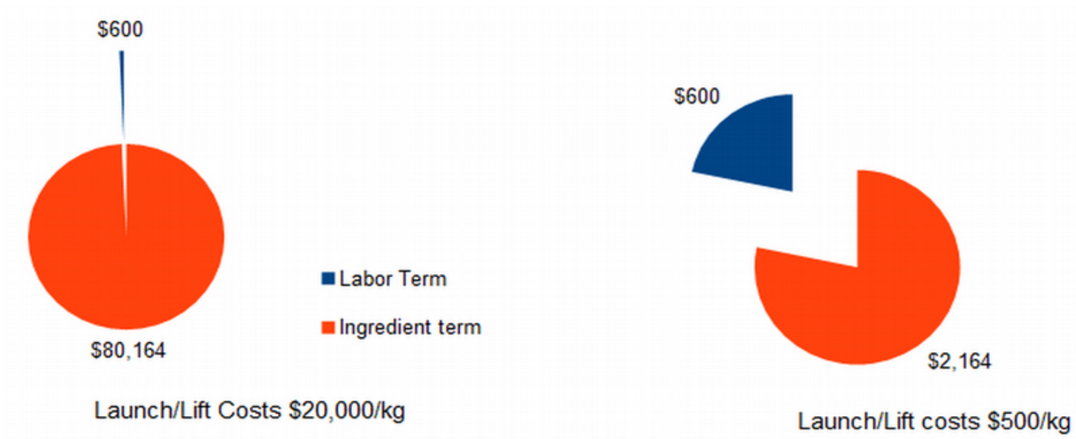

Figure 11. Scenario 4: All food is prepared at source, labor vs. ingredient costs.

The fourth scenario is the full realization of each guest's menu fully planned before they arrive. This does not allow for variation, unless the restaurant can pool an excess of ingredients among many guests, or have the crew eat the excess for short shelf-life items. The reverse of this could be true for a colony resort as in stage 4, where all the ingredients are lifted to the outpost (exotic to the colony residents), but the restaurant staff lives permanently at the colony, also lowering the labor cost to straight hourly rates.

Just like flat labor lowers menu costs, the same is true for ingredients. If all ingredients are locally sourced, even if five times the cost per kg, and all the labor is lifted in to prepare the food, the result is the reverse of the last graph:

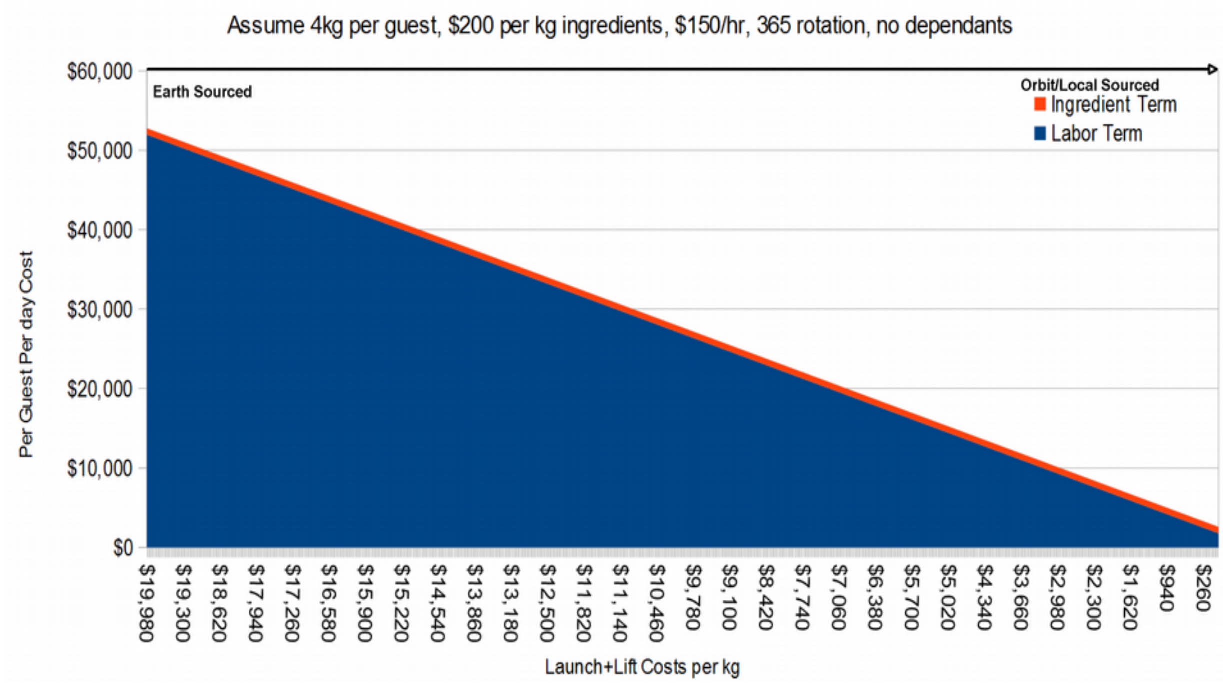

Figure 12. Scenario 5: Ingredients all locally sourced to restaurant, all restaurant labor lifted in.

Labor again is the significant term, and this fits a scenario similar stages 3 or 4, where all the restaurant labor is not from the colony, while all the food is from the colony. This is the case for stage 3 resorts on Earth, where the restaurant staff may be very highly skilled, or all an existing team, but are tenants at a resort owned and operated by a local group, and the local group sources local foods.

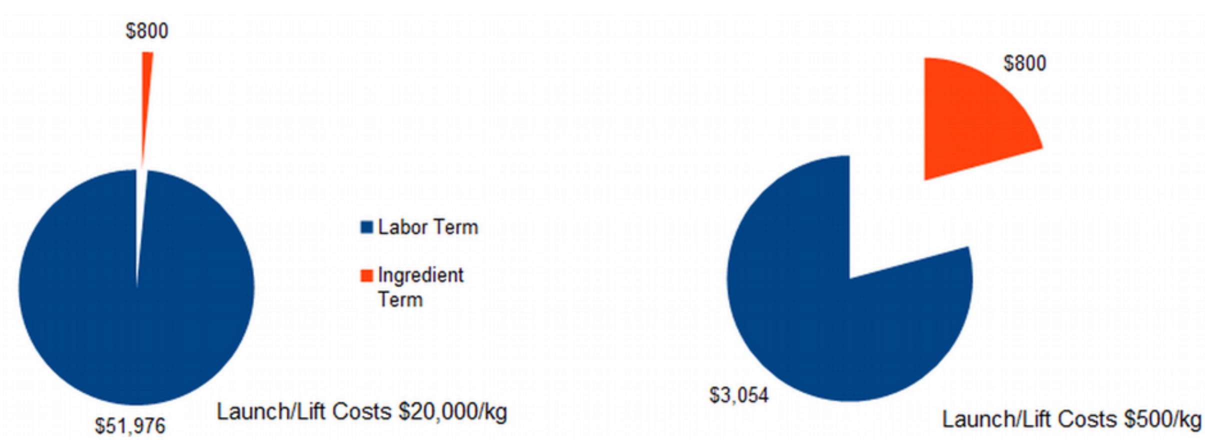

Figure 13. Scenario 5: Ingredients all locally sourced to restaurant, and all restaurant labor lifted in. Labor vs. ingredient terms.

III. Results

Sources are everything. Launch and lift are shown in all scenarios to contribute to both labor and ingredient costs. A key finding was that the rotation costs for labor, under current and near future cost conditions, are a major driver of costs for operations in a space restaurant. Associated with costs tied to tour length, is the cost to feed the crew, even if fed largely pre-processed and dried foods shipped with them. Tour length, i.e. rotation rate, is required to amortize the costs of travel to and from the restaurant for the crew. The tour length can be extended in gravity, and approaches a foreign tour or military change of station model, but in zero-g tour length is more limited to ISS tour lengths to date, limiting the ability to spread out high launch and lift costs.

Where ingredients are sourced and prepared is also key. Ingredients that do not require lift from Earth drop costs substantially. Likewise, if the labor does not have to be lifted in, the costs drop as well.

As stage increases, the sources of ingredients and labor result in lower use of launch and lift costs, bringing the overall meal cost per guest per day lower in all scenarios. Lowering ingredient costs can compensate for higher labor costs from rotation to a point, but there is a balance between labor and ingredient terms affected by sources for labor and ingredients, with the bulk of the costs shifting from labor to ingredient based on conditions in the scenario. As in stage 4 in Table 1, local sourcing both ingredients and labor bring costs to lower levels, even if ingredients are costly to grow, and even if wages are very high.

IV. Conclusion

The estimation in the paper is just a beginning and the coarse analysis will need to be followed by the inclusion of real foods and real menus, with complex recipes and real world preparation times. Many assumptions in this paper, while less than real, provide a hint of the costs to operate a restaurant in space. Well-healed visitors might very well be willing to pay $200,000 or more per day for food and service (as seen in the scenarios above for high launch and lift costs), even given zero-g eating challenges[9], especially given the likely $20,000,000 cost per person to get to the restaurant, and several million dollar a night cost for a room. This work, combined with other efforts to examine LEO economics[10] may be used to determine strategies for commercializing space. Further work will expand the modeling of costs, including specific ingredients and menus using a simulator.

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