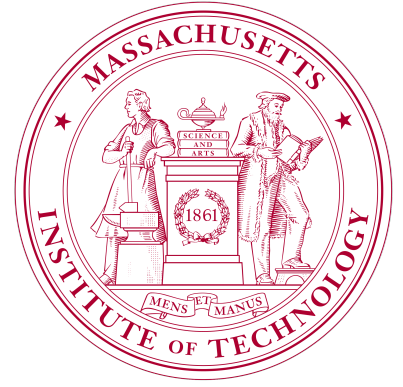


Final Paper



Cruise Ship Conversion into Affordable Housing

An investigation into the utility and feasibility of converting a cruise ship into an affordable housing community.

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Course: 2.704, Projects in Naval Ship Conversion Design

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Executive Summary

The United States, and especially its coastal cities, is facing an affordable housing crisis. Nearly 7 million United States citizens face unreliable access to affordable housing. In certain metropolitan regions, rent expenses exceed 40% of the median resident's gross income. Thus, alternative methods are required in order to narrow this disconcerting supply-demand gap.

As a result of the 2020 coronavirus pandemic, the cruise industry was forced to significantly curtail operations. This development, coupled with the increasingly stringent emissions standards levied by various environmental organizations, has placed a large supply of cruise ships on the market to be sold, or simply discarded outright. This conversion project assessed the utility and feasibility of converting a decommissioning cruise ship into an affordable housing community, with the stated requirements of providing affordable, dignified, and desirable housing on a vessel that could potentially be relocated.

A baseline cruise ship variant was selected based on criteria derived from the sponsor requirements. A corresponding 3D model was used to reflect weight change estimates and evaluate the vessel's performance against hydrostatics and stability criteria. 2D deck plan layouts were used as the basis for arrangement modifications. In total, the design proposed 246 affordable housing units following a mixed-income model that were able to accommodate approximately 350 people. The remaining decks were modified to provide all the additional amenities, facilities, and furnishings deemed necessary in order to provide an overall desirable living space. To provide the major utilities required for onboard living (*i.e.* electricity, water, sewage), significant but essential investments in pierside and shipboard infrastructure and equipment upgrades were analyzed and proposed to allow the cruise ship to connect to the city's power, water, and waste distribution systems on a permanent basis.

Cost estimates for all aspects of the conversion process were determined using comparable historical data and subject matter expert (SME) input. Capital costs including acquisition and refurbishment were assumed to be covered through various governmental funding mechanisms which already exist for affordable housing ventures. The expected annual rent revenue was predicted to fall just short of the total annual operational costs. This deficit could be accounted for with a marginal increase in additional public funding or slightly more favorable utility discount rates.

This project determined that the conversion of a cruise ship into an affordable housing community is feasible, and offers crucial advantages over comparable land-based approaches. The elimination of new construction, the existing habitable arrangements, and the availability of large-volume spaces for amenities suggest a compelling candidate to creatively address the affordable housing shortage besetting scores of cities and millions of citizens across the country. Future research and analysis are recommended to address the following key areas: comprehensive reviews of relevant regulations, zoning laws, and safety codes; detailed space and engine room analyses requiring high-fidelity models and drawings; corrosion control and periodic maintenance strategy; alternative energy supplementation to reduce utility cost.

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1. Project Overview

1.1 Introduction

Many large metropolitan areas have a greater demand for affordable housing than supply. In the U.S. alone there are 7 million renters whose income necessitates access to affordable housing, but this housing does not exist for them[14]. Without adequate affordable housing, the growth of Gross Domestic Product (GDP) slows and the economy suffers. According to research, the lack of sufficient affordable housing “costs the American economy about \$2 trillion a year in lower wages and productivity[15]”. Thus, alternative methods for addressing this problem are required in order to narrow this disconcerting supply-demand gap. Since the onset of the 2020 coronavirus pandemic, many cruise ship companies have been forced to significantly curtail operations. Consequently, this placed a large supply of cruise ships on the market to be sold, or simply discarded outright. In 2020 alone the amount of scrapped steel from cruise ships totalled 963,577 tons[2].

Unsurprisingly, many highly populated areas in need of more affordable living options reside next to bodies of water. In fact, the three cities with the largest affordable housing deficits in the United States are New York, NY, Los Angeles, CA, & Miami, FL[16]. Therefore, the idea has been proposed to turn a cruise ship from temporary, resort-style living quarters into temporary or even full-time residences.

Initial investigation into the idea of cruise ship conversion to affordable housing revealed previous explorations into the concept but no full-fledged efforts to actually reify the concept. The architecture firm CallisonRTKL (CRTKL) proposed the idea to address the affordable housing crisis in Miami in a report released in 2022[17]. In that rendering, a portion of the ship would be retrofitted with a parking garage and interior courtyard to permit natural lighting and plants.

In 2019, Oakland City Council President Rebecca Kaplan proposed the cruise ship to affordable housing conversion idea in order to provide housing for up to 1,000 people in her city where homelessness rates had spiked 47% in the preceding two years[18]. Although the Port of Oakland ultimately proved to be an untenable docking option due to federal regulations, the idea nonetheless gained traction with many residents of the city who wished to address the mounting social and public health issue.

Four years ago, Portland, Maine resident Kenneth A. Capron applied for a \$250,000 grant through the Robert Wood Johnson Foundation in order to study the feasibility of docking a cruise ship to address his city’s homelessness crisis[19]. At the time of his grant proposal, the city had a waiting list of 1,123 families in need of low-income housing. His study aimed to analyze the purchase point ranges, the cost of refurbishing the ship to make it ready for housing, and what sort of population base the ship would best serve (*i.e.* mixed income residents, low-income workers, the unhoused, or some combination thereof).

Furthermore, although the idea of dedicated afloat housing is relatively new, the practice of temporary housing in times of need (*e.g.* natural disasters), is not. In fact, the U.S. Navy has lent such aid in the past. In October 1989 the USS PELELIU



Figure 1: Discarded cruise ships at a ship breaking yard in Aliaga, Turkey.

(LHA 5) was sent to San Francisco to provide temporary housing for much of the city’s homeless population following the Loma Prieta earthquake[20]. Cruise ships specifically have also been used for this purpose. Three Carnival cruise ships provided relief for those recovering from Hurricane Katrina, and the Holland America Line MS *Volendam* provided temporary residences for Ukrainian refugees following the Russian invasion of Ukraine in May 2022[21][22].

1.2 Study Objectives

The objective of this conversion project is to analyze and determine the feasibility of converting a cruise ship into a viable affordable living space. Key areas of study were identified which directed the research and design process. These insights are provided below.

Key Insights

- *Arrangements.* Determine what major spaces and equipment need to be removed or modified, and what needs to be retained, in order to support conversion to an affordable housing community.
- *Habitability.* Determine the major design decisions and considerations necessary to convert the existing hotel-style cabins into apartments suitable for longer-term living.
- *Support Systems.* What pier-side and shipboard infrastructure and equipment needs to be put in place or upgraded (with respect to shore power, water, sewage etc.) to support long-term docking of this type of vessel? How will these additional costs be accounted for?
- *Cost.* Determine the affordability of purchasing a cruise ship from the parent company. Determine the affordability of the overall conversion and refurbishment process. Will it be feasible to establish a rent revenue stream that remains affordable while covering all annual operational and support costs? When all costs are considered, how does this proposal perform against a comparable land-based apartment complex?

1.3 Customer Requirements

The project sponsor did not provide specific customer requirements with respect to baseline cruise ship specifications, expected housing accommodations, per-unit cost, or overall conversion cost. Instead, a more holistic approach was adopted by the sponsor wherein the driving motivation was to provide “affordable, dignified, and desirable living” to address the affordable housing crisis besetting many American cities today.

Beyond that, there were a few strict requirements placed on the final design:

The converted design shall retain the ability to be “relocatable” to a certain extent. This requirement was issued not only to address the scenario of an extreme weather event requiring undocking and sortie, but also to address permanent site relocation due to potential untenable increases in docking lease prices at the origin site. The project sponsor described this requirement through four levels of increasing complexity and capability as follows, the full details of which are provided below.

Level I. Ability to transit the vessel across the harbor. Short transit time and distance permits accurate weather and tide predictions prior to the movement evolution, so intact stability requirements are less stringent. Self-propulsion not required.

Level II. Ability to transit the vessel to some other location along the same reference seaboard. For example, if the original host location were somewhere in Boston, the vessel would be able to be transported to some other port along the United States eastern seaboard. Although the transit would be longer than the Level I scenario, it would still be short enough to permit accurate weather and tide predictions prior to the movement evolution. Self-propulsion not required.

Level III. Ability to transit the vessel across the open ocean, possibly to an international location. Given the longer timescale and distances assumed in this scenario, accurate weather cannot be assumed *a priori* and therefore stricter stability requirements must be invoked. Self-propulsion not required.

Level IV. Ability to transit the vessel anywhere in the world organically. Self-propulsion required.

Level I relocatability was deemed mandatory by the project sponsor, and thus was treated as the requirement threshold. Level II was deemed highly desirable, and thus was treated as the requirement objective. Levels III and IV were recognized as generally desirable goals, but were not considered further throughout this conversion study.

Analysis of these baseline requirements yielded derived requirements, or the requirements that need to be met so that the customer requirements are achieved. The itemized list of given requirements with their derived requirements is as follows:

1. The per-month base unit price must be affordable based on the widely accepted “affordable housing” definition, wherein the occupant is paying no more than 30% of gross income for housing costs, including utilities[23].
 - 1.1 Cost comparison and determination is dependent on geographic region; therefore, a specific city and port will need to be used so the values for per-unit pricing have a reference.

- 1.2 The final proposal must be comparable to housing complexes built on land for the same target population.
2. The design shall have a primary and backup source of power, and shall maintain at least some portion of the onboard electrical power and distribution capability in order to provide power while being relocated (disconnected from shore power).

1.4 Major Assumptions

The following assumptions served as the entering arguments for the actual design decision, conception exploration, and concept development phases of the project. They were informed by the initial research conducted at the beginning of the conversion study, and were influenced primarily by common feedback received from subject matter experts (SME), the project sponsor, and the course instructors.

Capital Cost Funding. The venture has the full backing and approval of city and state governments such that relevant housing grants and subsidies would be provided to finance all of the upfront, capital fixed costs. This includes cost of vessel purchase, initial refurbishment and modification costs, and cost of any initial pier infrastructure upgrades to support the converted cruise ship.

Regulatory Approval. Any and all requirements and regulations that would need to be waived, modified, or approved by city housing authorities, the United States Coast Guard, relevant ship class societies, and any other relevant entities have been addressed as necessary.

Service Life. The average service life of a well-built and well-maintained cruise ship is approximately 30 years. However, this vessel will be docked in-port at all times except for the rare circumstances requiring sortie or permanent relocation, for which self-propulsion will still not be required. Because of the drastic narrowing in operational profile, the assumed projected service life of the chosen vessel, after conversion, will be an additional 30 years. This is driven almost entirely by the structural integrity of the hull and ship internals.

1.5 Information Resources

Sponsor

CDR (retired) Michael Bosworth, USN, is the sponsor for this project. He is a 1976 graduate of the United States Naval Academy and a 1985 graduate of the MIT 13A (now 2N) program. He spent the first half of his career in the Navy, and the second half of his career in the naval civil service, mostly at NAVSEA. His last tour was at Naval Ship Warfare Center (NSWC) Carderock, where he served as the Director of the Center for Innovation in Ship Design (CISD). Since retiring in June 2022, he serves as a consultant for a variety of enterprises. Relevant to ship design and conversion, he provides engineering consulting support to NAVSEA via AOC Incorporated, a 20-employee company specializing in early concept surface ship design and Research and Design (R&D) program management.

The Team

Avi Chatterjee

LT Avi Chatterjee graduated from the United States Naval Academy in May 2015 with a Bachelor of Science degree in Physics. Upon commissioning, LT Chatterjee was assigned to the USS ROSS (DDG 71) where he served as the Operations Intelligence Division Officer. LT Chatterjee then attended Nuclear Power School and Prototype training in Charleston, South Carolina from June 2017 to July 2018. He was assigned to the USS JOHN C STENNIS (CVN 74) where he served as the 2 Plant Reactor Mechanical Division Officer and 1 Plant Station Officer. LT Chatterjee then served as the assistant to the Deputy Project Superintendent during USS TRUMAN's (CVN 75) 2020-2021 Extended Carrier Incremental Availability (ECIA) at Norfolk Naval Shipyard (NNSY).

Jason Webb

LT Jason Webb graduated from Dallas Baptist University in May 2013 with a Bachelor of Science degree in Mathematics. Upon commissioning, LT Webb attended Nuclear Power School and Prototype training in Charleston, South Carolina from December 2013 to July 2015. He was assigned to the USS NEW HAMPSHIRE (SSN 778) where he served as the Electrical Assistant, Reactor Controls Assistant, Assistant Weapons Officer, Damage Control Assistant, and Information Systems Security Manager. He transferred to the Engineering Duty Officer community in August 2018 and completed a qualification tour at Portsmouth Naval Shipyard (PNSY) in Kittery, Maine. While at PNSY, he served as the Ship's Safety Officer, Work Integration Manager, and Nuclear Assistant Project Superintendent for the USS VIRGINIA's (SSN 774) Depot Modernization Period (DMP).

Heather Willis

LT Heather Willis graduated with distinction from the United States Naval Academy in May 2014 with a Bachelor of Science degree in Mathematics and a dual major in Operations Research. Upon commissioning, LT Willis attended Nuclear Power School and Prototype training in Charleston, South Carolina from August 2014 to January 2016. She was assigned to the USS LOUISIANA (SSBN 743) (Blue) where she served as the Electrical Assistant, Main Propulsion Assistant, Damage Control Assistant, Assistant Engineer, and Quality Assurance Officer. LT Willis then served at the TRIDENT Training Facility in Bangor, Washington as a Command and Control Exercise Instructor and the Fleet Scheduling Officer. In August 2022 she went on a 7-day cruise to Alaska aboard the Carnival Splendor.

Acknowledgments

This project relied heavily on the valuable input from the following people:

- **Ibrahim Desooky.** Design Research, Specialist
- **Nhuy Hoang.** Deputy Director, Capital Programs & Environmental Affairs, Massachusetts Port Authority

- **Callison RTKL.** Architecture Firm, Miami Cruise Ship Team
- **Kenneth Capron.** Subject Matter Expert
- **Rich Delpizzo.** Director, Global Government, American Bureau of Shipping
- **William Leyrer.** Passenger Ship Expert, American Bureau of Shipping
- **Rick Teichman.** Engineering Manager, Submarine Propulsion Shafting Systems, Naval Surface Warfare Center Philadelphia Division Code 427

2. Design Decisions and Framework

2.1 Design Philosophy

The design philosophy for this project was to create affordable and desirable housing by efficiently using available space and minimizing cost as much as possible. This philosophy manifested itself in the following list of priorities:

1. **Anchor to affordability.** Develop a reliable and sound approach to defining affordability and stick to that definition moving forward. Ensure that the base unit pricing remains tethered to that definition even if that requires revising design decisions.
2. **Do not sacrifice desirability.** The housing environment created in this project needs to be comparable to similar housing in the local area and be somewhere that people want to live. If desirability is not prioritized the project will do nothing to help solve the housing crisis.
3. **Minimize conversion complexity.** A cruise ship is in many ways already well-suited to accommodate people's basic living needs, which is frankly why this conversion idea has even been proposed. Therefore, it is a point of emphasis to retain as much existing infrastructure, usable spaces, and support systems as possible, which, in turn, will simultaneously drive down overall conversion costs and increase desirability.

2.2 Design Parameters

The full list of design parameters and associated threshold and objective values we determined for the final conversion design have been listed in Table 9 in Appendix C. The affordability criterion was derived from the definition of affordable housing as discussed previously. The desirability parameters were determined from the Miami survey and similar articles in Boston of the most desired amenities in an apartment complex[2][24][25]. Relocatability was a sponsor-defined requirement as described in Section 1.3.

2.3 Evaluation and Decision Framework

Region and Site Location

One of the early design decisions was determining which city and docking location would serve as the host site for the converted cruise ship. The project sponsor was largely lenient in which city was chosen, a reflection of the fact that the affordable housing problem is a common one throughout the entire United States, especially for waterfront cities. Given the proximity to the research team, the relatively high cost of living and housing, the existing cruise port infrastructure and facilities, and the infrequency of extreme weather events which would require undocking and sortie, Boston, Massachusetts was chosen as the host city.

Next, a more specific site location had to be determined. The first natural candi-

date was the Flynn Cruiseport, located on the southern tip of Boston’s Seaport district. The port is owned and operated by the Massachusetts Port Authority (Massport), and handled 402,346 passengers across 138 port calls, 34 different ships, and 21 different cruise lines in 2019 alone[26]. There are currently three berths specifically allotted for cruise ship docking as shown in Figures 2 & 3.



Figure 2: Flynn Cruiseport frequently operates at maximum capacity, with all three cruise berths reserved for arriving or departing vessels.

In order to better assess the feasibility of docking the converted cruise ship on a permanent or semi-permanent basis at one of these berths, there was extensive consultation done with Massport subject matter experts regarding the port’s capital programs, infrastructure, utilities, and operations. From a scheduling perspective, port officials indicated the infeasibility of being able to dock a vessel there on a permanent or even semi-permanent basis. During the port’s peak season, which runs primarily from September to November, the berths are generally at full capacity on a daily basis[27]. This high-volume schedule is planned out months ahead, and the revenue generated from docking these cruise ships provides a major profit stream for the Massport organization. For these reasons Flynn Cruiseport was eliminated as a possible location for the converted cruise ship to be docked; therefore, an alternate location had to be determined.

To this end, our Massport contacts also provided detailed information regarding the use of North Jetty Pier (located just north of Flynn Cruiseport) and the cruise ship *Grand Celebration* for emergent temporary housing in 2018 to accommodate hundreds of out-of-state workers brought in to repair a ruptured gas line. A full description of the *Grand Celebration’s* repurposing to emergency housing is provided in Appendix F.



Figure 3: Cruise ship berth layout at Flynn Cruise Port.



Figure 4: Grand Celebration docked at North Jetty Pier, 2018.

This real-world example demonstrated proof-of-concept viability of using North Jetty Pier to dock a cruise ship on a semi-permanent basis, and focused our research efforts by assuming that this would be the host location for the converted cruise ship design.

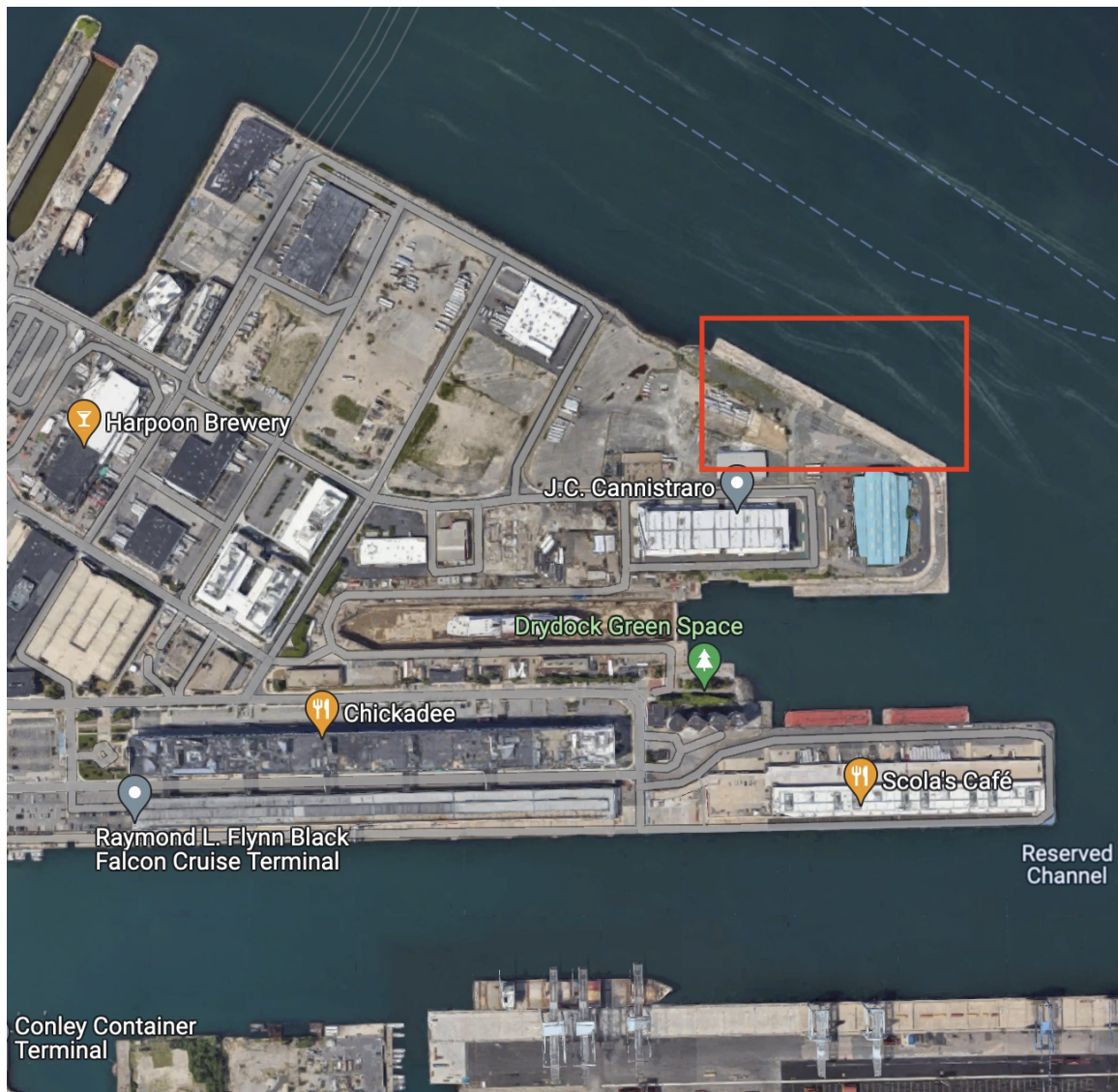


Figure 5: North Jetty Pier (highlighted in red) in relation to Flynn Cruiseport.

Utilities

Another key design decision was determining how to best provide major utilities (power, water, sewage, etc.) for the ship's future residents. The team conducted extensive research and comparative analysis of the main options available, such as using the installed systems onboard to the greatest extent possible, or taking advantage of land-based water and power distribution systems to which the ship could connect, as is often the case when vessels are docked. We conducted a thorough investigation into the feasibility of investing in shore-to-ship power (SSP, "shore power") technology as the long-term power solution for this proposal. These findings are provided in Appendix [A](#).

Defining Affordability

Addressing the affordable housing shortage requires going beyond just taking homeless people off the street; instead, it demands a more comprehensive approach to understanding the socioeconomic conditions of a given region and tailoring the potential solutions accordingly. At the same time, certain simplifying assumptions had to be made in order to arrive at a target cost per unit which would heavily influence a variety of other design factors.

In order to determine a common definition and value for “affordable housing”, the description provided by the United States Department of Housing and Urban Development (HUD) was used as a starting point. Under this definition, the occupant pays no more than 30% of gross income for housing costs, including utilities[23].

It is assumed that this occupant earns the mean per-capita income in Boston of \$50,344, which is based on U.S. Census Bureau Data aggregated from 2017 to 2021[28]. Applying the above definition and dividing by a per-monthly basis yields a housing unit target monthly cost of \$1,259. For reference, the actual median gross rent during that same period was \$1,783[28]. This is \$524 in excess of the desired 30% threshold and represents 42.4% of the mean income earner’s gross income.

Defining Desirability

Defining what constituted “desirable” living emerged as one of the central challenges in determining suitable cabin and deck modifications. Absolute minimum requirements were derived from the Massachusetts Sanitary Code, which provides a list of rules and regulations for housing in the state. Code of Massachusetts Regulation 105 (105 CMR) states that each unit must have at least 150 square feet of total space for one tenant[29]. For each additional tenant, the unit needs another 100 square feet. Moreover, the room must get natural light from a window that is equal to at least 8 % of the floor space.

To actually provide a “desirable” alternative housing solution, the team assessed that the allotted square footage had to be at least in a comparable range to the average housing options currently available to city residents. To this end, research was conducted to determine what the average size and rent price were for studio and one-bedroom apartments in various Boston neighborhoods, as well as the city writ large, in order to gain a better understanding of the expectations that a median income renter may have when considering the prospect of living onboard a converted cruise ship. A summary of these findings is provided in Table 1.

The underlying socioeconomic reality is that certain neighborhoods are simply more expensive than others, and that the assumed average income earner previously described may not correspond to the average renter in any one of these given neighborhoods. Nonetheless, these data provide useful insights to guide further assumptions and design decisions. For example, Beacon Hill and North End studio renters’ monthly housing costs are proximal to the city’s median gross rent, and thus those corresponding apartment sizes represent a first-pass approximation of desirable unit sizes for the converted cruise ship. Moreover, by anchoring the base unit monthly rent to meet the “affordable housing” definition, the converted cruise ship base units will be more

Table 1: Average Apartment Sizes and Prices by Neighborhood[10][11][12]

Neighborhood	Apartment Type	Average Size (ft^2)	Average Rent ($\$/month$)
Beacon Hill	Studio	362	1,757
Beacon Hill	One-Bedroom	583	2,524
North End	Studio	490	1,743
North End	One-Bedroom	650	2,837
Jamaica Plain	Studio	501	2,371
Jamaica Plain	One-Bedroom	547	2,130
South End	Studio	545	2,222
South End	One-Bedroom	741	2,763
Fenway	Studio	412	2,517
Fenway	One-Bedroom	662	2,763
Overall	Studio	536	2,367
Overall	One-Bedroom	629	2,900

desirable from a strictly economic perspective.

It was initially believed that the primary target demographic for this proposed housing would be individual renters with assumed earnings mirroring that of the median income earner described above. However, the project sponsor indicated the desire for there to be a range of housing options made available in order to meet renter demand across a range of income levels. Specifically, there needed to be affordable options for the majority of individuals and families who fall at or below the median income earning level. This would likely manifest itself in having to consider a range of housing unit layouts whose rent values roughly corresponded to the unit size.

Although a principal concern, unit square footage is just one of many factors driving the desirability of a housing complex project. To better understand what sort of amenities and housing accommodations would be most valued in this type of arrangement, data from the 362-person Miami case study survey was used and analyzed[2]. The most important features in ranked order of importance were:

- Parking
- On-site laundry
- Outdoor green space
- Security
- Pool

Although the needs of Miami residents are not identical to the needs of Boston residents, these results nonetheless provided a valuable framework to inform subsequent design decisions with respect to which spaces and amenities to either retain or include, and which could be repurposed to better suit the needs of prospective residents.

3. Concept Exploration and Selection

3.1 Baseline Ship Variant Selection and Description

The initial exploration of baseline candidates for conversion began through consultation with the Miami-based architecture firm CallisonRTKL which had previously explored this topic. Their lead researcher has periodically collected data on cruise ships that are for sale, and this data was provided to our project team[30]. A down-selection process was then conducted to narrow the list to actual viable candidates, based on the following criteria:

Draft and Displacement. Although the chosen port could theoretically be dredged to accommodate larger vessels, the associated costs incurred could quickly add to the overall project cost. The average underwater dredging costs start at \$70 per cubic yard and can balloon to several hundred dollars per cubic yard based on sea floor type, such as sensitive soil[2]. Therefore, any additional dredging was deemed infeasible. Ships were first eliminated if their maximum drafts exceeded the 35 foot water depth of the chosen site location at the North Jetty Pier, to include an additional 10% clearance as recommended by port engineers[2]. Although it was predicted that the selected cruise ship would not be docked at its current reported maximum draft given eventual weight removals, there were too many uncertainties this early in the design process to justify a different draft approximation and so the more conservative approach was taken.

The selected variant had to retain the ability to potentially dock at other ports along the United States eastern seaboard in order to meet the objective “relocatable” requirement. A broad assessment of additional Eastern seaboard cruise port locations and their draft limits was conducted because it was initially assumed that cruise ports would be the most fitting sites to dock the converted cruise ship. Examples include:

1. *Cape Liberty Cruise Port (Bayonne, New Jersey)*. NOAA chart data did not provide sufficiently detailed information regarding the water depth specifically at the location where cruise ships dock at Cape Liberty. However, Royal Caribbean Group (RCG) is the port’s main tenant, and in 2015 the 168,000 GT Quantum of the Seas cruise ship was homeported there[31][32]. That vessel has a maximum draft of 29’, and so this was treated as the upper bound for this port.
2. *Baltimore Cruise Port (Baltimore, Maryland)*. Reported cruise ship berth water depth of 35 feet[33].
3. *Port Charleston (Charleston, South Carolina)*. Reported cruise ship berth water depth of 47 feet[34].

Ultimately, the vast majority of similarly-sized cruise ports did not have limiting water depths, and did not appreciably narrow the baseline variant tradespace. In reality, canvassing potential site locations should not be limited to just cruise ports, especially since many cruise ports likely face the same volume-heavy schedule at Flynn Cruiseport and thus may not be able to support this type of long-term docking. Further

research could uncover additional site candidates which do not face the same traffic volume concerns of a cruise port but may also have more restrictive draft requirements since they are not necessarily accommodating large cruise ships and container vessels.

Housing Capacity. Although there were no strict requirements to provide a certain number of housing units, in order to make such a conversion worth the cost, the chosen cruise ship needed to be a relatively large ship. Based on achieving just the bare minimum square footage requirements, and in assessing the general layout and sizing of cruise ship cabins, it was clear that some extent of cabin merging would be necessary to meet the design goals. Therefore, it was critical to choose a variant with a relatively high number of cabins. Ultimately, it was determined that the candidate cruise ship had to have at least 500 existing cabins.

Cost of Purchase. From this resulting smaller tradespace, the key determining factors were overall cost, and cost per tonnage. Although the fixed capital costs, including cost of purchase, are assumed to be fully government funded, it was still a priority to minimize upfront costs where possible in order to more strongly argue for the ultimate feasibility of this proposal.

Amongst the remaining options, the RCG *Monarch of the Seas* Sovereign-class cruise ship was the most affordable choice. The listed purchase price was \$35 million, which corresponded to approximately \$473/ton[30]. Further research indicated that the *Monarch* had, in fact, already been sold to the Spanish cruise line Pullmantur, who subsequently declared bankruptcy during the COVID-19 pandemic. The ship was then sold for scrap metal to the main shipbreaking facility in Aliaga, Turkey[35]. A review of the RCG fleet was conducted to identify a comparable vessel and was cross-referenced to commercially-available 3D cruise ship models which would be used throughout the project for modeling, redesign, and engineering analysis. Ultimately, the Vision-class *Rhapsody of the Seas* cruise ship was selected.

3.2 Concept Exploration Approach

3.2.1 Housing Unit Layout and Arrangement

Considerable time was dedicated to exploring possible housing unit layouts and arrangement strategies, since this represents the central goal of the conversion project. One of the principal considerations was balancing the desire to efficiently reorganize and utilize the pre-existing living spaces while maintaining a requisite level of desirability within each proposed unit. For example, one extreme end of this design spectrum was the purely spartan approach, wherein all the cabins were simply designated as apartments as-is or nearly as-is, with as little modification as possible in order to minimize cost and maximize occupancy. However, this strategy was quickly dismissed as non-viable given its inability to not only meet the minimum housing requirements set forth by 105 CMR, but also to offer almost nothing in terms of in-unit desirability.

Two Exterior Cabin Merge

The first seriously considered housing schema was to combine two exterior units to the largest extent possible, and account for some small number of more bespoke

units where it would not be numerically or architecturally feasible to combine two units. Figure 8 shows a rough sketch of this schema on Deck 2. Using Deck 2 as an example, the majority of cabins are of the “Oceanview” type, most of which are 126 ft^2 [36]. Therefore, the most common base housing unit would be approximately 252 ft^2 . In this approach, approximately 60% of the interior units would also be combined on a two-for-one basis, with the remaining cabins designated for communal space usage. In order to provide sufficient natural light to the interior housing units, it was proposed to remove large portions of the ship’s central volume in order to construct a centerline open atrium which would allow light to enter and reach the interior units, similar to that shown in Figure 7 from the aforementioned Miami-based study[2].



Figure 6: Layout of a typical Oceanview cabin pre-conversion[1].

The technical risk and engineering complexity involved in this level of structural redesign were enough to eliminate this approach from serious further consideration. Moreover, the base unit square footage was deemed too small to be considered sufficiently desirable based on the estimated monthly cost and in comparison to similar land-based options.

Four Cabin Merge with Walk-Through

The next proposal was to instead merge four cabins into one. The baseline approach was that where feasible, two exterior cabins would be merged with two interior cabins. This would simultaneously address the major concerns engendered in the first design iteration: (1) alleviation of the insufficient unit square footage issue by roughly doubling the base unit size to approximately 500 ft^2 , and (2), elimination of the need for significant structural renovation vis-a-vis construction of a central natural light atrium. In the forward and aft portions of the main cabin decks, four exterior units would instead be merged owing to the irregular arrangement of the corresponding interior units. These interior units would instead be repurposed for communal and general storage space.

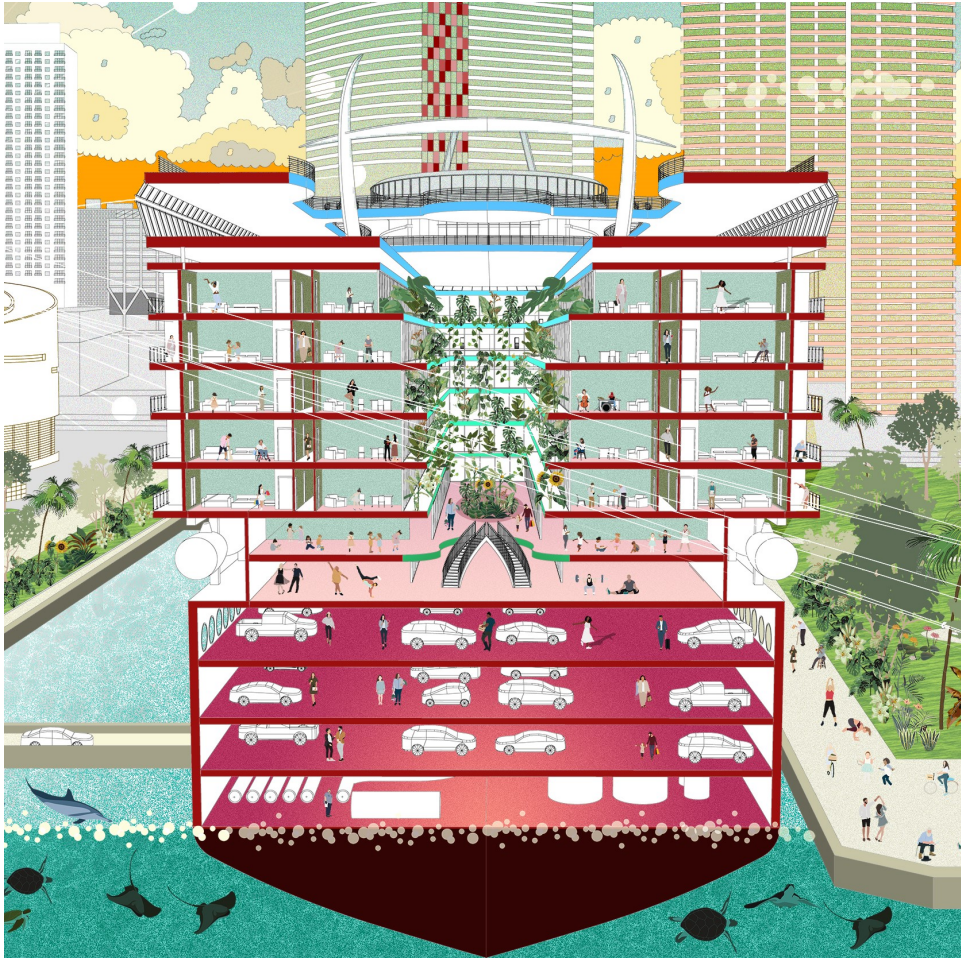
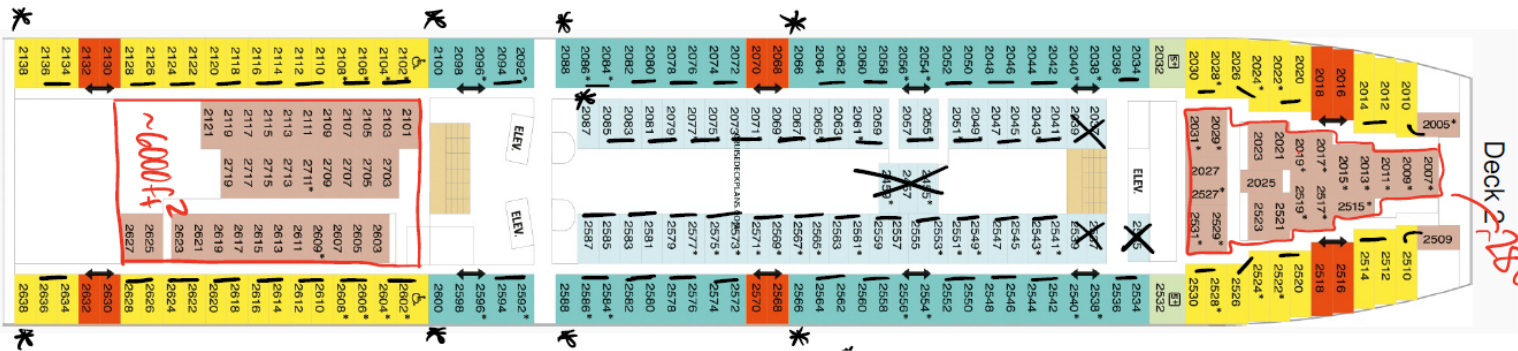


Figure 7: Example of centerline atrium in Miami study[2].



The primary concern with this layout strategy was the oddity of a single base unit being separated by a hallway, which forces certain residents to transit through a common space in order to access different parts of their apartment. This feature minimized the alterations necessary to the existing units while still providing adequate square footage, which is one of the key traits to achieving desirability. However upon further discussion, we ultimately determined the walk-through to be an unacceptable design decision. Despite a likely increase in refurbishment cost we continued to explore further arrangement options.

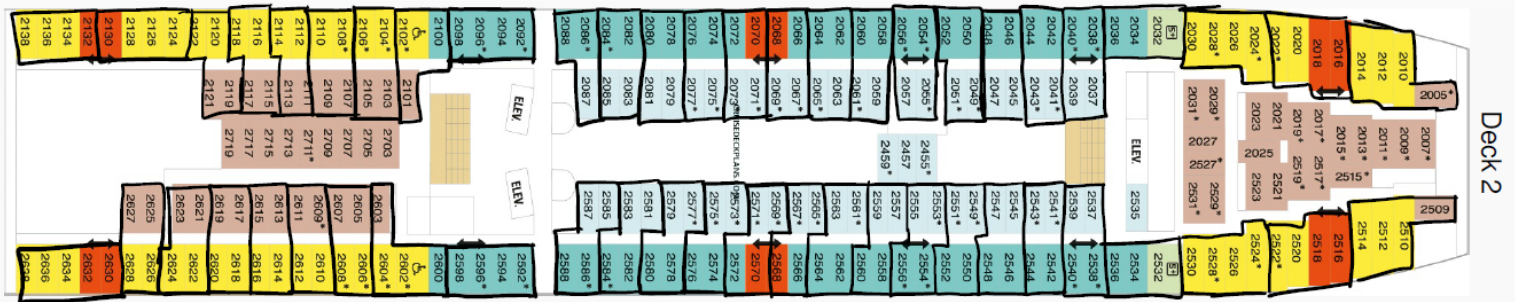


Figure 9: Deck 2 layout with four cabin merge and walk-through.

Providing Unit Variety

In the previous design iteration, the base unit provided the desirability we aimed to achieve, was replicated to the largest extent possible throughout the decks, and was slated to be priced exactly at the assumed affordable median rent value of \$1,269. However, we determined that this approach ultimately lacked legitimate practicality. In order to provide affordable housing to a wider range of people—the primary stated goal of this proposal—we had to offer a broader range of housing options at a wider range of price points. If we remained strictly tethered to the median affordable rent value, we would effectively be cutting out the lower income-earning population for whom affordable housing is even that much more of a financial strain. This also aligned with the feedback we received from our project sponsor that we should provide more variety in our unit offerings, such that even those earning around \$20,000 a year would have at least some options available at this housing complex.

This mixed-income approach allowed us to design smaller units, which in turn afforded greater flexibility in the cabins we could merge and in what manner we could merge them. On the other end of the spectrum, some rooms were already larger in size than the “standard” 500 *ft*² combined units, particularly the suites (see Figure 10). Many of these rooms were turned into larger units, closer to 700 *ft*² to allow for possible family accommodations or 2-bedroom equivalent units. Ultimately, this enabled the most efficient use of the existing cabin infrastructure and resulted in our design being able to provide a greater number of housing units with greater variety, but all of which remained affordable.



Figure 10: Layout of the Royal Suite pre-conversion[3].

Including In-Unit Kitchens

Although 88% of the Miami case study respondents indicated at least some interest in the general idea of living on a converted cruise ship, only 56% of respondents said they were willing to lose an in-unit kitchen[2]. The prospect of modifying cabins to include in-unit kitchens was initially perceived to be non-viable given the various marine vessel safety codes prohibiting such accommodations and discussions with multiple SMEs [30][37][38]. However, the United States Coast Guard no longer provides Certificates of Inspection (COI) to vessels that are classified as Permanently Moored Vehicles (PMV)[39]. The fire safety and inspection requirements also shift from maritime standards to local municipal jurisdiction. Although additional research is required to determine the process by which to classify the converted cruise ship as a PMV, the existence of this legal framework strengthens the plausibility that in-unit kitchens can be provided.

Moreover, at this point in the design process, the project sponsor indicated that the complete prohibition of in-unit kitchens would be considered a “fatal flaw”. Therefore, the majority of units would be outfitted to satisfy 105 CMR Section 410.100 minimum requirements for kitchen facilities, namely to include a sufficiently sized sink, a stove and oven in good repair, and the space and proper facilities for the installation of a refrigerator[29].

It is important to note that adding in-unit kitchens will add additional refurbishment costs and complexity, to include[30]:

- Cost for HVAC installation
- Waste removal operational costs
- New appliance installation
- Adding clearances for cooking space
- Adding soffits to hide exhaust ducts above the stove and oven
- Adding plumbing in the interior walls of the units; current units only have plumb-

ing along the corridor, which is the reason why the unit bathrooms are always along the corridor.

- Increased usage and need for fire-resistant and fire-tested materials for any unit with a kitchen include.

3.2.2 Major Utilities

Given the present lack of SSP infrastructure at Flynn Cruiseport and the North Jetty Pier (and the majority of the Eastern seaboard cruise ports for that matter), an easier and cheaper alternative would be to assume the ship’s currently installed diesel engines would remain in place and provide the primary source of power for the converted design. However, the deleterious environmental and public health implications of this decision are potentially severe and may prove impossible to navigate politically. We surmise that there would be very little public appetite for the docked cruise ship to be running its diesel engines at all times along the pier, and that it could possibly render the entire proposal non-viable.

To better assess this environmental impact, as well as the positive impact that conversion to shore power could bring, the EPA’s Shore Power Emissions Calculator (SPEC) was utilized. This online tool assists port stakeholders in evaluating whether shore power would be an appropriate means to reduce pollution, and to estimate emissions reductions from installed systems[40].

SPEC accounts for power grid subregion location, vessel type, fuel type, number of annual vessel calls, average hotel hours per vessel call, and the nominal auxiliary engine hotelling load while in-port in order to calculate the ship’s annual energy consumption, annual vessel power emissions, annual corresponding shore power emissions, and the difference between the two power-providing methods.

The keel of the *Rhapsody of the Seas* was laid on December 11, 1995, therefore its four installed Wärtsilä 12V46C diesel engines are classified as “pre-2000 engines” and are subject to IMO Tier 1 emission standards under the 2008 Annex VI amendments[41][42]. Moreover, because Boston was chosen as the site location for this study, the ship’s emissions limits also fall under the jurisdiction of the North American ECA, which as of 2020 implemented a 0.10% SOx emission limit. Therefore, it was assumed that if the installed engines remained in place for use, they would have to burn Marine Gas Oil (MGO) 0.10% Sulphur Tier I fuel.

Given the year-round docking of the proposed design, the number of annual vessel calls was maximized at 365. The average “hotel hours” allotted for the base load was set at 16 hours for each 24-hour period, in order to cover the majority of the day and account for variances in individuals’ schedules, while also assuming that certain common spaces and amenities would not be available for around-the-clock service.

The nominal auxiliary engine hotelling load for a 60,000-ton cruise ship was given as 3500 kW[40]. Considerable attention was taken to reassess an appropriate baseline hotelling value. The primary factors driving a reduction in the base demand included:

- **Significant reduction in personnel.** The maximum actual occupancy of the *Rhapsody* is 3,181 persons (including crew), whereas the projected onboard living

population for the converted design is approximately 350. This represents an order of magnitude difference that will significantly reduce general power demand and energy consumption.

To further specify this energy consumption contribution, relevant residential electricity data for Boston was used to predict expected usage rates for the future converted cruise ship residents. The average electricity customer energy consumption for a one or two-bedroom apartment in the city is 900 kWh per month and 10,800 kWh per year[43]. Given the proposed 246-unit converted layout, this results in a base annual resident energy consumption of 2,656,800 kWh, and corresponds to an instantaneous hotelling load demand of 304 kW.

- **Elimination of large refrigerated storage spaces.** Food storage will shift from the currently installed massive reefers to the in-unit refrigerator options.
- **Significant reduction of industrial kitchen appliance usage.** Given the mandate to include in-unit kitchen accommodations, the large current cooking spaces and attendant industrial-size kitchen appliances will be repurposed and thus require significantly less power.
- **Reduced cooling requirements within engineering spaces.** A large portion of the equipment and machinery will either be retired in place or operated at a significantly lower capacity, including the main diesel engines. This removal of large heat loads within these spaces will drastically reduce the corresponding cooling requirements.
- **Elimination of below deck berthing.** The proposal to convert the majority of the berthing and general storage spaces on Decks 0 and 1 to parking eliminates even more spaces that would otherwise require full HVAC services.

Thus, the overall power demand is expected to be much lower than the nominal value originally proposed by the SPEC tool. For the purposes of all follow-on calculations, the auxiliary engine hotelling load was assumed to be **2000 kW**. This power demand projects a total annual energy consumption of **11,680,000 kWh**.

This annual energy consumption was correlated both with vessel fuel emission factors and grid subregion emission factors in order to calculate the expected annual vessel power emissions and shore power emissions. The results are described in Table 2, which illustrates the massive potential for emissions reductions by investing and shifting to SSP technology.

Table 2: Predicted Annual Emissions, Vessel Power vs. Shore Power

Emission Type	Vessel Power Emissions (MT)	Shore Power Emissions (MT)	Annual Percent Reduction
NO_x	142.496	2.156	98%
SO_x	4.592	0.758	85%
$PM_{2.5}$	1.939	0.256	87%
CO_2	8,129	2,909	64%
CO_{2eq}	8,234	2,938	64%

Cost Estimate: Vessel Power vs. Shore Power

To estimate the cost of providing this energy with the installed diesel engines, their specific fuel consumption (SFC) data was correlated with the previously determined expected annual energy consumption. Each of the 12V46C engines has a capacity of 12,600 *kW*, so it is assumed that only one diesel engine would be running to supply the required hotelling load of 2000 *kW* [44]. This loading condition on the diesel engine approximately corresponds to a SFC of 189.3 g/kWh[45]. Per unit fuel cost was then found using up-to-date marine shipping data. New York City port fuel prices were utilized given the proximity and cost-of-shipping similarities between the two cities, as New York’s price data was readily available online while Boston’s was not. The average cost of MGO Tier I fuel was \$987/MT[46]. The projected annual electricity costs using the installed vessel power were **\$2.2 million**.

To estimate the annual consumption costs by switching to SSP, the same annual energy consumption total was used and then multiplied by the average electric rate in Boston as of 2022, which was 27 ¢/kWh[43]. The projected annual electricity costs by switching to shore power were **\$3.2 million**.

While these cost projections are not immediately favorable to the SSP proposal, there is more flexibility and potential for cost reduction in the SSP approach. The Massport Shore Power feasibility study noted that negotiation of an amenable electric rate would likely be critical to the success of SSP implementation[9]. Moreover, Eversource Energy, the main utility provider in Massachusetts, offers its discount rate incentive to a wide range of individuals associated with certain social welfare benefit programs, including those in the Low Income Home Energy Assistance Program (LIHEAP/Fuel Assistance), and those living in public or subsidized housing[47]. Therefore, it is entirely plausible that a discounted rate could be agreed upon for this affordable housing venture, especially if it has the support and backing of the local and state government, as is the current assumption. Eversource’s discount rates can save residents anywhere from 9-77% off their electric rate. If it is modestly assumed that the electric rate were discounted at 25% to 20 ¢/kWh, then the projected annual electricity costs by switching to shore power fall to **\$2.3 million**, well within a competitive range to the vessel power costs, especially when the accrued environmental benefits are considered.

Addressing Installed Electrical Capacity

Given the many compelling reasons for shore power conversion, we assess it as the most viable option to provide electricity for the converted cruise ship and should be considered an essential investment to the overall conversion. As such, the vessel’s installed electrical power must be reconsidered for repurposing, removal, or some combination therein. Each main diesel engine is rated at 12,600 kW, weighs 235 tons, and has the following principal dimensions: 15.4 *m* x 4.1 *m* x 6 *m*[44]. Additionally, the ship is equipped with two GMC 16V-92TA Emergency Diesel Generators, each rated at approximately 700 kW[48][49]. The customer requirement to retain some form of onboard electrical capacity—to mitigate primary power loss and achieve relocatability—meant that we could not simply remove all of the installed electrical capacity on board. Beyond that, removing that much weight that low on the ship could have unfavorable implications for the ship’s resulting center of gravity and overall stability. Therefore,

there had to be a truly compelling reason to substantiate the need for engine removal.

We had originally believed that removing most of the diesel engine footprint would open up additional volume to include more parking in the design. However, detailed deck plan drawings for the engineering spaces were not publicly available, so we had to rely on very basic diagrams from a previous 2.704 conversion project, created based on input from an RCG technical POC[50]. To supplement this relatively sparse information, we also reviewed online videos of *Rhapsody* engine space walkthroughs, which helped to illustrate the challenge of repurposing the engine room spaces without a nearly complete gutting and overhaul[51]. The amount of equipment and piping distributed through the spaces would result in unavoidable interference issues, such that simply removing the diesel engines would not result in parking-suitable spaces. Given the expectation to retain most of the auxiliary engineering systems (*i.e.* air conditioning, heating, plumbing), and the necessity to retain the diesel engine support systems (*i.e.* hydraulics, lube oil, cooling water), it was ultimately deemed infeasible to repurpose the engineering spaces for parking.

In turn, we were unable to find a compelling enough reason to remove the non-operational diesel engines and incur the overhaul cost and complexity associated with that decision. At the same time, we recognized that keeping all the diesel engines in an available status would incur unnecessary operational and maintenance costs over the lifetime of the ship, and thus some of the engines should be ‘retired in place. Only one installed Wärtsilä diesel engine would need to be online to provide the ship’s electrical loading if required to divorce from shore power, or in the event of its loss. To provide an additional level of redundancy, and also to support relocation evolutions where shore power may be unavailable for an extended period, we decided to maintain two Wärtsilä diesel engines in an operational status and retire in place the remaining two Wärtsilä engines and the two GMC emergency diesel generators.

Water

The *Rhapsody* is capable of producing 1200 tons of freshwater per day with its installed freshwater generation systems[52]. RCG’s cruise ship fleet on average produces 90% of its freshwater onboard through two main processes: desalination/evaporation and reverse osmosis[4]. The desalination system boils and evaporates seawater, which is then condensed into freshwater. This process is enabled by repurposing the diesel engines’ jacket water waste heat to facilitate the evaporation process. Given the proposed shift to shore power technology and lack of propulsion demand, this source of waste heat will be unavailable, and thus retaining the desalination units for water production will not be possible.

The reverse osmosis (RO) units produce freshwater by pumping seawater through coarse strainers at low pressure, and then through a series of semi-permeable membranes and filters at high pressure[53]. This process yields clean permeate which is then transferred to the ship’s water treatment systems until it meets all standards for human consumption and can be stored in the potable water tanks. Although the RO units are not reliant on engine waste heat, they are normally only operated outside four nautical miles from shore, and in water at least 50 meters deep, to avoid shore-based contamination, strainer blockage, and filter exhaustion[54][55]. Our research was un-

able to determine specific restrictions that RCG implements on its RO usage in port, but it was clear that nearly all water production occurs while the ship is transiting in open waters. Water capacity shortfalls while in-port are abetted by bunkering, the process of taking on freshwater supply from a land-based provider.

As such, the team determined that it would be infeasible to attempt to maintain the installed onboard freshwater production systems for the converted cruise ship. Instead, the ship will rely on connecting to the city’s water distribution system, managed by Boston Water and Sewage Company (BWSC).

Wastewater

Similarly, we determined that the operational upkeep of the main wastewater treatment systems installed onboard would have no real benefit. Once pierside, there is no material distinction between graywater (*i.e.* water from sinks, showers, laundry, air conditioning condensate) and blackwater (*i.e.* water from toilets and medical facility), since neither of these water types can be discharged overboard when docked. Thus, the main wastewater collected onboard will still have to be landed with some relatively frequent periodicity, and ultimately conveyed like the “normal” city wastewater—to the deep waters of Massachusetts Bay via the 9.5-mile long Effluent Outfall Tunnel[56]. The “normal” city wastewater is not segregated in any meaningful way prior to its arrival at the Deer Island Wastewater Treatment Plant, where it then undergoes preliminary primary and secondary treatment before discharge. Therefore, the team assessed that the most logical and long-term cost-effective approach was to invest in the necessary pierside and shipboard infrastructure and upgrades to permit ship wastewater discharge directly to the city’s sewer system.

Over 88% of RCG cruise ships feature a wastewater system architecture that incorporates a merging of the graywater and blackwater collection trains to the Advanced Wastewater Purification (AWP) system[4]. Under normal operations, the AWP treats both water types to sufficiently stringent standards such that the resulting combined effluent can be discharged beyond three nautical miles from shore. MARPOL/IMO policy allows normally treated blackwater to be discharged beyond three nautical miles, but RCG policy extends that limit to 12 nautical miles, so the increased stringency to which AWP adheres has clear operational benefit.

It was initially believed that the existence of the AWP presented a valuable opportunity to maintain this infrastructure largely in place, and retrofit just the AWP holding tank with the necessary piping and fittings to connect to the off-hull sewer system. This would minimize the number of structural upgrades which would be required for off-hull connections, and reduce associated refurbishment costs. However, additional research determined that *Rhapsody* is one of the few RCG cruise ships outfitted with the Navalys Poseidon AWP system (see Figure 12) which maintains separate graywater and blackwater trains throughout the entire treatment process until the final ultraviolet (UV) polishing process prior to discharge[5]. Without maintaining the AWP system fully operational, it did not seem likely that this approach could be feasibly pursued. Instead, we propose to disassociate the graywater and blackwater trains from the AWP system, retain each of their holding tanks (see Figure 11), and provision them with the necessary connections to allow off-hull discharge to the pier sewage system.

Types of Waste:

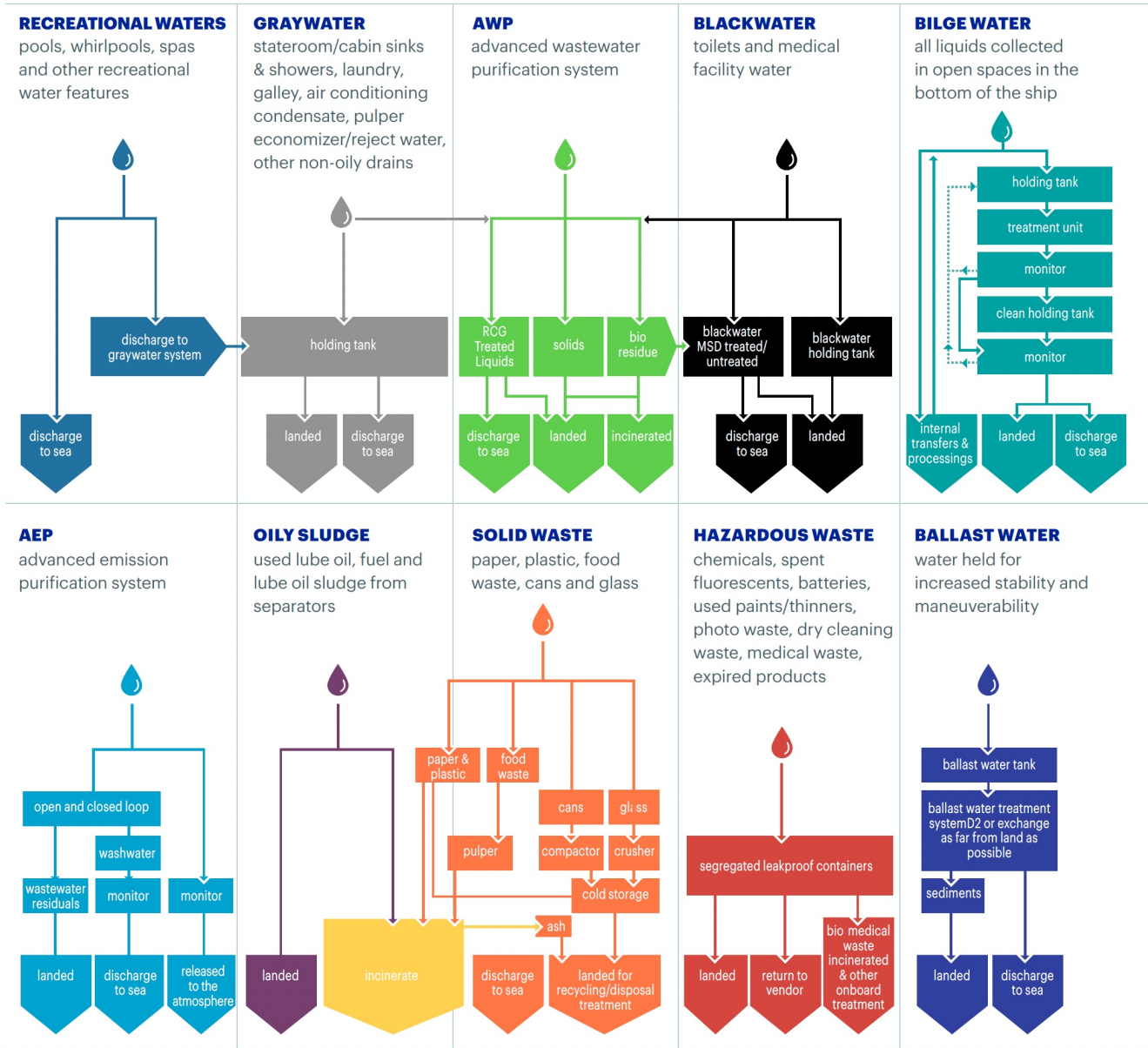


Figure 11: Waste management infrastructure onboard RCG cruise ships[4].

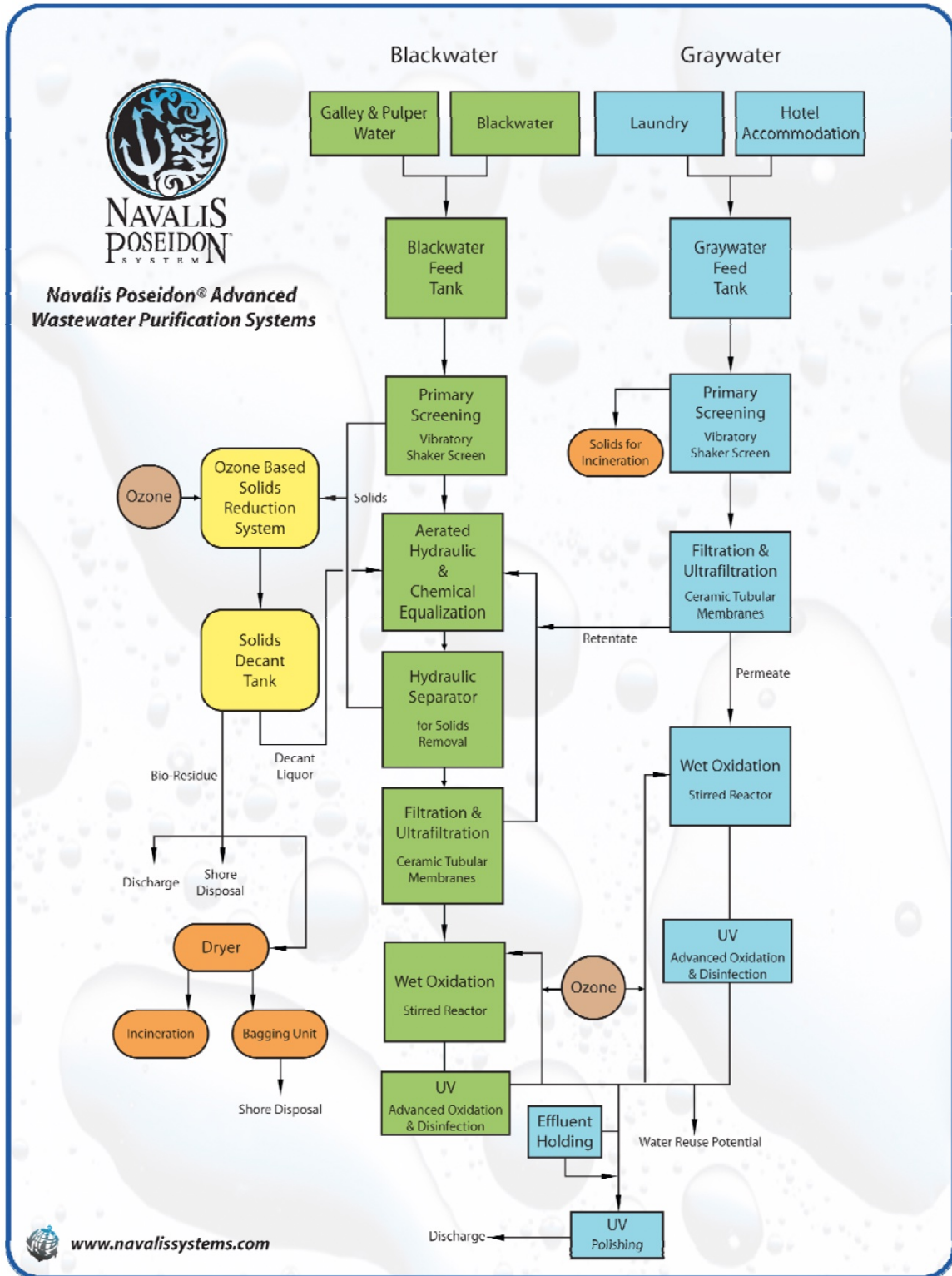


Figure 12: Diagram of Navalis Poseidon AWP system currently onboard Rhapsody[5].

4. Concept Definition and Feasibility/Performance Analyses

4.1 Design Definition

Our converted cruise ship design focuses on achieving the primary goals of affordability and desirability in order to create a promising and dignified alternative housing solution. We gained valuable insight from experts and researchers who had previously explored this topic in order to determine what sort of housing we could feasibly provide, what sort of amenities were necessary to include, and what major changes or upgrades would be required to effectively create a successful housing community afloat.

Our baseline variant selection process identified the Vision-class *Rhapsody of the Seas* cruise ship as a strong and viable candidate for conversion, based on its adequate size, potential capacity for housing, estimated cost, and expectation that it would soon be retired and decommissioned.

However, given the proprietary nature of information, there was no fully rendered 3D model of the *Rhapsody* publicly available for our study. Instead, the model we used and redesigned in Rhino3D and ORCA was a merged product of a 3D “shell” of the original *Rhapsody*, and a model imported from ASSET which approximated the principal dimensions and the first six decks of a Vision-class cruise ship which was used in a previous 2.704 conversion project[50]. This 3D model is shown in Figure 13. The remaining decks were added to the model by assuming a constant vertical distance between them. Curves of form and sectional areas were calculated in order to establish a representative baseline volume and displacement. These values corresponded closely to publicly available information regarding the *Rhapsody’s* actual characteristics, indicating a valid pre-conversion model in which to implement our conversion changes.

The team used publicly available deck plans to develop 2D layouts with our arrangement modifications. On the resident decks, multiple housing unit strategies were proposed before deciding on the final design which offers a variety of unit types, scaled by size and price, in order to provide increased housing options for a wider range of potential residents. Simultaneously, our intention was to make best use of the large volume of available spaces onboard to provide not only the requisite housing we envisioned but also an impressive array of additional amenities. We emphasized retaining existing spaces and facilities as much as possible in order to minimize overhaul complexity and in recognition that many of the features already provided on a cruise ship would be equally well-suited for a long-term housing community. Where this approach was not possible, such as converting portions of the lower decks into parking garages, a more detailed analysis was performed to determine the requirements, costs, and safety implications of implementing such a significant change.

During this modification process, we accounted for weight additions and removals resulting from the proposed conversions, specified by deck and weight group type, in order to apply these changes back into our 3D model for post-conversion stability analysis.

The other major concurrent effort in this design was to account for how utilities would be addressed in order to ensure safe, sanitary, and successful day-to-day operations on a long-term basis, which represents a significant departure from a cruise ship’s normal operations in-port. Detailed research was conducted in order to effectively argue that significant but essential investments in pierside and shipboard infrastructure and equipment upgrades should be coupled to this conversion proposal in order to enable shore power operations and permanent interoperability with the host city’s water and sewage distribution systems.



Figure 13: Rendering of 3D Model.

4.1.1 Ship Geometry

In accordance with the design philosophy, we tried to maintain as much of the original ship structure as possible. No changes were made to the external geometry of the ship other than minor modifications in the aft superstructure to allow for more natural light.

4.1.2 Arrangement Modifications

The crux of this project was modifying the arrangements of the cruise ship to create a desirable housing environment. We used the publicly available deck plans of the *Rhapsody* for Decks 2-12[36]. Decks 0 and 1 are proprietary information and therefore were inaccessible, but we used renderings created by a previous 2.704 project (obtained through discussion with a RCG point of contact) as a best estimate of these deck plans[50]. The engine room, located below the “Tween” deck, was also not available and is not shown. We did not make any changes to the layout of the engine room.

Deck 0 and “Tween” Deck

Figures 14-17 show the reference and modified layouts of Decks 0 and the “Tween” Deck. The “Tween” Deck is a shortened deck above the engine room and below Deck 0.

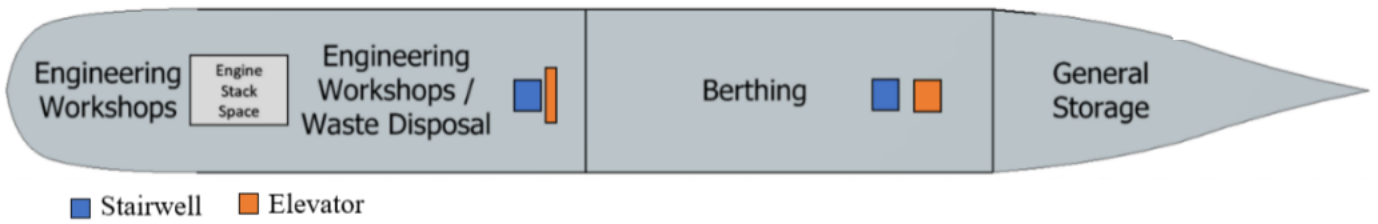


Figure 14: Deck 0 Layout Before Modification

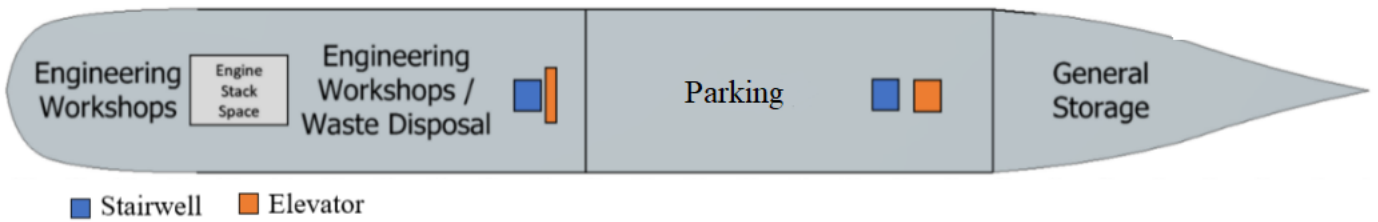


Figure 15: Deck 0 Layout After Modification

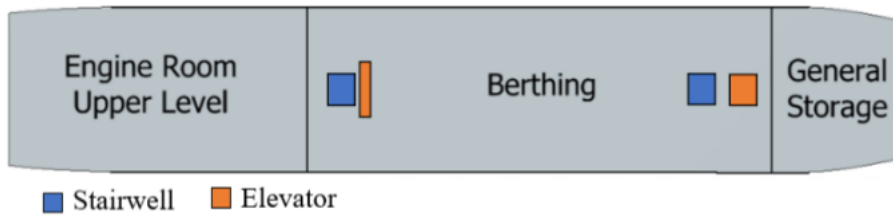


Figure 16: "Tween" Deck Layout Before Modification

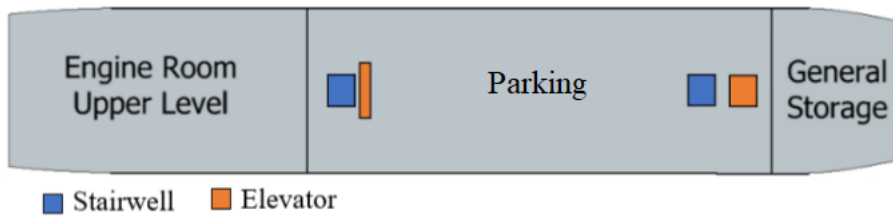


Figure 17: "Tween" Deck Layout After Modification

As mentioned previously these deck layouts were not publicly available, and we could not find any information on the layout inside the engineering spaces. For these reasons we chose to leave these engineering areas unchanged and converted the crew berthing areas into a parking lot.

Deck 1

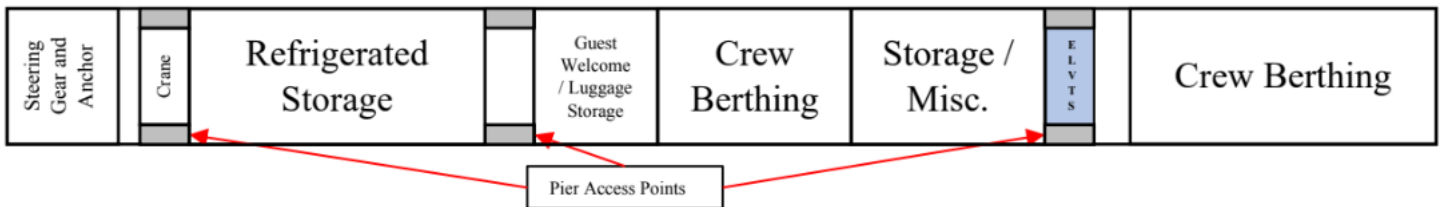


Figure 18: Deck 1 Layout Before Modification

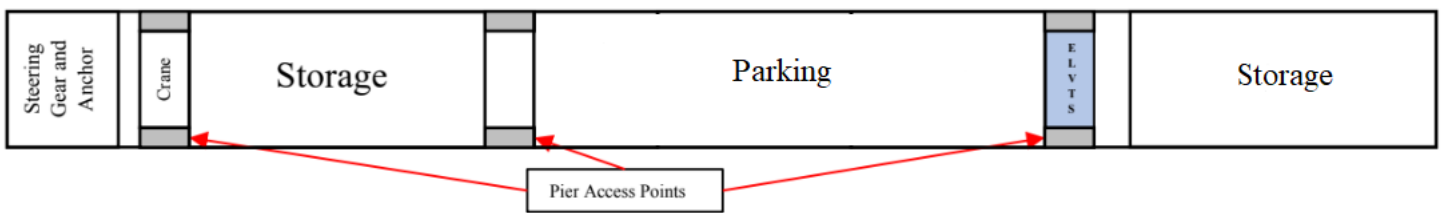


Figure 19: Deck 1 Layout After Modification

Figures 18 and 19 show the reference and modified layouts of Deck 1. This deck layout was not publicly available, so the spaces and locations are approximate. We did not alter the steering gear and anchor or the crane, but we converted the refrigerated storage and the forward most crew berthing into general storage. We also maintained all of the pier access points and converted the areas between the two most forward pier access points into parking.

Deck 2

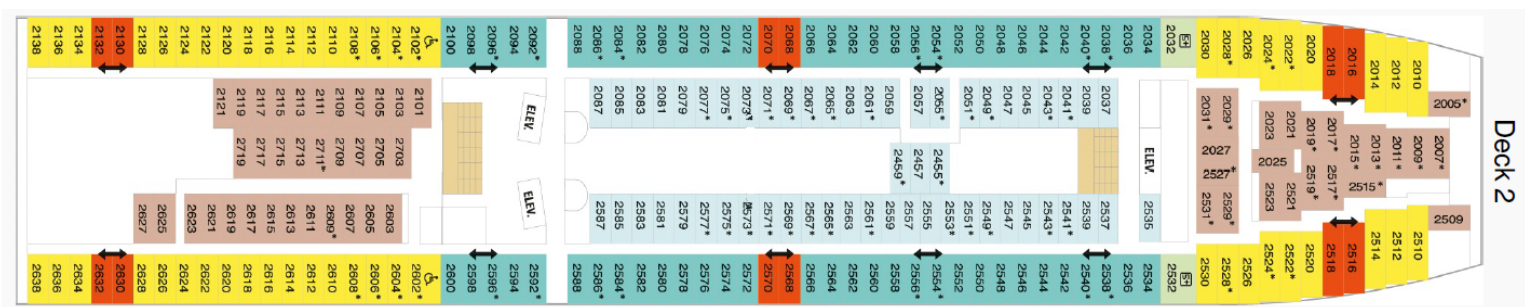


Figure 20: Deck 2 Layout Before Modification

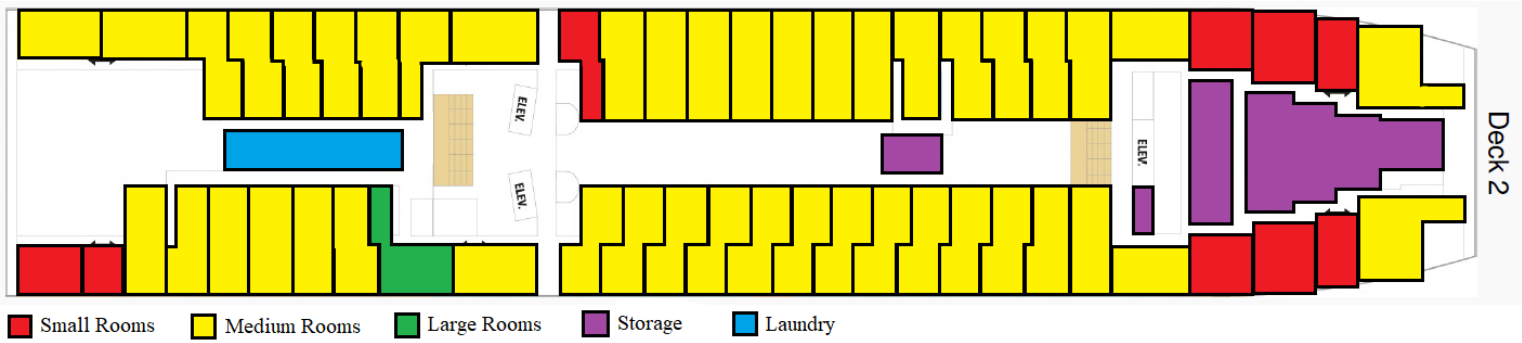


Figure 21: Deck 2 Layout After Modification

Figures 20 and 21 show the reference and modified layouts of Deck 2. This is the first deck with passenger staterooms which were the largest focus of our arrangement modifications. All of the exterior staterooms and some of the interior staterooms were used to create larger "apartments," separated into small, medium, and large rooms. The remaining interior cabins were converted into either a shared laundry space or storage units.

Deck 3

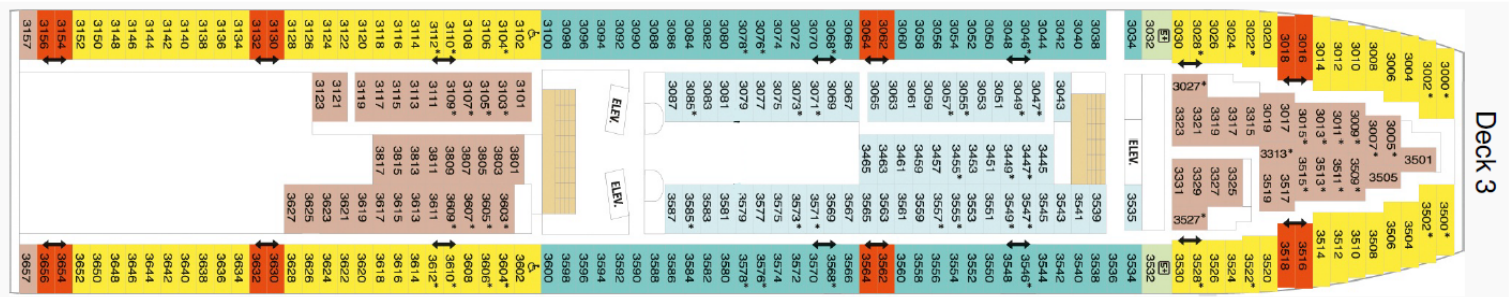


Figure 22: Deck 3 Layout Before Modification



Figure 23: Deck 3 Layout After Modification

Figures 22 and 23 show the reference and modified layouts of Deck 3. As on Deck 2, all of the exterior staterooms and some of the interior staterooms were used to create

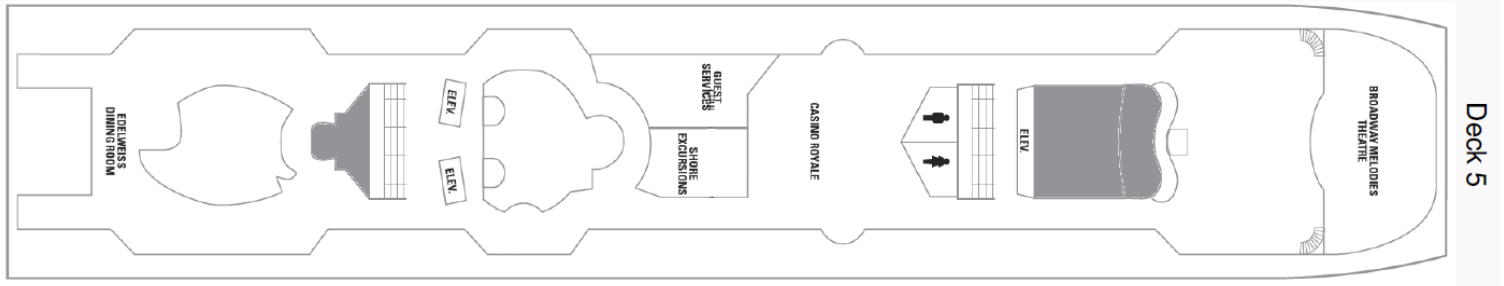


Figure 26: Deck 5 Layout Before Modification

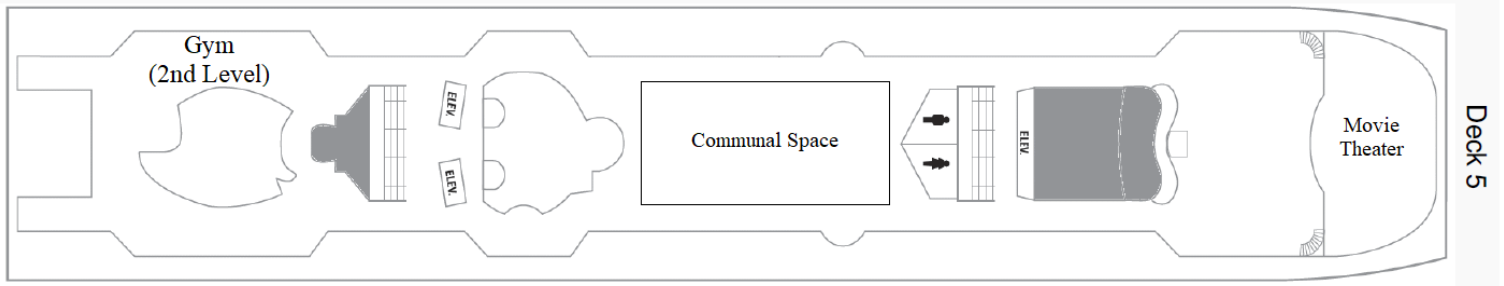


Figure 27: Deck 5 Layout After Modification

was maintained and can be utilized as a movie theater or meeting space with a capacity large enough to fit all residents.

Deck 6

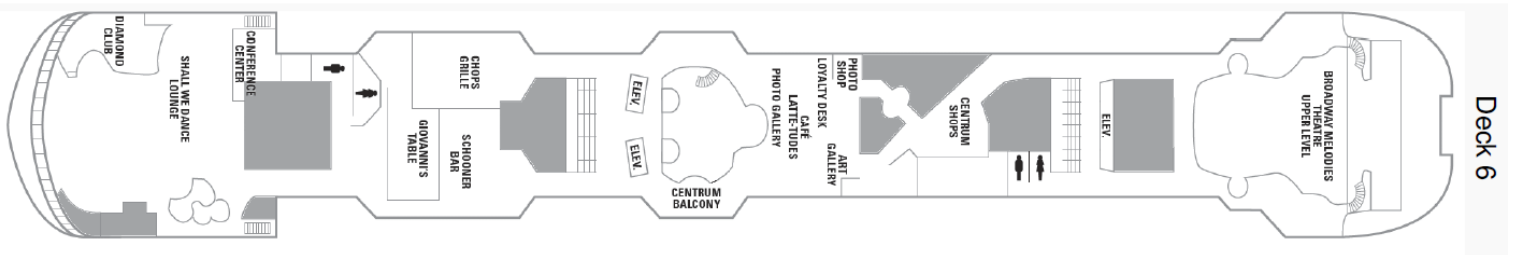


Figure 28: Deck 6 Layout Before Modification

Figures 28 and 29 show the reference and modified layouts of Deck 6. As on Deck 5, this deck contains only amenities and no living spaces. The second level of the Broadway Melodies Theatre was maintained as described on Deck 5. All of the shops and areas just forward of the Centrum Balcony were cleared out and replaced with one coffee shop and a business center containing computers and printers for resident use. The three restaurants and bars were converted into a grocery store. The Shall We Dance Lounge and Diamond Club will be repurposed into a daycare facility that will be open to the public.

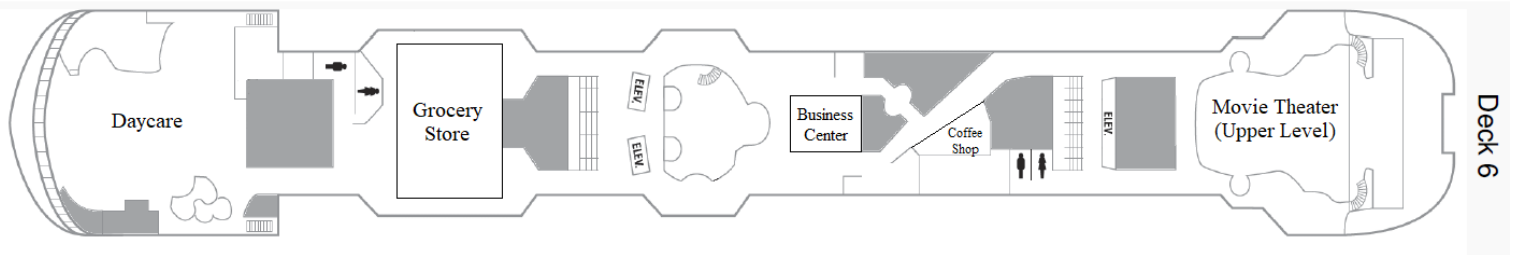


Figure 29: Deck 6 Layout After Modification

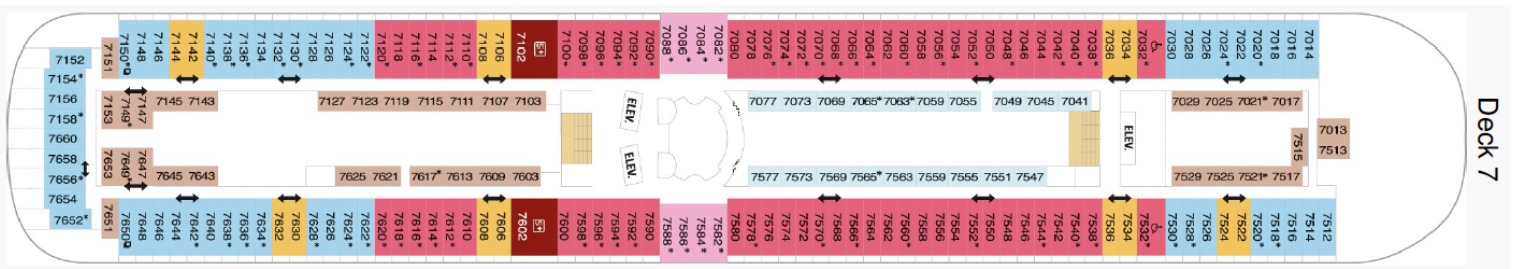


Figure 30: Deck 7 Layout Before Modification

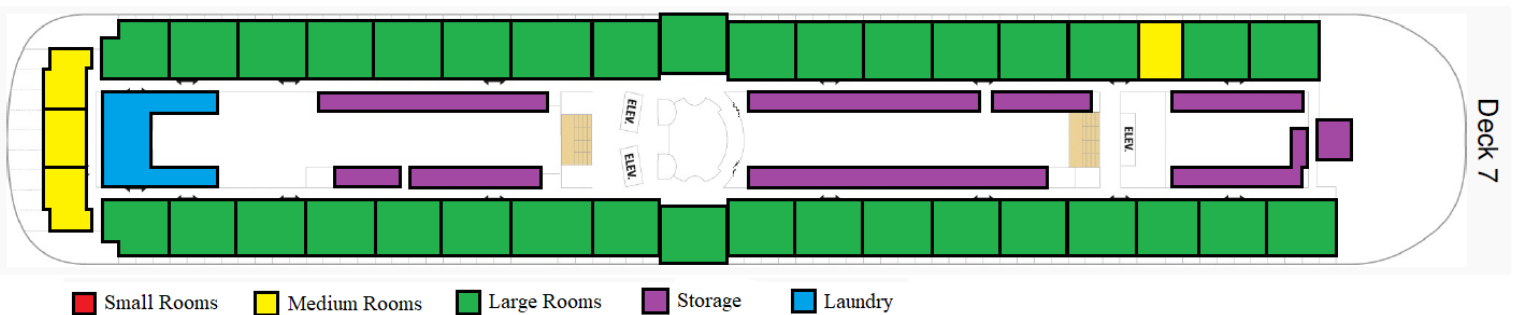


Figure 31: Deck 7 Layout After Modification

Deck 7

Figures 30 and 31 show the reference and modified layouts of Deck 7. All of the exterior staterooms were used to create apartments. The interior cabins were converted into either a shared laundry space or storage units.

Deck 8

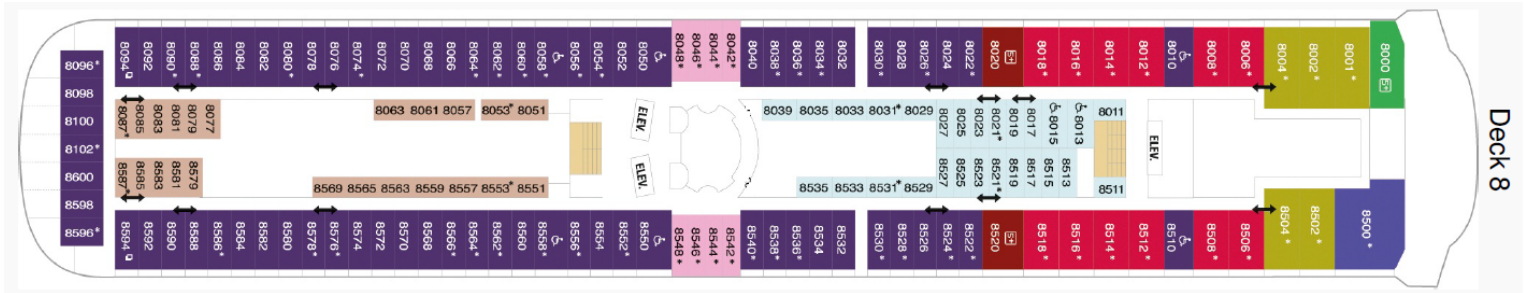


Figure 32: Deck 8 Layout Before Modification

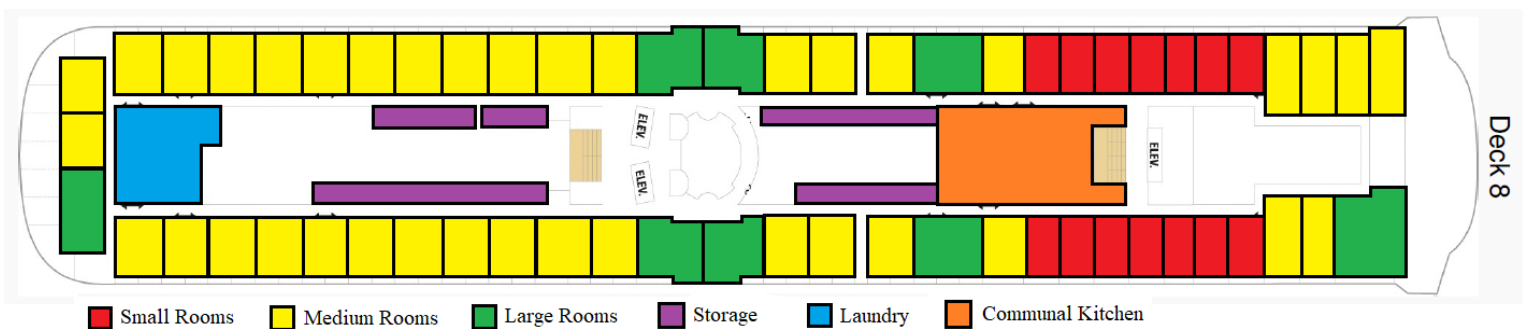


Figure 33: Deck 8 Layout After Modification

Figures 32 and 33 show the reference and modified layouts of Deck 8. All of the exterior staterooms were used to create apartments. The forward interior cabins were converted into a communal kitchen space to be used by the residents of the small units. The remaining interior cabins were converted into either a shared laundry space or storage units.

Housing Unit Summary

In total, there are 246 housing units that have been created from the original cabin arrangement, which we predict will be able to accommodate approximately 350 people. The units break down into the following notional major categories:

“Small/Studio” (42) – Unit sizes range from 252-438 ft^2 . Rent prices range from \$475-1000 per month. No in-unit kitchens; cooking/food storage needs are accommodated by communal kitchen spaces.

“Medium/One Bedroom” (160) – Unit sizes range from 482-590 ft^2 . Rent prices range from \$1269-1500 per month. In-unit kitchens provided.

“Large/One+ Bedroom” (44) – Unit sizes range from 629-1326 ft^2 . Rent prices range from \$1550-3000 per month. In-unit kitchens provided.

A complete breakdown of the rooms is shown in Figure 61 in Appendix H.

Deck 9

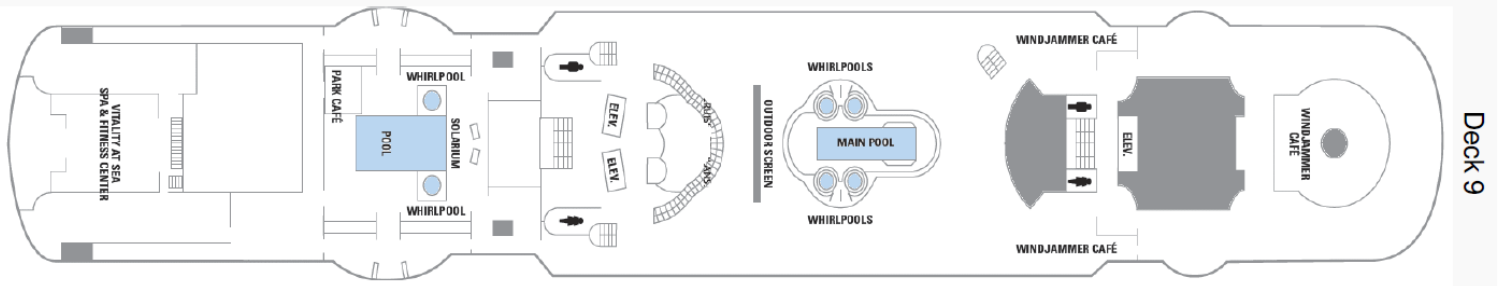


Figure 34: Deck 9 Layout Before Modification

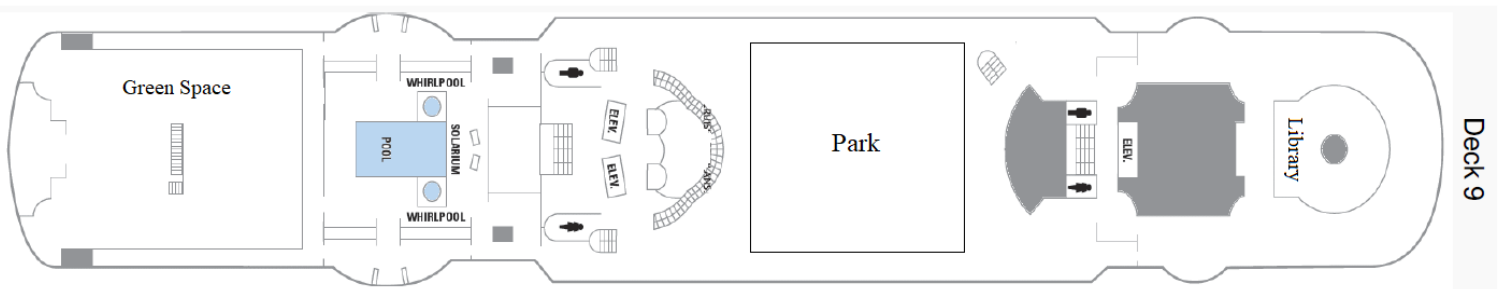


Figure 35: Deck 9 Layout After Modification

Figures 34 and 35 show the reference and modified layouts of Deck 9. The Windjammer Cafe was converted into a library. The main pool and surrounding area were removed and replaced with a large park. The indoor pool was maintained as is, other than removing the Park Cafe. The Vitality At Sea Spa and Fitness Center and as much of the surrounding area as possible were converted into a green space for the residents.

Deck 10

Figures 36 and 37 show the reference and modified layouts of Deck 10. The kid friendly amenities towards the front were converted into another green space. The running track and Crystal Canopy were maintained. The upper level of the Vitality At Sea Spa and Fitness Center was also converted into a green space, while the rock climbing wall was removed.

Decks 11 and 12

Figures 38-41 show the reference and modified layouts of Decks 11 and 12. These decks consist of relatively small usable areas in the superstructure. On both decks we converted the existing amenities into additional green space.

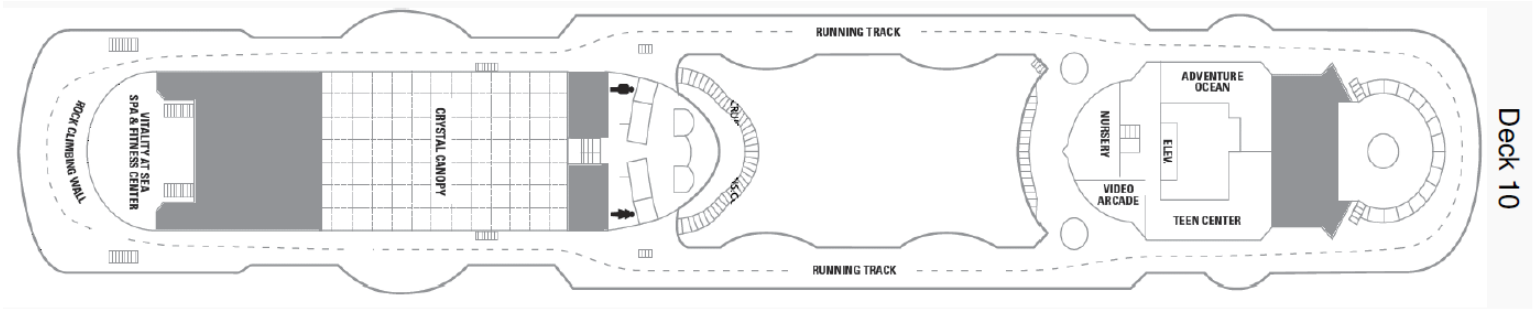


Figure 36: Deck 10 Layout Before Modification

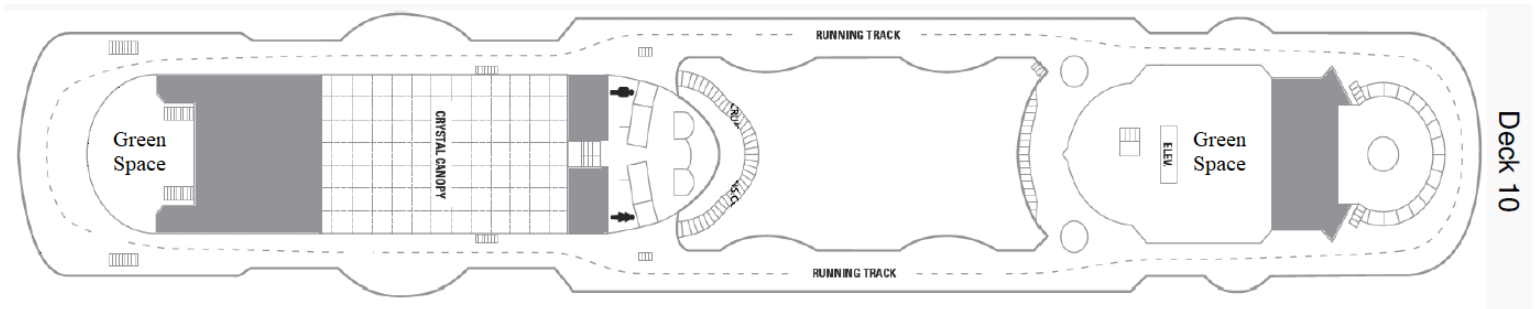


Figure 37: Deck 10 Layout After Modification

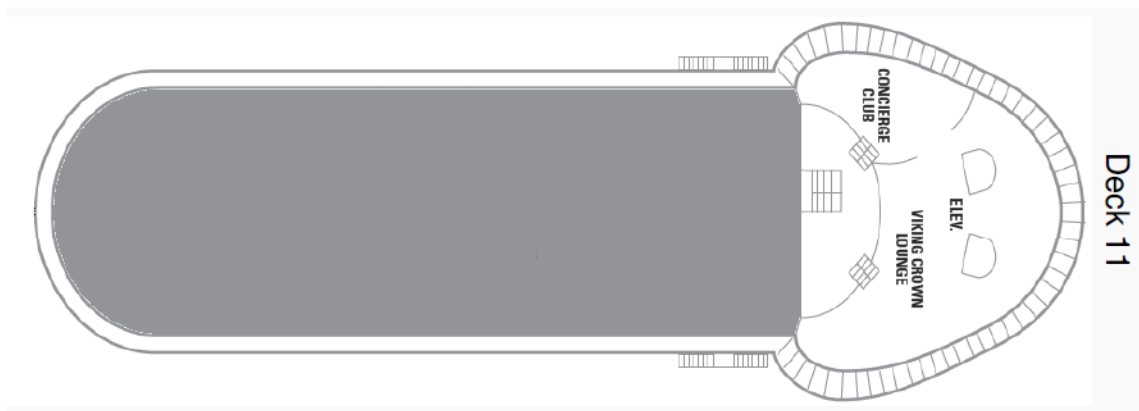


Figure 38: Deck 11 Layout Before Modification

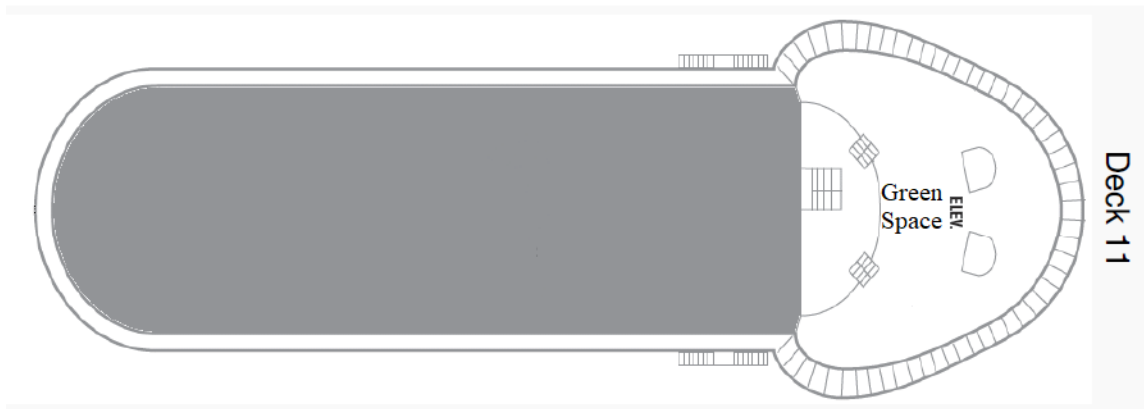


Figure 39: Deck 11 Layout After Modification

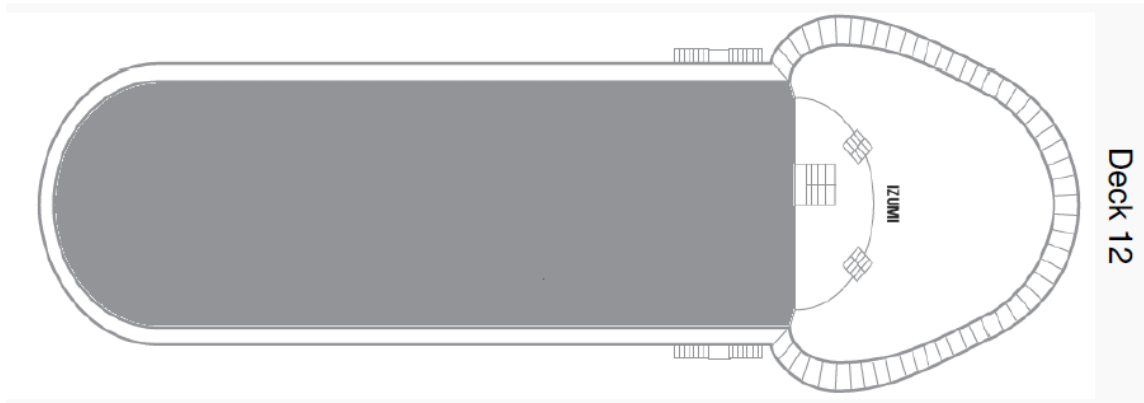


Figure 40: Deck 12 Layout Before Modification

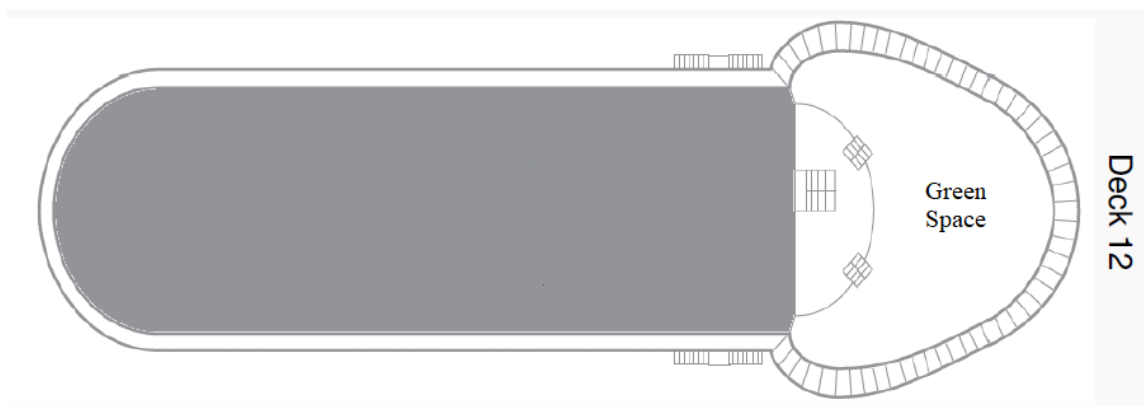


Figure 41: Deck 12 Layout After Modification

4.1.3 Hull Subdivision

The *Rhapsody*'s registry page reports that the ship has 20 transverse bulkheads [48]. The actual longitudinal positions of the watertight bulkheads were not publicly available, so we assumed they were evenly spaced along the length of the ship. We also assumed that the collision bulkheads were located at 5% of the total ship length aft of the forward perpendicular (FP) and forward of the aft perpendicular (AP). Floodable length analysis was first conducted with the pre-conversion bulkhead locations, with the resulting floodable length curve provided in Appendix B. This analysis demonstrated that the *Rhapsody* hull satisfies the SOLAS 90 two-compartment floodable length standard. Because this ship is not a U.S. Naval vessel, no additional requirements were assessed.

The addition of parking spaces in the lower decks would require the removal of certain transverse bulkheads. The allotted parking spaces span from approximately 75 meters to 140 meters aft of the FP. We conservatively estimated that this correlated to five transverse bulkheads (bulkheads 7 through 11). These bulkheads were removed and the floodable length analysis was re-performed. Despite this substantial widening of hull subdivisions, the floodable length criteria are still met, as seen in the post-conversion floodable length curve provided in Appendix B. The two-compartment standard remains satisfied.

Beyond these damaged stability considerations, more rigorous structural analysis is required to determine the bulkheads' removal on the ship's overall strength characteristics and performance.

4.1.4 Structural Arrangement/Design

Decks 0, 1, and the "Tween" deck were significantly altered to accommodate space for parking. As such, a minimum of three factors must be evaluated to determine the feasibility of such a conversion: the effect on the vessel's floodable length, the effect on structural integrity, and the amount of parking spaces that can be afforded. Because the decks that were converted to parking reside below the margin line, they must be evaluated to ensure that floodable length requirements are met since the intention is for the vessel to reside in the water. This evaluation can be found in Section 4.1.3 and in Appendix B. The deck stresses must be analyzed to ensure that the spaces can indeed function as a garage. Finally, the number of spaces created must be sufficient for the number of residents for the effort to be worth the cost.

The lack of fidelity in our 3D model—with respect to the material type and the bulkhead/beam/strake layout in these spaces—did not lend itself to a meaningful finite element analysis (FEA) performance. Therefore, to determine if the structure of the cruise ship is capable of performing as a partial garage, it is better to compare the requirements of a structure designed for parking versus one designed for people. The International Building Code (IBC) requires land-based parking structures to be designed for a live load of $40 \frac{\text{lbs}}{\text{in}^2} (1.69 \frac{\text{kg}}{\text{m}^2})$ [57]. Comparatively, the IBC requires areas designed for public assembly to withstand a live load of $100 \frac{\text{lbs}}{\text{in}^2} (4.24 \frac{\text{kg}}{\text{m}^2})$. Since the ship was designed to accommodate thousands of passengers, it is assumed that the decks were built with similar pressure requirements. Therefore, using the aforemen-

Table 3: Parking Spaces by Deck.

Deck	Area (m^2)	Spaces Available
1	2400	72
0	2400	72
Tween	1700	50
Total		194

tioned live load numbers required by the IBC as a guide, it is assumed that the decks, which included berthing spaces for crew members, are sufficient to withstand the loads of vehicles. More detailed structural analysis, along with the requisite construction information, is necessary if this concept goes to further feasibility level design.

Given the beam of the vessel is 32 meters it was determined that the ship is wide enough to incorporate ninety-degree parking. Since this is the most efficient layout it would allow for the maximum number of spaces[57]. Using the square footage from the 3D model at each of the applicable decks, between the above-mentioned frames, gave a baseline area to reserve for parking. Taking this area and dividing by an efficiency rating of $32.5 m^2$ [57], to account for lane widths for vehicular travel and parking space width, gives the total number of viable parking spaces per deck. Table 3 shows the number of spaces per deck and the total number of spaces.

Considering that there are 246 units, 194 parking spaces means that 78% of units could have a designated parking space. However only 66% of Boston residents have a car, so it is reasonable that these 194 spaces would cover all the residents with vehicles[58]. Given that more space is available to dedicate to parking, it is possible to expand the parking capacity to accommodate additional guest parking, staff parking, and even potentially public parking. Sufficient structural analysis and any required waivers or alternatives to ensure continued satisfaction of floodable length requirements would be necessary. Therefore, it was determined that converting portions of the three lower decks into a parking facility is feasible and provides a highly desirable amenity in a densely populated area.

4.1.5 Power and Propulsion Plant

The converted *Rhapsody* uses shore power as the primary source of electrical power. Two Wärtsilä 12V46C marine diesel engines are maintained in an operational status as a backup source of power in the event of a loss of shore power or when the vessel cannot connect to shore power (*i.e.* being towed, inclement weather, etc.). Although consideration was given to removing the propulsion shafts, no clear benefit could be identified to warrant the engineering complexity, technical risk, and added costs to the conversion project. For these reasons the shafts will remain in place but all support systems will be retired in place to alleviate the maintenance burden and lifecycle costs. As such the converted ship maintains no propulsion capability.

Table 4: Typical Form Coefficients[13].

<i>Coefficients</i>	<i>Destroyer</i>	<i>Cargo Liner</i>	<i>Harbor Tug</i>	<i>Great Lakes Bulk Freighter</i>	<i>Passenger Liner</i>	<i>Model</i>
C_B	0.52	0.64	0.58	0.87	0.59	0.64
C_{WP}	0.74	0.76	0.80	0.91	0.72	0.84
<i>Ratios</i>						
L/B	9.82	6.92	4.18	9.67	8.38	7.83
L/T	32.75	16.82	9.33	29.00	26.25	35.23
B/T	3.33	2.43	2.23	3.00	3.14	4.50

4.1.6 Weight Estimation

In order to assess the converted cruise ship’s approximate weight, our major steps were as follows: estimate the weight of the pre-converted cruise ship; categorize the weights and allocate them to each deck; evaluate the expected change in weight due to additions and removals on each deck in the converted design.

Once an estimate of the ship’s displacement was determined, ORCA software was used to get a cross-curve stability analysis. The results yielded a block coefficient of 0.64, which falls within the range of expected values for a ship of this size (see Table 4). Additionally, a positive value was obtained for metacentric height (GM), proving that the modeled hull was stable. The value of GM found during this initial stability analysis was high, but this was to be expected since the model was analyzed in an light load state while the displacement given was for a ship at full load condition. To get the full load displacement baseline from which to conduct conversion, we had to allocate appropriate weight estimations throughout the ship.

In order to get an estimation of weights, Ship Work Breakdown Structure (SWBS) groups were taken from a similar-sized Landing Platform Dock (LPD) class naval vessel. Factors of applicability were applied to each weight group. The new weights were summed and normalized to provide a representative ratio weight group to total weight. These normalized ratios were applied to the calculated displacement of the ship to obtain estimated weight groups for the cruise ship as seen in Table 5. Using open source layouts of the ship, and leveraging previous knowledge of ship arrangements, area data for each deck was then extracted from the Rhino model and the weights of each SWBS group were divided and spread across each applicable deck of the ship. With the weight of each group spread longitudinally and vertically across the ship, another stability and hydrostatics analysis was performed. As seen in Figure 55 of Appendix E, a more realistic GM of 0.878 was found with a loaded ship with all other data remaining close to its initial value. This proved that the baseline model, much like the actual ship, was stable. Therefore, conversion could now be reflected and accurately analyzed using the model.

Post-Conversion Weight Assignments

Given our pre-conversion estimates for SWBS group weight allocations for each deck, we employed a process for post-conversion weight estimation using this same framework. We reassigned SWBS weight group allocations based on the scope and nature of the modifications proposed on each deck.

For example, the main structural weight (*i.e.* SWBS Group 100) changes on the residents decks are due to the rearrangement of the living spaces to provide larger and more desirable housing, which required the knockdown of steel walls dividing adjacent cabins. To better evaluate this portion of the redesign, we generated 3D representations of the original cabin layout on Deck 2 and its converted housing layout based on their corresponding 2D deck plans provided in Section 4.1.2. These 3D renderings for Deck 2 pre-conversion and post-conversion are shown in Figures 42 & 43, respectively. The same steel material was assumed for both models. The resulting difference was **27.7 metric tons**, and this was taken as the structural weight removal value for Deck 2. Owing to the relative similarity between Deck 2 and the other resident deck layouts (for both pre and post-conversion), this same value was assumed for the structural weight removal of all the resident decks. The only slight exception was Deck 4, where the cabins and housing account for approximately half of the deck space, so appropriate factors were applied to reflect this specific arrangement.

Other proposed structural modifications were not as detailed, and therefore were not modeled and reanalyzed. Instead, the team assessed the 2D post-conversion renderings to estimate an appropriate factor for the amount of structural weight being added to or removed from each deck.

We followed a similar process across all decks and SWBS groups. For example, on Deck 0, we proposed converting the crew berthing area into a parking garage, and therefore would have to remove significant amounts of SWBS Group 600-associated weight (*i.e.* bedding, lockers, common area furniture, etc.). Therefore, we estimated a 70% SWBS Group 600 weight reduction for Deck 0. A similar methodology was employed on the other decks where parking was proposed.

To address the resident decks, we envisioned that much of the furniture in each existing cabin would be removed in order to create more open space in the housing units. For example, while every cabin currently includes at least two twin beds, the resulting base unit which merges four current cabins will not need eight twin beds. The same logic can be applied to the other furnishings within each cabin, such that we predict a considerable non-structural weight reduction from this perspective. However, this will be counter-acted by the installation of kitchen appliances in the majority of the new units. More detailed analysis is warranted to better ascertain the net effect of these competing changes, but the team determined that it will likely result in relatively minimal Group 600 weight changes across the resident decks. In order to apply conservatism to the design, we assumed that there would be a 10% Group 600 weight reduction in all resident decks below the initial vertical center of gravity (KG), and a 10% weight increase in all resident decks above KG. Deck 4 again proved to be a slight exception to this heuristic, as we also had to account for the inclusion of the main gym space in the aft portion of this deck, which drove up the SWBS Group 600 weight estimate. Overall, by effectively removing weight low and adding weight

Table 5: SWBS Breakdown of Cruise Ship Weights

SWBS Group	Pre-Conversion Weight (MT)	Post-Conversion Weight (MT)
1	21428.7	19761.9
2	2600.4	2600.4
3	1973.2	1973.2
4	938.3	187.7
5	5807.7	5343.1
6	11063.4	9625.2
7	0	0
Total	43811.6	39491.3

high, we aimed to demonstrate that the converted design would still satisfy all intact stability requirements.

All remaining decks were handled on a more specific case-by-case basis by evaluating the major amenity changes and determining an appropriate weight addition or reduction factor for each SWBS group. One major driver of weight reduction higher in the ship was the anticipated removal of SWBS Group 400-related command and control surveillance equipment. Nearly the entire navigational radar and communications suite can be removed since the converted ship will only be operated as a towed vessel.

The pre-conversion and post-conversion total weight estimates are provided in Table 5. We estimate an overall net weight reduction of **4300 MT**, which represents a **10%** reduction from the pre-conversion total weight estimate.

After determining the post-conversion weights, the Rhino model was adjusted to reflect these changes, and stability and hydrostatics analysis was conducted in ORCA once again. The results of this analysis can be seen in Figures 57 & 58 in Appendix E. The calculated post-conversion GM was found to be 1.34 m, higher than that of the pre-conversion model, meaning the ship became more stable through the conversion process.

4.1.7 Synthesis and Convergence

Because we did not have an accurate ASSET model for this project, we had to determine if our modified cruise ship met the MIT 2N Convergence Criteria through different methods. We used a breakdown of “essential” and “desired” convergence criteria requirements as shown in Tables 6 & 7, respectively.

4.2 Cost Analysis

4.2.1 Producibility and Acquisition Cost

Purchase and Refurbishment

As previously detailed in the baseline variant selection process, purchase cost data was taken from the for-sale cruise ship spreadsheet provided by one of our subject

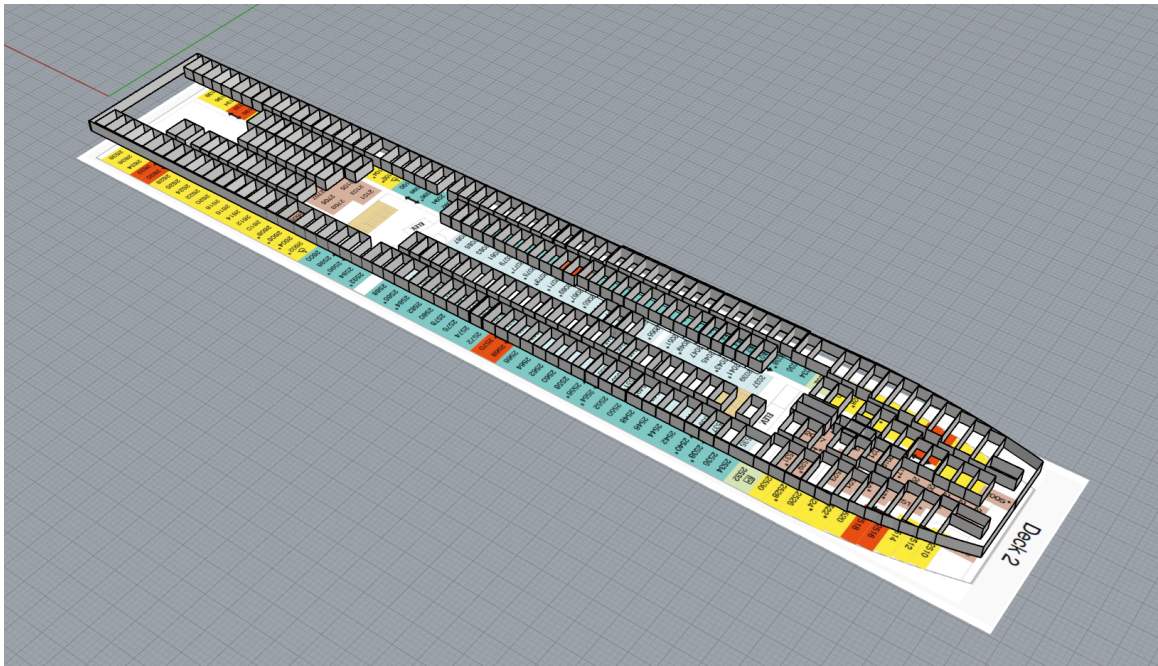


Figure 42: 3D rendering of Deck 2, pre-conversion.

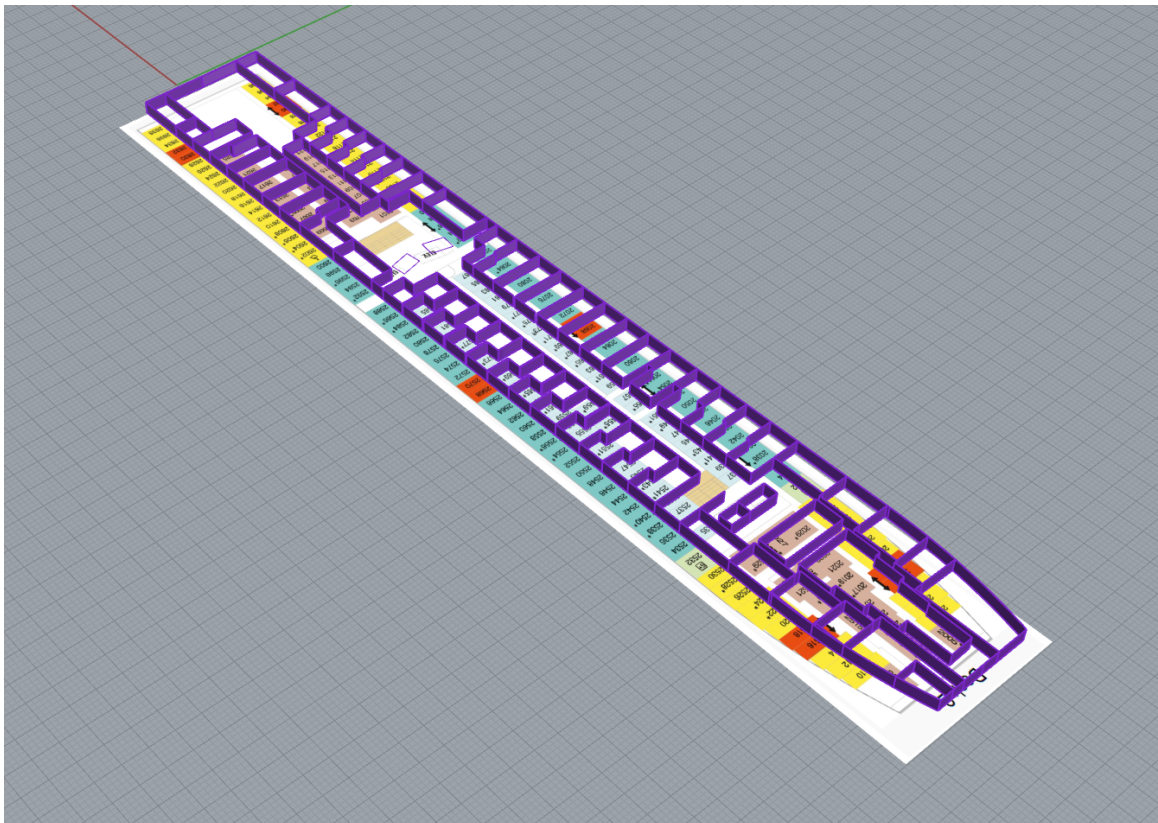


Figure 43: 3D rendering of Deck 2, post-conversion.

Table 6: Essential Convergence Criteria Requirements

Requirement	Confirmed or Assumed	Reasoning/Additional Information
Design satisfies requirements?	Confirmed	This design meets all requirements as laid out in Section 1.3.
Does it float?	Confirmed	The service record of the <i>Rhapsody of the Seas</i> proves that it floats. Additionally, predicted weight calculations from the model show an increase in stability.
Does it float upright?	Confirmed	An ORCA stability analysis of the modified <i>Rhapsody</i> vessel indicated the ship had a GM of about 15 ft. This report is shown in Figure 55 in Appendix E.
Is there sufficient reserve buoyancy?	Confirmed	The modified cruise ship had significant reserve buoyancy due to the large amount of enclosed volume the <i>Rhapsody</i> has above the waterline. The estimated tons per inch (TPI) immersion for the <i>Rhapsody</i> , given the water plane area of 69,107 ft^2 from ORCA, was calculated to be 164.5 LT/in. This estimate was based on Equation (3-15) of <i>Introduction to Naval Architecture</i> [13]. The <i>Rhapsody</i> features approximately 44 ft of freeboard, indicating that the ship has approximately 88,600 LT of reserve buoyancy[50]. The <i>Rhapsody</i> has a deadweight tonnage of 8000 LT according to the DNV GL vessel register.
Is it big enough?	Confirmed	The size of the cruise ship was evaluated throughout the project and deemed satisfactory.
Is it arrangeable?	Confirmed	The arrangeability of the cruise ship was fully evaluated in Section 4.1.2 and deemed satisfactory.
Is there enough electrical power?	Confirmed	The electrical power demands will normally be handled by shore power. Still, the electrical capacity being retained onboard was fully evaluated in Section 3.2.2 and deemed satisfactory to accommodate the new estimated base and peak loads.
Will it make speed?	N/A	This design is intended to be docked pierside indefinitely. It maintains no self-propulsion ability.
Is it strong enough?	Assumed	The strength of the vessel was proven by the <i>Rhapsody</i> service record, but a hull life analysis would need to be completed to determine years of remaining service.
Are floodable length requirements met?	Confirmed	We created a floodable length diagram in Excel using the 20 transverse bulkheads on the <i>Rhapsody</i> [48]. Collision bulkheads were placed at 5% of the distance from the bow and the stern, and the other 18 bulkheads were evenly spaced between the collision bulkheads. To accommodate the parking garage on the lower decks, five bulkheads were removed as detailed in Section 4.1.3. This evaluation proved the post-conversion design met the SOLAS 90 two-compartment standard and is shown in Appendix B.

Table 7: Desired Convergence Criteria Requirements

Requirement	Confirmed or Assumed	Reasoning/Additional Information
Is it maneuverable enough?	N/A	This design is intended to be docked pierside indefinitely. It can be relocated but only by being towed, not self-propelled.
Are the ship motions acceptable?	Assumed	Assumed satisfactory when pierside due to the protected location of the cruise ship within Boston Harbor. In the event of extreme weather a location-specific plan will need to be followed.
Are the coefficient/ratios within appropriate “design lanes”?	Confirmed	Given that the calculated block coefficient of $C_b = 0.64$, water plane area coefficient of $C_{WP} = 0.84$, and $\bar{GM} = 1.34m$ all fall within normal ranges of similar sized vessels as observed in Table 4. Therefore, it can be concluded that the design parameters reside within appropriate design lanes[13][59].
Is there appropriate freeboard?	Confirmed	Currently the <i>Rhapsody</i> has 44 ft of freeboard which was deemed more than sufficient. Furthermore, the conversion resulted in a net reduction in displacement which caused an increase in freeboard.
Is there appropriate trim/heel?	Assumed	Assumed satisfactory as the <i>Rhapsody</i> likely has no static trim or heel; however, the weight changes due to the conversion process would likely cause changes to static trim/heel. Therefore, post-conversion analysis would need to be conducted.
Is damaged stability satisfactory?	Assumed	Assumed satisfactory based on the initial construction, further analysis will be required to account for structural changes on Decks Tween, 0, and 1.
Is damaged strength satisfactory?	Assumed	Assumed satisfactory, based on the initial construction and its compliance with SOLAS 90. Further analysis of damage strength is warranted for future work.

matter experts[30]. Our purchase cost estimate was based on the **\$35 million** listed sale price of the *Monarch of the Seas*, which was the vessel initially targeted for selection but ultimately not chosen since it had already been sold. The *Monarch* shares many of the same general features as the *Rhapsody* but is approximately 20,000 tons smaller[60]. Therefore, a scaling factor was applied to arrive at a purchase cost estimate of **\$45 million**.

In order to estimate the refurbishment costs, we retrieved historical cost data spanning from 2005 to 2021 of cruise ship refurbishments, refits, and overhauls[61]. Refurbishment cost was analyzed as a function of tonnage to get a better sense of how cost scaled with ship size, as shown in Figure 44. Additionally, details of these previous refurbishments were surveyed for similarities between the work accomplished on those ships, and the conversions proposed in this design. For example, the *Rhapsody* itself underwent a \$54 million refit in 2012 which involved adding new cabins, an outdoor movie screen, new restaurants, and a nursery[5]. In addition to these general refurbishment costs, we also had to specifically account for costs associated with retrofitting the ship to support shore power operations. All previous shore power retrofit projects reported an approximate \$1 million cost to upgrade, and so this was the value assumed for our conversion[9]. The United States Bureau of Labor Statistics Inflation Calculator was used to reflect end-of-2022 inflation-adjusted prices. As such, the refurbishment costs were estimated at **\$50 million**.

A second method to determine an estimate for the refurbishment cost was done by calculating the individual costs of major portions of the refurbishment. In order to achieve the desired room layouts as shown in Figures 21, 23, 25, 31, & 33, major renovations to the staterooms were needed. These renovations can be split into two major categories: adding kitchens to each of the medium and large units, and combining the pre-existing cabins into the designated apartments. To estimate the cost of adding a kitchen, we used an average cost of \$24,000 for a minor remodel which includes “the addition of entry-level cabinets, appliances updated to new, energy-efficient models, new countertops, kitchen sink and faucet, new flooring, and freshly painted walls[62].” Applying this cost estimate to each of the 204 medium and large units designed with kitchens results in a \$4.9 million overall cost estimate for adding kitchens.

To remodel the rooms, we used an estimate of \$10 per square foot for paint and flooring resulting in a cost of \$1.3 million[63]. The biggest difference between these estimates and the actual work on the ship is the labor cost. The 1-3-8 thumb rule represents “the relative costs of work performed in shops, assembly areas, and aboard ship after launch, respectively[64].” Assuming the labor cost is 40% of the cost of these estimates, we applied this rule and multiplied the labor cost portion of the estimates by 8 to get a final estimate of \$25 million[65].

We used a similar method to determine the cost of constructing the parking lot on the lower decks. Starting with an estimate of \$6 per square foot followed by the application of the 1-3-8 rule to the entire cost instead of just labor gave an estimate of \$5.2 million[66]. For the other large amenity renovations we assumed \$1 million for the gym, \$250,000 for the grocery store, and \$100,000 for the daycare[67][68][69]. Once again applying the 1-3-8 rule to the assumed 40% labor cost resulted in an estimated \$5.4 million cost for these three conversion projects.

Because we are not maintaining propulsion capability onboard the ship, we considered removing the propeller and the shaft as they are no longer necessary. Following a discussion with the Engineering Manager of Submarine Propulsion Shafting Systems at Naval Surface Warfare Center Philadelphia Division (NSWCPD), we came to the conclusion that the cost of removal would be substantial and far outweigh any potential benefits of doing so.

Finally, as a conservative estimate of the cost of construction to demolish and rebuild walls, minor amenity renovations, and in general higher construction costs aboard a ship in dry dock compared to shore construction, we added a factor of 50% on top of all the estimates. This gave us a final total refurbishment cost of **\$53.3 million**, a data point that supports the estimate determined from historic cruise ship repair data.

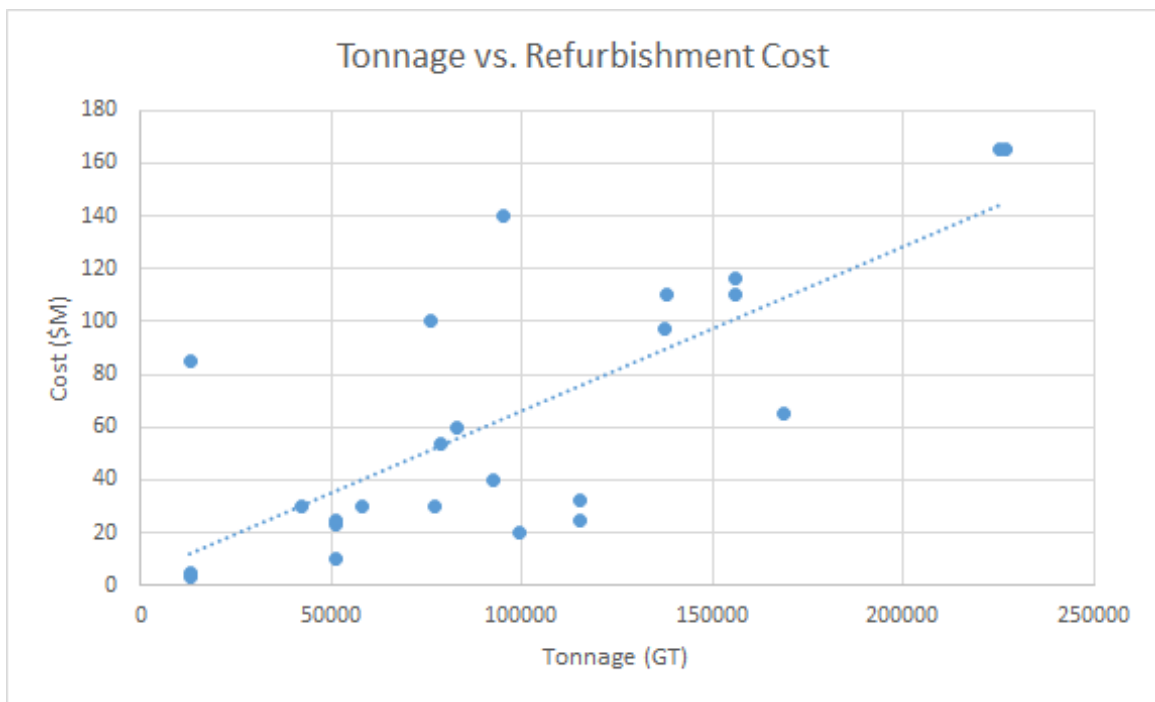


Figure 44: Tonnage vs. Refurbishment Cost (2005-2021)

Pierside Infrastructure Upgrades

In addition to the shipside refurbishments and upgrades, this conversion will also require considerable pierside upgrades to infrastructure and utility systems to support essential services onboard. The most significant of these upgrades will be the installation of shore power technology at the North Jetty Pier. In consideration of the previous East Coast shore power projects recently completed, about which information can be found in Appendix A, and adjusting properly for inflation, we estimate the pierside shore power costs to be **\$18.5 million**. This includes the installation of plug-in ports directly at the pier, acquisition costs of all necessary power cabling, and the establishment of ancillary facilities and equipment to support successful shore power operations.

Based on the expected average and peak electrical loading previously estimated for the converted cruise ship, it was assessed that the actual city electric grid would have sufficient capacity to take on this new power demand without requiring additional infrastructure upgrades. This eliminated the need for the construction of a new 40 MW substation which would have added an additional \$15-\$20 million in upgrade costs.

The other major systems requiring pier upgrades are potable water, sewage, and waste management. The currently installed water distribution systems at Flynn Cruiseport and the North Jetty Pier are only used for washing and cleaning and do not provide water suitable for human consumption. Therefore, the ship will rely on connecting to the city's water distribution system, managed BWSC, as described and justified in Chapter 3. To provide a long-term solution for sewage and wastewater disposal, permanent underground piping installation and integration with the city's sewage system would be required. The Miami case study determined that these upgrades at Port Miami would cost between \$2-\$4 million[2]. Conservatively assuming this estimate's upper bound and properly accounting for inflation, the cost of these infrastructure improvements are estimated to cost **\$4.8 million**.

4.2.2 Operations and Support Cost

Utilities

Based on the previous power demand estimates detailed in Chapter 3, the use of shore power technology, and assuming the discounted electric rate of 20 ¢/kWh, the annual total electricity cost is estimated to be **\$2.3 million**.

In order to estimate the total annual costs associated with water and sewage services, we first analyzed the resident-specific usage rate and costs. We referenced the most current Boston resident water usage data city's water and sewer revenue rates, current as of January 1, 2023. The average Boston consumer uses 41 gallons of water per day (GPD), so this was assumed for the resident usage rate[70]. This per-day usage falls within the lowest-tier revenue rates of \$8.222/1000 gallons for water and \$10.996/1000 gallons for sewage[71]. In total, this results in an annual per capita cost of \$287.58. Our current proposal assumes a 350-resident capacity, therefore the total annual resident water and sewer costs are estimated to be **\$100,659**.

Next, we considered the fitness center as the other principal driver of water and sewer usage to better estimate the overall utility cost. We referenced a case study that discussed the water-saving efforts of the Longfellow Clubs, a consortium of seven Boston-based fitness clubs, implemented from 2006-2013[72]. The report cited that they were able to reduce their average water consumption to 165,600 gallons per month. In recognition that not all of their measures could be replicated on the converted cruise ship, we conservatively estimated that the onboard fitness center's water consumption rate would be 200,000 gallons per month. Using the same revenue rate figures, this corresponds to an annual water and sewer cost of **\$64,259**.

Finally, we estimated that the remaining amenities and facilities that were yet unaccounted for would contribute roughly 20% to the overall water usage. As such, the total annual water and sewage costs were estimated to be **\$205,000**.

Staffing/Payroll

To determine our full-time staffing requirements, and associated annual salary costs, we first considered the typical staffing needs of a land-based apartment complex to determine an appropriate benchmark. We recognized that our staffing needs would be greater than this base estimate due to the number and size of the amenities offered onboard, and the retention of larger engineering equipment and distribution systems. Per the National Apartment Association’s Best Practices briefing from June 2020, we found that the general rule has been to employ one full-time office staff and one full-time maintenance staff for every 100 units[73]. In recent years, that rule has evolved such that for properties with 200 to 299 units, there are on average 44.6 units per full-time employee. Applying this metric to our 246-unit arrangement yields a minimum requirement of six full-time employees. For a more typical apartment complex, this would likely result in hiring two full-time employees each for service staff (front desk-type workers), unit maintenance technicians, and cleaning personnel. However, in consideration of the number of general-use amenities and spaces requiring upkeep, we propose staffing five full-time cleaning employees. Thus, we account for nine full-time employees strictly to handle the apartment-specific workload comparable to a land-based residential complex.

We believed it was important to specifically address the staffing needs of two of our larger amenities: the fitness center and daycare center. We found that for centers of comparable size, each of these facilities would require five full-time employees, thus adding 10 employees total to our payroll.

Finally, we assessed what sort of engineering department would need to be stood up to maintain and operate the larger equipment and systems which would remain onboard to enable day-to-day operations. Exact data on normal engineering crew sizes for RCG ships was unavailable, but the *Anthem of the Seas*, which is a *Quantum*-class vessel, reportedly has an engineering department of approximately 100 personnel[74]. The *Anthem* has a gross tonnage (GT) of approximately 168,000 GT, which is over twice the size of the *Rhapsody*, and has twice the installed electrical capacity[75]. Therefore, we applied a scaling factor of 0.5 to estimate that the nominal engineering crew size for the pre-converted *Rhapsody* to be 50 personnel.

We then conducted a broad assessment to determine what additional manning reductions we could claim given the equipment and systems which will no longer be operated, the equipment and systems which will be operated far less frequently compared to the ship’s original operational profile, and the equipment and systems which will operate with relatively similar frequency as before. For example, the entire propulsion suite will be retired in place, half of the main electrical generation suite will be retired in place, and the remaining half will only be used in an emergency scenario or in rare cases when the ship is being relocated. All of these operational condition changes enable significant manning reductions. Conversely, the electrical distribution system will remain fully operational, requiring the maintenance, monitoring, and safe operation of its 6,600 kV main bus bar, and 440V/220V smaller buses. Similarly, although potable water will be provided from BWSC via the pierside connection, its distribution throughout the ship will still require the reliable operation of portions of the as-installed water distribution system. Taking all these factors into account, we

justified the establishment of a 10-person engineering full-time staff.

We determined average salaries for these employee types in Boston to calculate an approximate total annual payroll of **\$1.1 million**[76][77][78][79][80].

Pier Lease

The North Jetty Pier in Boston is the proposed docking location for the modified cruise ship. This pier and over 10 acres of the surrounding land (Parcels 7 & 8 shown in Figure 45) are currently being leased to a company called Eastern Salt[81]. Under this lease Eastern Salt will upgrade the site for several million dollars and will pay \$202,000 a year in rent[6]. We used the same assumptions for rent costs because as mentioned previously if the ship were to be docked there, millions would also be invested into infrastructure upgrades. Therefore the assumed annual cost of leasing the North Jetty Pier is **\$202,000**.

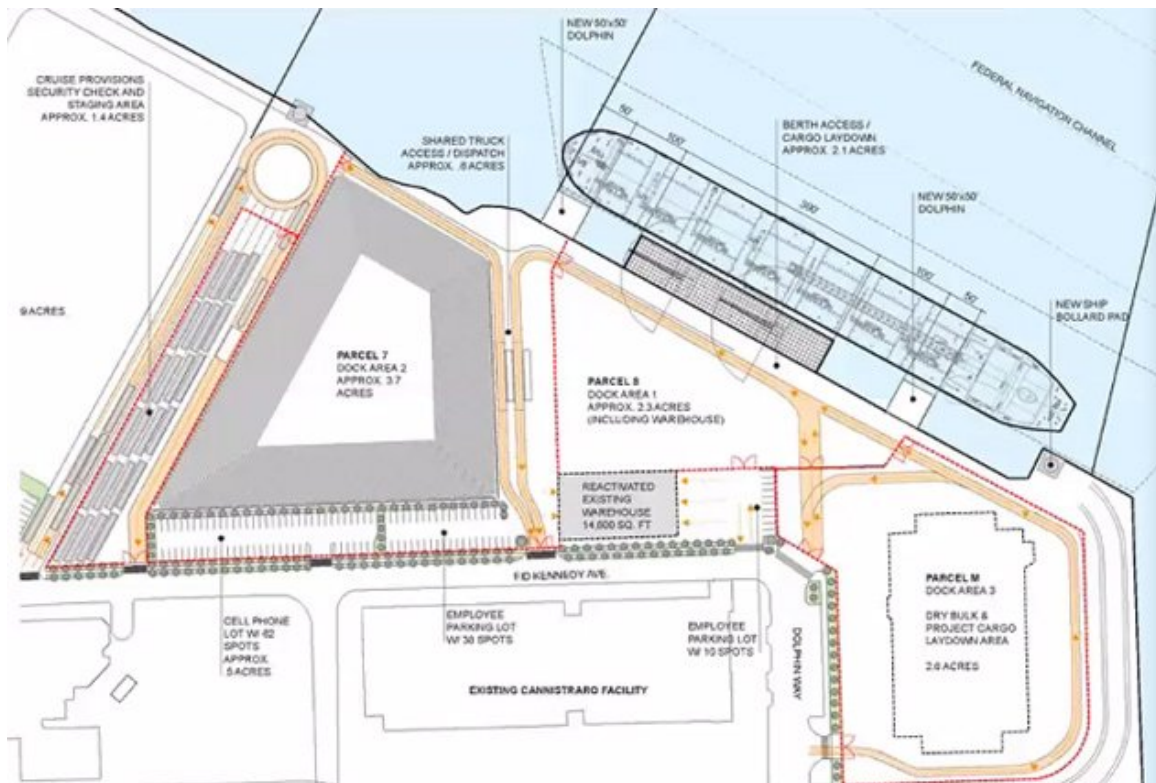


Figure 45: Map of the Eastern Salt leased facilities[6].

4.2.3 Cost Summary

Given the novelty of the proposed design, it was unclear how to ascertain which total life cycle costs (TLC) would reasonably apply to the converted cruise ship, and to what extent. Many of the capital and variable costs associated with TLC no longer apply to the converted cruise ship given it will largely function more as an affordable housing complex than an actual seagoing vessel moving forward. It has no meaningful operational profile. Some sort of maintenance period cadence will need to be established but should be significantly less burdensome than an actual cruise ship's upkeep schedule

Table 8: Cost Summary

	Fixed Costs (\$M)		Operational Costs (\$M)
Purchase:	45.0	Utilities:	2.6
Refurbishment:	53.3	Staffing:	1.1
Infrastructure:	23.3	Lease:	0.2
Total:	121.6		3.9

given its near-permanent pierside status. One estimate was calculated using the MIT 2N Cost Model and is shown in Appendix G.

All of the above mentioned costs are summarized in Table 8 with a total fixed cost of \$121.6 million and an annual operational cost of \$3.9 million. Given the unit allocation and cost breakdown shown in Figure 61 in Appendix H, and assuming 100% occupancy, we estimate that the annual rent revenue is **\$3.8 million**. While there may be additional revenue from opening up some of the amenities to the public, specifically the gym and daycare facilities, we did not account for this as a guaranteed source in our cost estimates.

4.3 Feasibility and Performance Analysis

Converting a cruise ship into affordable housing can certainly be done, but the driving question is how much it will cost. The feasibility of this project relies heavily on this cost discussion. As stated in Section 1.4, we assumed that the fixed costs will be covered through various state or federal grants and subsidies, as is often the case with affordable housing as it currently exists[82]. Therefore the remaining costs that are not assumed to be covered are the operational and support costs. Based on the estimates in the previous section, we calculated the operational costs to be \$3.9 million and the annual revenue from rent to be \$3.8 million. This results in a deficit of approximately \$100,000, a relatively small difference when considering the overall cost estimates of the conversion. It is reasonable to assume that this deficit could be covered by one or more of several different methods (*i.e.* additional government funding, discounted utility or lease rates, etc.). Based on the cost estimates we determined, converting a cruise ship into affordable housing is feasible.

It is difficult to define a metric for the performance of this converted cruise ship. The only “mission” it has is to serve as affordable and desirable housing. Having met the requirements listed in Section 1.3, the only other distinct performance criteria to evaluate was post-conversion stability. Certainly, if the converted cruise ship were unstable, it would not perform well as a housing complex. The post-conversion stability of the ship was discussed in detail in Section 4.1.6, and with a positive GM of 1.34 m, the ship is stable.

4.3.1 Comparative Cost Analysis

Affordable housing already exists in apartments and housing complexes ashore. The driving factor for this project was to determine if it could be done feasibly on a cruise ship. For this to be a reasonable alternative we must compare the cost of the

conversion to the cost to build an equivalent apartment complex. Cruise ships are uniquely suited for conversion into housing because of the number of accommodations already in place. It is clear that no other type of ship would prove as effective a housing platform for the cost, so we did not consider any other ship-based platforms.

One way we estimated the cost to build an apartment complex was by using a construction cost per square foot of area. Using the national average cost of \$398 per square foot and the combined square footage of only the living units (none of the amenities or common spaces), the cost to build an equivalent-sized apartment complex from scratch on land would be approximately \$52 million[83]. The living units make up less than 50 percent of the usable floor space on the cruise ship, so to build an apartment complex with the same amenities, common spaces, and parking would easily exceed \$100 million. However in Boston, the construction cost for a mid-rise apartment building ranges from \$392 to \$510 per square foot, so realistically the cost to build this complex in Boston could be significantly higher[84].

One of the biggest drivers in construction cost estimates comes from the cost of land at the locations where these apartments would be built. To build a complex with 246 units near Seaport or Downtown Boston, the building would almost certainly need to be a high-rise which increases the cost of construction. One source estimates anywhere from \$23.8 to \$240.8 million to build a 100 unit apartment building, but notes that “if the high-rise building is located in an urban area, expect costs to be much higher[85].” Assuming \$100 million would be enough to build a 100 unit building, but needing another 146 rooms and the amenities to go with it, it would be safe to assume such a building could cost in excess of \$200 million, significantly more than the cost estimate we found for the cruise ship conversion.

Another comparison can be made by looking at two similar construction projects in the Seaport neighborhood of Boston. Gables Seaport is a 307 unit luxury apartment building completed in 2020 and located less than a mile from the dock. The apartments vary from 469 square foot studio units to 1289 square foot two bedroom units[86]. The estimated construction of this project was \$157 million, again much higher than the fixed costs we found for our conversion[87]. While not a residential building, another large scale construction project in Seaport was the office building 121 Seaport, also located less than a mile from the dock. This 458,000 square foot building was completed in 2018 at a cost of \$170 million[88][89]. However the executive vice president and general manager at Skanska USA Building in Boston predicts that if this building were to be constructed today it would cost \$276 million, driven by increased material costs, shortages in labor, and a potential zoning policy change requiring stricter environmental standards[89]. It is clear that construction costs for apartments can far exceed our conservative cost estimates including purchase, refurbishment, and infrastructure upgrade costs to convert a cruise ship into affordable housing.

5. Conclusions and Recommendations

5.1 Summary of Final Concept Design

This study evaluated the feasibility of converting a cruise ship into an affordable housing community. This idea is motivated by a confluence of factors: the affordable housing crisis besetting many cities and regions across the United States, the windfall of cruise ships available for purchase at reasonable prices in a post-pandemic world, and the apparent suitability of cruise ships to be repurposed for housing. In many ways, this project aimed to address whether that last assumption was actually valid, and whether this sort of proposal could prove feasible and cost-competitive against a traditional, land-based housing approach.

Despite the relative novelty of this concept, it is not without precedence, and thus our team was able to reach out to various SMEs who had explored this idea to some extent in order to better develop and refine our design parameters and associated requirements. Throughout the entire design process, the two main design parameters were affordability and desirability, as we strove to maintain the proper balance between these two central, and at times competing, qualities. They drove the design process as we attempted to not just convert cabins into housing units, but to actually create a space where people would want to live, and could afford to do so.

In order to assess this idea's feasibility, we selected a baseline cruise ship variant based on vessel size, potential housing capacity, price, and availability of a representative model to perform additional analysis. Our 3D model was used primarily for weight estimations, intact stability analysis, and baseline remodeling to render a final proposed ship design. In order to properly account for conversion-related weight changes, a pre-conversion weight estimate was calculated using the SWBS group weight allocations for a similar-sized LPD warship, and modified with applicability factors to better reflect the cruise ship weight breakdown. Publicly available 2D deck plans were used as the basis for arrangement modifications. Each deck was evaluated individually and redesigned to provide some aspect of the envisioned affordable housing community.

The five current cabin decks were repurposed for the actual housing units. The most common unit merges four current small-sized cabins in order to provide a desirable unit size and permit the installation of an in-unit kitchen. This "base unit" is priced such that the median Boston income earner could reasonably afford it, *i.e.* spend no more than 30% of their gross income on rent, including utilities. The base unit served as a reference point from which smaller and larger units were then designed, with corresponding scaling rents, such that a spectrum of affordable housing units was established to cover a wider range of income earners, not just the median representative. In total, our design proposes 246 housing units that are able to accommodate approximately 350 people.

The remaining decks were modified to varying levels of complexity in order to provide all the additional amenities, facilities, and furnishings we deemed necessary in order to provide a desirable living space. These included:

- Fitness Center

- Indoor pool
- Parking garage
- Business center
- Grocery store
- Movie theater
- Multiple green spaces/outdoor park
- Daycare center

Weight removal and addition estimates were calculated on a per-deck basis in order to determine a post-conversion weight estimate and facilitate post-conversion stability analysis, which demonstrated improved stability performance compared to the pre-conversion model.

To provide the major utilities required for onboard living—electricity, water, sewage, waste management—we propose concurrent investments in pierside and shipboard infrastructure and equipment upgrades to allow the cruise ship to connect to the city’s power, water, and waste distribution systems on a permanent basis. The continued use of installed onboard systems to account for these needs proved either infeasible or unwise, whereas investments in ship-to-shore power technology and interoperability with the existing BWSC infrastructure were shown to have long-term environmental, operational, and economical benefits. Despite this approach rendering much of the installed onboard equipment no longer necessary, we were unable to identify compelling reasons to pursue large-scale engine room equipment removal. To this end, the final design maintains the engine room largely in the as-is configuration but with systems and equipment no longer necessary being retired in place in order to avoid undue maintenance and upkeep costs. Moreover, to ensure the vessel’s relocatability, our design maintains two of the four main diesel engines in an operational status to provide redundant sources of organic power generation.

Cost estimates for all aspects of the conversion process—acquisition, refurbishment, retrofit, operations, maintenance, staffing—were estimated using comparable historical data and SME input to determine the overall feasibility of the proposal. One of the major assumptions maintained throughout the entire study was that all capital and upfront fixed costs would be paid for through an assortment of government grants, subsidies, and public funding. As such, the key cost consideration was whether the annual net revenue from rent could cover the annual operational, staffing, and utilities cost. We determined that the expected revenue would not fully cover all of these expenses, but that this shortfall could be accounted for with a small amount of additional public funding or more favorable utility discount rates.

Additional areas of study and recommendations are provided below. This project determined that the conversion of a cruise ship into affordable housing is both technically and financially feasible, and offers crucial advantages over comparable land-based approaches. To be sure, much of this argument hinges on the assumption of robust government support and financial backing, but that has proven itself an immutable truth regarding affordable housing for decades, a truth that has come into even sharper relief

in recent years and is not unique to the converted cruise ship design.

This conversion study demonstrated that a project of this undertaking would not fail due to infeasible challenges, but rather a failure to imagine a more dignified society where housing is considered a fundamental right.

5.2 Areas for Study

Addressing Regulations. One of the major assumptions in this study was that all relevant housing regulations, zoning laws, housing and marine fire and safety codes, security protocols, and other legal ramifications were resolved in one form or another to green light this conversion. In reality, these issues would all have to be systematically resolved to determine which rules would apply to the converted cruise ship, which rules could be waived or exempted since it is no longer operating as an actual seagoing vessel, and which rules may have to be modified or specified to address the ship's unique status as a permanently moored vessel functioning as an affordable housing complex. This is a major effort that will likely require government and housing agency members, United States Coast Guard (USCG) and Customs and Border Protection (CBP) officials, marine safety legal experts, ABS certification representatives, and others to comprehensively ensure that all legal matters have been appropriately addressed and approved.

Detailed Space and Engine Room Analysis. Throughout this conversion study, our team had to make many assumptions concerning space arrangements, structural architecture, and existing onboard systems, due to the relative lack of detailed information which is publicly available. For example, the 2D deck plans used as the basis for arrangement modifications provided a starting point for an initial feasibility and redesign assessment, but lacked the granularity to propose truly detailed changes. Moreover, the unavailability of any sort of engine room drawing layout severely limited our team's ability to recommend meaningful changes within this space.

Having access to more official detailed ship information, perhaps through some sort of partnership or agreement with RCG, will enable more specific redesign and subsequent analysis concerning areas such as: overall weight estimates and locations, the scope of retrofitting to enable the use of land-based utilities, intact and damaged stability, and the structural integrity implications of merging and converting cabins.

Roll-Off, Roll-On Requirements. The inclusion of parking in our design was considered a major boost to the design's overall living desirability but is one of the more challenging aspects of the conversion. A more rigorous structural engineering analysis would need to be performed to determine if, and to what extent, deck strengthening is required to ensure the structural safety of those decks with margin. Additionally, more research and analysis are required to address how the parking garage entry would be designed with respect to watertight integrity and SOLAS 90 compliance (or whatever equivalent standard would be applied to the converted cruise ship).

Corrosion Control. Given that the converted cruise ship will be docked for the vast majority of the time, our team felt confident in assessing that its service life could be significantly extended past its nominal 30-year limit. The ship will not be subject to any of the stresses normally associated with a seagoing vessel. The one exception

is corrosion. Since the hull will remain waterborne, it will still be subject to galvanic corrosion, the most common and dangerous form of corrosion that ships experience. Therefore, corrosion control will remain a pertinent concern that must be addressed in the converted design.

Our team was unable to determine the specific corrosion control protocols currently implemented on the *Rhapsody*. The standard industry solution for decades has been the use of sacrificial zinc anodes. These anodes, attached to the ship's hull, are more electrically reactive than the hull material, and therefore corrode and dissolve instead of the hull itself. These anodes generally have to be replaced every three to five years, dependent on the given ship's drydocking schedule[90]. Newer RCG ships are outfitted with Impressed Current Cathodic Protection (ICCP) technology, which provides longer-lasting active protection for up to 25 years.

Further research can determine what corrosion control technologies are already in place, and how that would affect the converted ship's long-term maintenance schedule. If sacrificial anode swap-outs were to necessitate drydocking the ship every few years, that would severely upend residents' living arrangements and thus degrade the concept's overall feasibility. Initial research indicated that anode replacement can be conducted while the ship is still in the water through the use of divers and special equipment, but more detailed information on this method must be pursued to determine its cost and impact on shipboard operations.

Alternative Energy Sources. As discussed in the feasibility analysis in Section 4.3, the calculated deficit between the annual operational cost estimate and revenue from rent is only \$100,000. Electrical power, at a cost of \$2.3 million, was the largest single contributor to the annual operational cost of the converted cruise ship design, as discussed in Section 4.2.2. Even a small reduction in the cost for electricity could turn this operational deficit into an income, increasing the feasibility of this conversion idea. Supplementing shore power with alternative energy generation sources in the converted design could reduce this electrical power cost and the demand on the electrical grid. There are several examples of ships that use solar power as either the primary source of power (MS *Tûranor PlanetSolar*) or as an auxiliary source (*Auriga Leader*, *Emerald Ace*—shown in Figure 46), and a similar implementation could be done on the converted cruise ship[91]. Further research into the use of solar power and other alternative energy sources in this design is warranted.

Military Application. Beyond the affordable housing crisis afflicting millions of citizens throughout the United States, military members are dealing with a similar shortage of on-base housing. Living in on-base housing has become increasingly desirable as the cost of living off-base has drastically increased over the past two years. At Marine Corps Base Camp Lejeune in Jacksonville, North Carolina—one of the two largest Marine Corps bases in the country—the wait time for some on-base housing is 14-16 months, and this is an issue facing multiple military installations across the country[92]. The U.S. Department of Defense is not equipped to rapidly address this shortage of housing. In a recent interview with Newsweek, Pentagon Spokesperson Major Charlie Dietz discussed the unique challenges in increasing on-base family housing, which can take five or more years to implement, citing the slow federal budget cycle and requirements for congressional authorization and appropriations[93]. A con-



Figure 46: *Emerald Ace*, the first solar hybrid car carrier, in Boston Harbor[7].

verted cruise ship could be a feasible approach to address this issue as well, particularly because of the reduced construction required.

5.3 Recommendations

Upon completion of this project we determined that the conversion of a cruise ship into affordable housing is a feasible and creative approach to address the housing crisis. While there is certainly much more research and analysis to be done in the subject, we hope our analysis has shown enough merit to warrant further pursuit of this idea. The driving factors for our recommended continued research into this conversion idea are summarized below:

- Purchasing a cruise ship instead of building an apartment complex from scratch eliminates the ever-rising cost of construction. Some refurbishment and modification will need to be done on the ship, but there is supporting data that these costs are still **significantly** less expensive than constructing a new building.
- A cruise ship offers an incredibly large usable volume for both living spaces and amenities. Even with our limited arrangement modifications, we were able to retrofit the ship to provide 246 competitively-sized units and a wide range of amenities that rival the most expensive luxury apartments in Boston.
- Over 80% of the nation's population lives in coastal states along the oceans or the Great Lakes[94]. Waterfront areas in major cities will always be some of the most desirable locations to live and work. A cruise ship offers a unique opportunity to add a large amount of housing to these locations, allowing people to live closer to where they work.

A. Shore Power Investigation

In 2016, Boston city officials commissioned a shore power feasibility study as part of a comprehensive modernization of operations plan within the Port of Boston by Massport and its maritime partners[9]. Unlike military naval bases, the vast majority of cruise ship ports are not equipped with shore-to-ship power (SSP) technology. As of 2022, only 22 cruise ports had an SSP capability, which represents just 2% of cruise ports worldwide[95]. However, there have been major efforts in recent years to accelerate SSP technology implementation and availability in order to significantly reduce vessel emissions while in-port. As the U.S. Navy has demonstrated for many decades, shore power infrastructure has the potential to significantly reduce emissions as it provides the ship’s auxiliary power needs through connections to the local electrical grid, allowing vessels to turn off their engines while at berth[40]. Indeed, the Port of Seattle estimated that connecting a ship to shore power for the average cruise ship docking duration “eliminates the equivalent emissions to driving an average car from Seattle to New York 30 times[95].”

These efforts have been further spurred on by the adoption of stricter emissions and fuel standards by various regulatory agencies, such as the Environmental Protection Agency (EPA), the International Maritime Organization (IMO), and the California Air Resources Board (CARB). The IMO established its ship pollution rules in the “International Convention on the Prevention of Pollution from Ships” (MARPOL 73/78) and has increasingly set forth increasingly stringent Tier I-Tier III standards throughout the intervening years. These specifically govern the allowable emissions levels of nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) dependent primarily on diesel engine size and speed. Additionally, there are designated Emission Control Areas (ECA) around the world which implement yet stricter emissions control, including a North American ECA which includes most of the United States coast[42].

More recently, CARB has instituted some of the most ambitious emission reduction targets and demanding standards. In 2007 they adopted the At-Berth Regulation requiring the use of SSP or equivalent emissions reduction technology for container ships, refrigerated cargo ships, & passenger ships in order to reduce PM and NOx emissions starting in 2014[96]. A review of this regulation in 2020 reported an 80% emission reduction, and the announcement of a more expansive updated regulation to begin in 2023 for additional vessel types[97]. However, there are currently no corresponding zero emissions standards or SSP technology mandates instituted for vessels berthed at any United States East Coast ports.

The Massport case study documented many potential challenges to successfully installing and operating SSP technology[9]. It was crucial to identify which of these challenges would be common between the general use case (*i.e.* cruise ships arriving and departing on a roughly daily basis) and our goal of a permanently or semi-permanently sited singular cruise ship converted to affordable housing.

New off and on-site electrical infrastructure would be required to dock a cruise ship at the North Jetty Pier for an extended period of time. Previous studies indicated that a new 40 MW substation would be required to support corresponding SSP

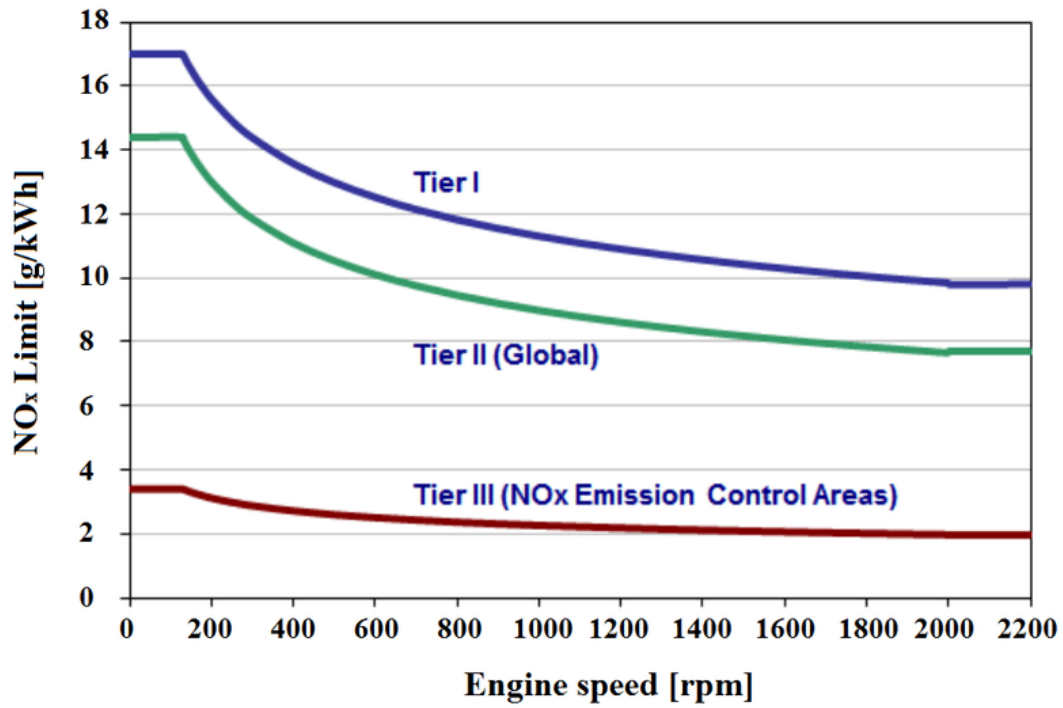


Figure 47: MARPOL Annex VI NOx emission limits[8].

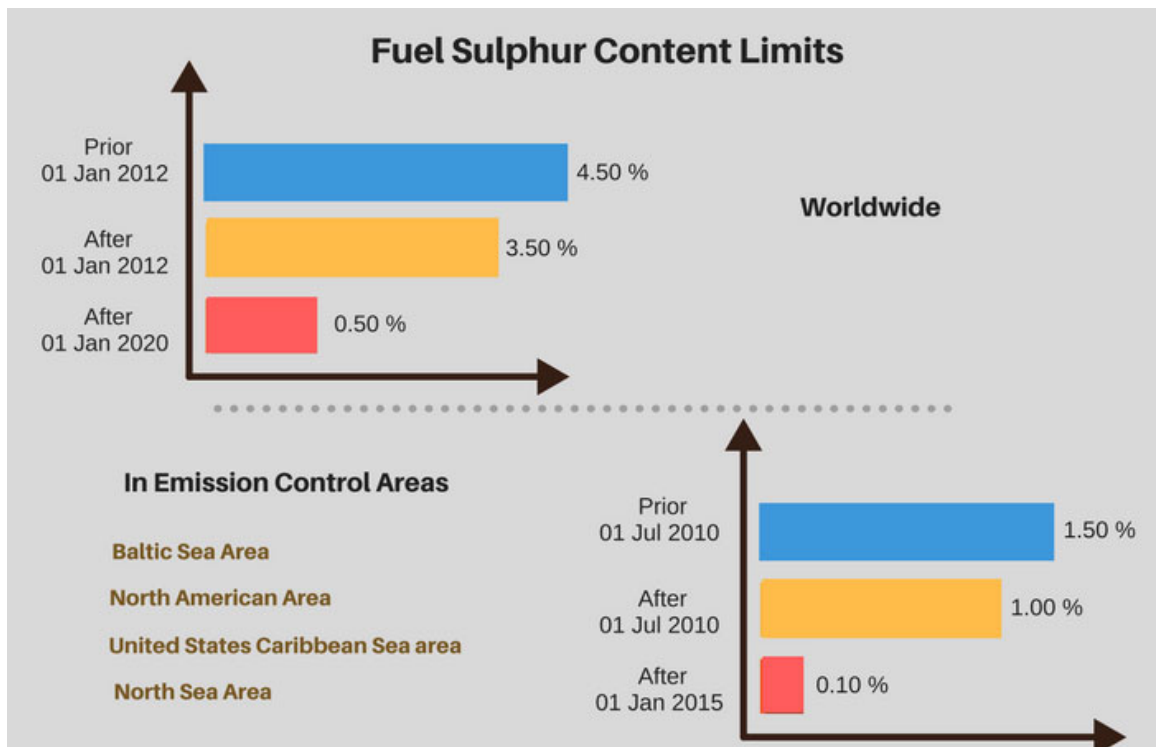


Figure 48: MARPOL Annex VI SOx emission limits[8].

upgrades, at an estimated cost of \$15 million[9]. However, this assumption was predicated on the fact that a cruise ship represents a significant peak power demand on the electrical grid. The study specifically used the roughly 3000-passenger vessel *Queen Mary 2* as the use case example and found that its peak power demand (13 MW) exceeded the power demand of all the terminals combined at Logan International Airport (11 MW). As such, the larger South Boston electrical infrastructure is currently insufficient to handle this type of SSP electrical demand, thus begetting the need for electrical grid upgrades within South Boston itself and not just at the port.

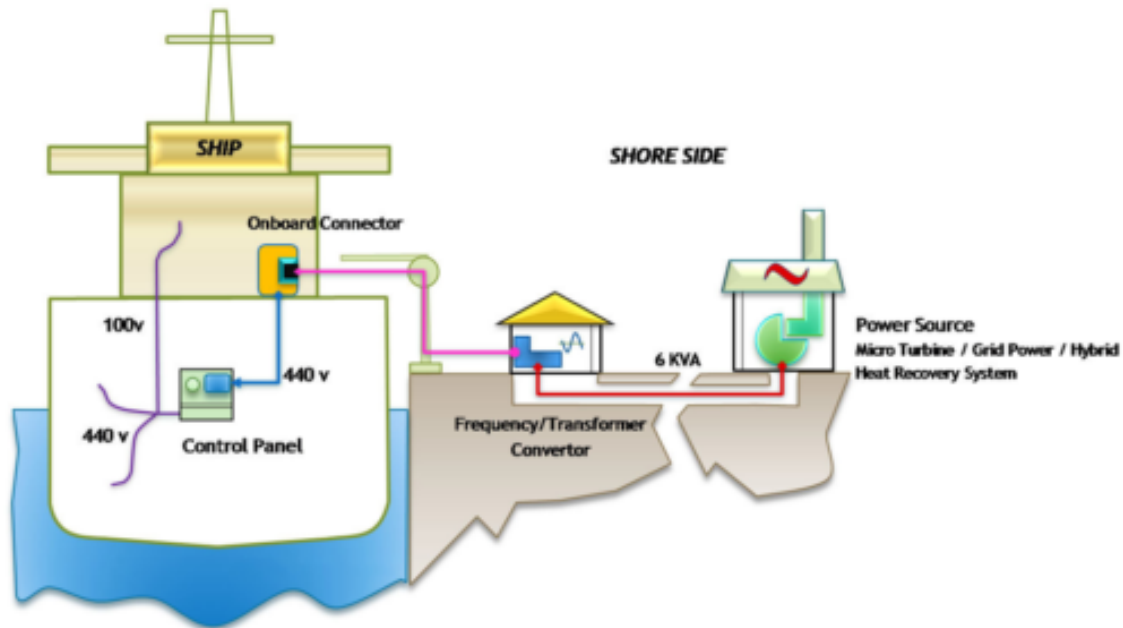


Figure 49: Basic schematic of SSP operations[9].

The converted cruise ship proposal crucially departs from some of these major assumptions. First, given the expected cabin reduction schema to accommodate larger and more desirable housing units, there will be significantly fewer personnel onboard (by a projected order of magnitude) which will drastically drive down overall demand compared to the typical large cruise ship. Moreover, the permanent siting of the ship at the pier effectively eliminates the threat of unpredictable and excessive power-peaking demands. There would be a generally known steady base demand with predictable and reasonable peaks as exists in the typical residential housing complex. As such, it is assumed that the city substation installation and upgrades, and the corresponding \$15 million cost, would not be necessary for the converted cruise ship.

Large capital costs are still incurred for shore power infrastructure upgrades. The following cost data was obtained from the Massport provided shore power study[9]. It was estimated based on previous SSP implementation projects in Halifax, Canada and Brooklyn, New York that the shoreside capital investments would cost between \$10-20 million per berth. Additionally, it was estimated that it would cost approximately \$1 million to retrofit the ship with the necessary SSP upgrades. These costs would also be incurred for the converted cruise ship proposal and would be significant contributors to the project's overall cost estimate.

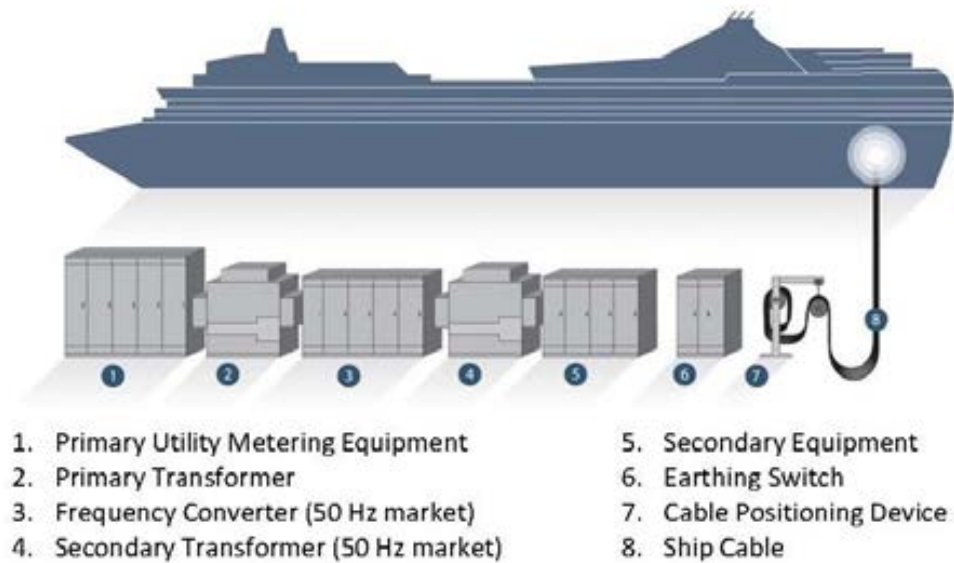


Figure 50: Major equipment necessary to enable SSP technology [9].

However, it is essential to recognize that in nearly all of these previous infrastructure improvement ventures, there has been significant investment and funding by government sources. The California government provided over \$1 billion for air emissions reduction-related projects and specifically allocated \$80.4 million in state grants to four of its major ports (Long Beach, Los Angeles, Oakland, and San Diego) to support SSP infrastructure projects. The Port of Halifax received \$5 million in federal grants and \$2.5 million in state grants to support its single-berth SSP installation. Brooklyn Cruise Terminal received \$3 million in federal grants and \$4.3 million in state grants to help fund its single-berth SSP project.

Based on these numbers, and in properly adjusting for inflation, it is assumed that the cost of installing the necessary pierside SSP infrastructure would be **\$17.3 million**, and the cost to retrofit the ship itself would be **\$1.2 million**, resulting in a total cost estimate of **\$18.5 million**.



Figure 51: Possible sites for new electrical substations to support SSP implementation at Flynn Cruiseport and North Jetty Pier[9].

B. Floodable Length

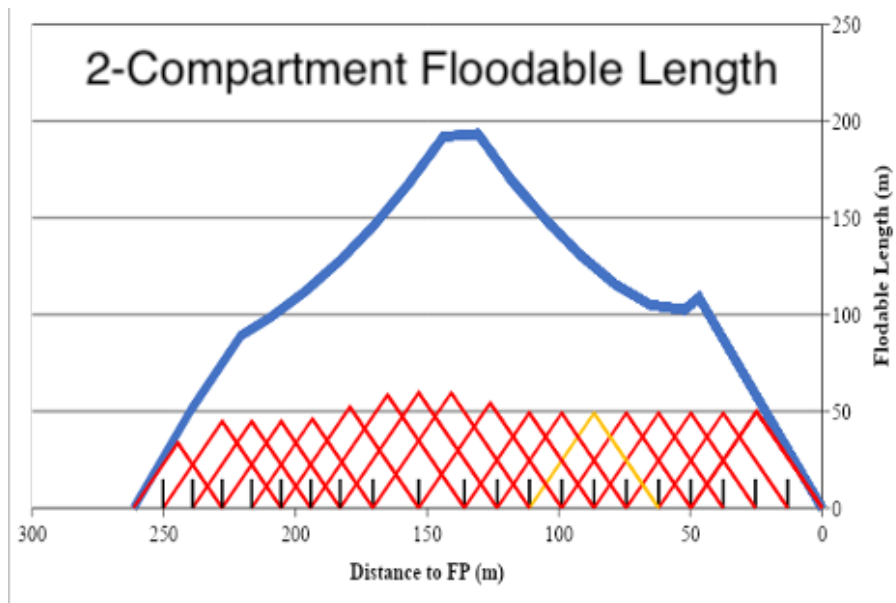


Figure 52: Floodable Length Curve, pre-conversion.

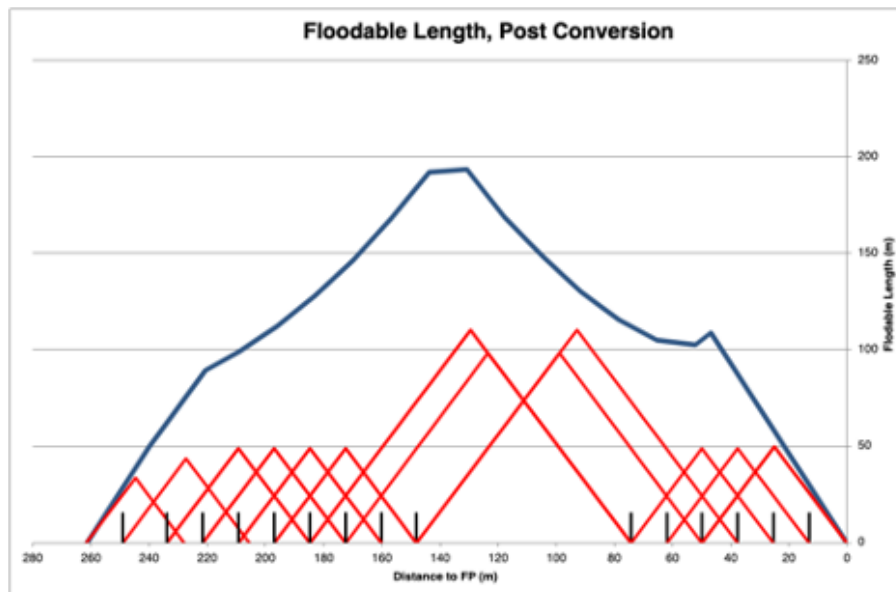


Figure 53: Floodable Length Curve, post-conversion.

C. Design Parameters

Table 9: Design Parameters

Capability	Characteristic	Threshold	Objective
Affordability	Monthly Rent	Base unit price <30% gross income, including utilities	All unit prices <30% gross income, including utilities
Desirability	Square Footage	150 ft^2	500 ft^2
	Natural Lighting	Some natural lighting in all rooms	Meet 105 CMR requirement (8%)
	Outdoor Spaces	Not Offered	Included
	Co-working Areas	Not Offered	Included
	Advanced Package Delivery Technology	Not Offered	Included
	Fitness Centers & Fitness Classes	Not Offered	Included
	Bicycle Sharing Services	Not Offered	Docking station nearby
	Parking	Off-site parking available	On-site parking
	Building Wide Wi-Fi	Not Offered	Included
	Controlled Access	Not Offered	Included
	Indoor Pool	Not Offered	Included
Relocatability	Level of Relocatability	Level I	Level II
	Electrical Power Sources	Primary & back-up source (at least one method installed on ship)	Utilize shore power as the primary means

D. Weight Calculations

SWBS Group	Initial Weights (LT)	Applicability Factor (AF)	Weights*AF (LT)	Percent of Full Load	Cruise Ship Weights (MT)
1	9009.5	1	9009.5	48.9	21428.7
2	1093.3	1	1093.3	5.9	2600.4
3	829.6	1	829.6	4.5	1973.2
4	493.1	0.8	394.5	2.1	938.3
5	2441.8	1	2441.8	13.3	5807.7
6	1550.5	3	4651.5	25.3	11063.4
7	233.5	0	0	0	0
Sum	15651.3		18420.2	100	43811.6
Cruise Ship Full Load Displacement (MT):			43811.6		

Figure 54: Pre-conversion weight calculations.

E. ORCA Hull Geometry Reports

Condition Summary

Load Condition Parameters					
Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)	
Condition 1	41222890.676 kgf	0.000 deg	0.000 deg	7.749	

Resulting Model Attitude and Hydrostatic Properties				
Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
Condition 1	0.217	0.000	0.000	496.93

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
Condition 1	41223107.141	113.149	-0.244	-3.236	26467.903

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
Condition 1	6501.572	111.658	-0.217	0.217

Condition	BMt(m)	BMI(m)	GMT(m)	GMI(m)
Condition 1	11.863	560.490	0.878	549.506

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Condition 1	0.644	0.337	0.836	1.910	8.523	0.770

Figure 55: Pre-conversion condition summary table.

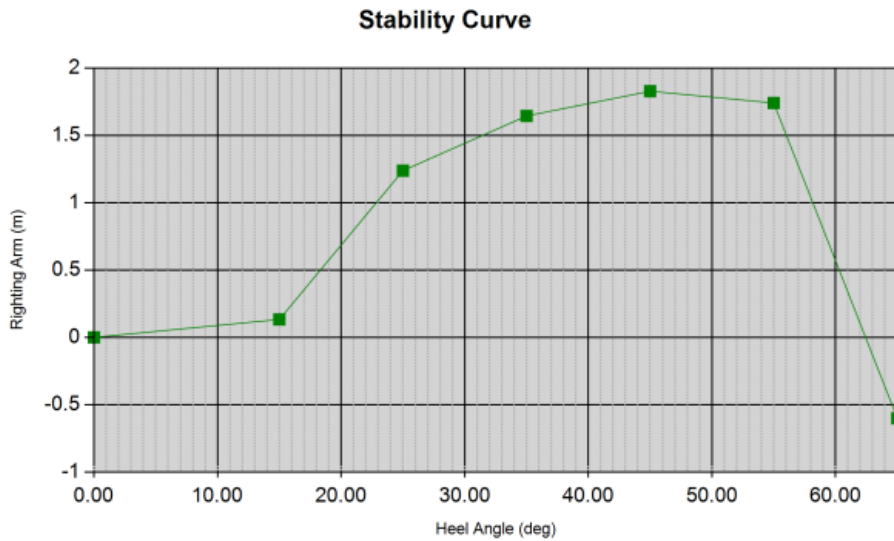


Figure 56: Pre-conversion stability curve.

Condition Summary

Load Condition Parameters					
Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)	
Condition 1	38934962.834 kgf	0.000 deg	0.000 deg	7.524	

Resulting Model Attitude and Hydrostatic Properties				
Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m ²)
Condition 1	-0.128	0.000	0.000	476.30

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m ²)
Condition 1	38935215.607	113.235	-0.246	-3.428	26047.756

Condition	Awp(m ²)	LCF(m)	TCF(m)	VCF(m)
Condition 1	6420.325	111.682	-0.226	-0.128

Condition	BMt(m)	BMI(m)	GMt(m)	GMI(m)
Condition 1	12.296	574.397	1.344	563.444

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Condition 1	0.636	0.332	0.827	1.915	8.635	0.770

Figure 57: Post-conversion condition summary table.

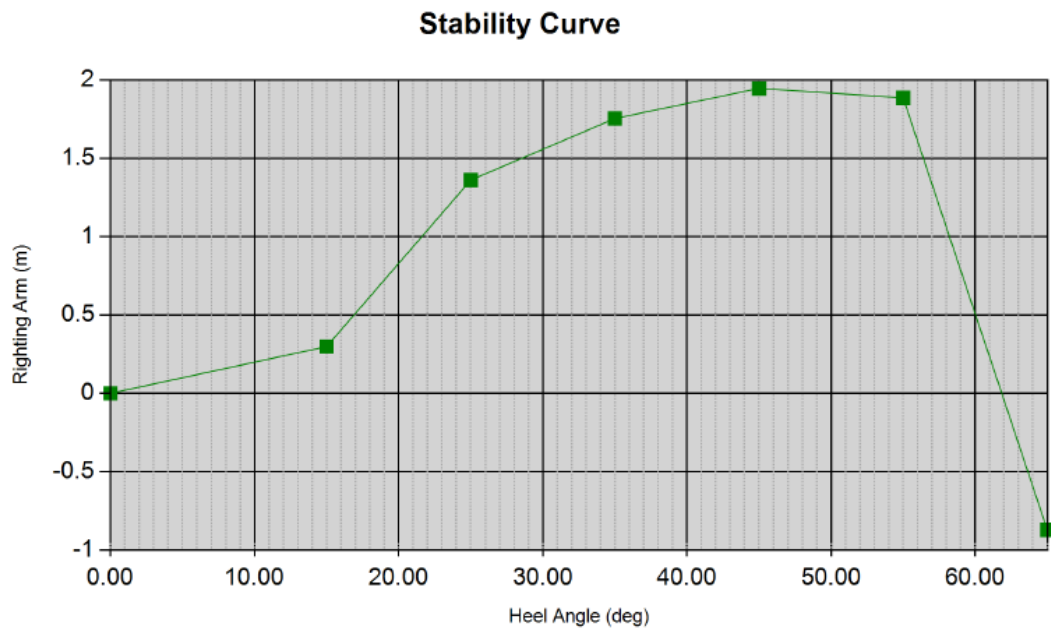


Figure 58: Post-conversion stability curve.

F. *Grand Celebration* Case Study

On September 13, 2018, pressure build-up in natural gas lines owned by Columbia Gas of Massachusetts caused a significant gas explosion in the Merrimack Valley, causing property damage to nearly 100 homes and resulting in one fatality[98]. In order to repair the 48 miles of affected piping and restore services to the 8,600 affected customers, Columbia Gas marshaled hundreds of additional gas workers from outside the state, but there was insufficient conventional housing to support this sudden influx of personnel for the three-month repair period.

Columbia Gas chartered the active cruise ship *Grand Celebration* from *Bahamas Paradise Cruise Line* to provide housing in Boston for the construction crews, canceling all previously scheduled sailings from October to December that year[99]. Massport was tasked to support the vessel's semi-permanent docking on an emergency basis invoked by the state. Since Flynn Cruiseport itself was deemed a non-viable option given the high-volume port schedule, Massport worked with regulatory agencies to instead site the ship along the North Jetty Pier, located just north of the actual cruise terminal, shown in Figures 4 & 59.

Within a very quick period, all essential services such as potable water, sewage, gas, and electricity were established to varying levels of robustness. To provide sewage transfer, an above-ground piping connection was made connecting the vessel's onboard holding tank to an existing sewage manhole which was part of the Boston sewage distribution system. Small generators were brought pierside to provide the relatively low electrical demand from the vessel, since the workers were off the ship for the majority of the day. According to our subject matter expert at Massport, parking, utility, and docking fees amounted to approximately \$2 million for the three-month period[27].

Despite the various challenges, Massport successfully supported the semi-permanent docking of the *Grand Celebration* for over three months, and in doing so, provided proof-of-concept viability to the idea of docking a cruise ship at the North Jetty Pier on a more permanent basis. One major technical hurdle is the upgrade of pierside infrastructure, support equipment, and utilities required to adequately support the converted cruise ship around the clock. The cruise port itself has non-potable water connections for washing and cleaning, but no permanent sewage connections since the cruise ships are normally only there for a short duration. The temporary sewage connections put in place for the *Grand Celebration* were adequate for short-term use, but long-term usage would necessitate shifting from above-ground connections to permanent underground connections more fully integrated with the overall sewage system. Moreover, the generators brought pierside to provide the modest electricity needs of *Grand Celebration* would not be viable to address the long-term needs of the converted cruise ship. Indeed, addressing electricity production and distribution represents one of the central and consequential tasks of this conversion project.

G. MIT 2N Cost Model

To get at least one estimate for TLC we used the MIT 2N Cost Model in full recognition that this would be a very coarse approximation, particularly because it is intended for new construction combatant vessels, not cheaply purchased cruise ship conversions. This cost model incorporates estimates for research and development, basic construction, investments, operations and support, and residual value at the vessel's end of life. Although the current design only proposes one cruise ship conversion, for the purposes of calculations, we assumed there would be one follow-on ship. We also assumed there would be no propulsion requirements (to avoid fuel cost additions), approximated our staffing needs to fit the model inputs for Navy personnel manning, and anticipated a 30-year service life. The adjusted TLC estimates from the MIT model are shown in Figure 60.

Inputs			INPUTS FOR CALCULATING LIFE CYCLE COS	
Weights	Long Ton		Total Brake Horsepower (hp)	0
SWBS 100	19449		SWBS 420-439 Weights (LT)	5
SWBS 200	2559		Average Deck Height (ft)	8.5
SWBS 300	1942			
SWBS 400	210			
SWBS 500	5259		CREW/MANNING	
SWBS 600	9473		Officer	5
SWBS 700	0		CPO	5
Margin	20		Enlisted	20
Loads	100			
			Number of Ships in Class	1
Change Orders (Lead)	10%		Ship Service Life (years)	30
Change Orders (Follow)	5%		Initial Operational Capability (year)	2028
Profit	12%		Production Rate (ships/year)	1
Lead Ship T unit =	1			
Follow Ship T Unit =	1		Inflation	
			Base Year	2021
Learning Curve %	92%		Average Inflation Rate	5
Life Cycle Cost Factor (from table)	1	FIX	Number of Operating Hrs Per Year	8760
			Fuel Cost (\$/gal)	3.00
GRP 1 HULL STEEL			Fuel Consumption Rate (lton/hr)	0.00000001
GRP 2 PROPULSION				
GRP 3 ELECTRIC				
GRP 4 COMMAND				
GRP 5 AUXILIARY				
GRP 6 OUTFIT				
GRP 7 ARMAMENT				
P5 Cost Output			FY05 \$k	FY05 \$k
			Lead	Follow
Plan Costs			\$ 1,201,792	\$ 320,478
Basic Construction			\$ 4,005,975	\$ 4,005,975
Change Orders			\$ 400,597	\$ 200,299
Electronics			\$ 196,293	\$ 196,293
Hull, Mech, Electrical			\$ 232,379	\$ 232,379
Other Costs			\$ 184,179	\$ 184,179
Ordnance			\$ 360,538	\$ 360,538
Total			\$ 6,581,753	\$ 5,500,139
			LCC	
Total Ship R&D Cost			\$ 7,102,631,514	
Total Investment Cost			\$ 8,482,794,944	
Total Operating and Support Cost			\$ 6,154,481,652	
Residual Value			\$ (428,254,819)	
TOTAL PROGRAM LIFE CYCLE COST			\$ 21,311,653,291	

Figure 60: MIT 2N Cost Model assessment.

H. Complete List of Units

<u>Size/Deck</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>7</u>	<u>8</u>	<u>Total</u>
Small (<460 ft ²):	9	15	4	0	14	42
Medium (460-600 ft ²):	45	48	25	4	38	160
Large (>600 ft ²):	1	0	0	35	8	44
						246
	<u>Quantity</u>	<u>Area (ft²)</u>	<u>Balcony Area (ft²)</u>	<u>Windows</u>	<u>Rent/mo.</u>	<u>Income/mo.</u>
Small:	2	252		4 portholes	475	950
	2	252		2	500	1000
	5	302		2	550	2750
	2	347	74		600	1200
	12	349	104		650	7800
	1	372		3	800	800
	9	378		3	800	7200
	4	378		6 portholes	800	3200
	4	388		2	900	3600
	1	438		2	1000	1000
Medium:	1	482	93		1269	1269
	28	486	128		1269	35532
	5	498		4	1269	6345
	18	504		4	1269	22842
	2	507		3	1269	2538
	2	514		6 portholes	1269	2538
	1	517		2	1269	1269
	5	517	104		1269	6345
	77	524		2	1269	97713
	2	529		4	1269	2538
	2	532	56		1269	2538
	1	535		1	1269	1269
	4	549		2	1300	5200
	2	554		4	1300	2600
	2	564		3	1400	2800
	3	574		2	1400	4200
	3	585	105		1500	4500
	2	590	138		1500	3000
Large:	2	629	64	2	1550	3100
	1	643		3	1550	1550
	1	677	128		1600	1600
	2	721	105		1700	3400
	3	729	192		1700	5100
	2	733	74	2	1700	3400
	2	772		4	1750	3500
	28	780	140		1900	53200
	2	922	126		2500	5000
	1	1326	110		3000	3000
				Total Rent Income:		3808632

Figure 61: Breakdown of all units.

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