Chapter 4: Case 2-1 - Yeosu to Busan

4.1 Overview

Parameter	Value
Case ID	case_2_yeosu
Storage at Busan	**No**
Route	Yeosu to Busan
Distance	86 nautical miles
Travel Time (one-way)	5.73 hours (86 nm / 15 knots)
Bunker Volume per Call	5,000 m3
Optimal Shuttle Size	**10,000 m3**

4.2 Cycle Time Calculation

4.2.1 Formula (Case 2 - Direct Supply)

For Case 2, the shuttle serves **multiple vessels per trip**:

```
Vessels_per_Trip = floor(Shuttle_Size / Bunker_Volume)

Cycle_Duration = Shore_Loading + Travel_Out + Travel_Return + Port_Entry_Exit
               + (Vessels_per_Trip × (Movement + Setup + Pumping))

where:
  Shore_Loading = Shuttle_Size / Shore_Pump_Rate = Shuttle_Size / 1500
  Travel_Out = 5.73 hours (86 nm / 15 knots)
  Travel_Return = 5.73 hours
  Port_Entry_Exit = 2.0 hours (1.0 entry + 1.0 exit)
  Movement = 1.0 hour per vessel
  Setup = 2.0 hours per vessel (1.0 inbound + 1.0 outbound)
  Pumping = Bunker_Volume / Pump_Rate = 5000 / 1000 = 5.0 hours per vessel
```

4.2.2 Example: 10,000 m3 Shuttle (Optimal)

Step 1: Vessels per Trip

```
Vessels_per_Trip = floor(10000 / 5000) = 2 vessels
```

Step 2: Fixed Components

```
Shore_Loading = 10000 / 1500 = 6.6667 hours
Travel_Out = 5.73 hours
Travel_Return = 5.73 hours
Port_Entry_Exit = 2.0 hours
```

```
Fixed_Time = 6.6667 + 5.73 + 5.73 + 2.0 = 20.1267 hours
```

Step 3: Per-Vessel Components

```
Per_Vessel_Time = Movement + Setup + Pumping
                = 1.0 + 2.0 + 5.0
                = 8.0 hours/vessel

Total_Vessel_Time = 2 vessels × 8.0 hours = 16.0 hours
```

Step 4: Total Cycle Duration

```
Cycle_Duration = Fixed_Time + Total_Vessel_Time
                = 20.1267 + 16.0
                = 36.1267 hours
```

CSV Verification: `Cycle_Duration_hr = 36.1267` [PASS]

4.2.3 Example: 5,000 m3 Shuttle

Step 1: Vessels per Trip

```
Vessels_per_Trip = floor(5000 / 5000) = 1 vessel
```

Step 2: Fixed Components

```
Shore_Loading = 5000 / 1500 = 3.3333 hours
Travel_Out = 5.73 hours
Travel_Return = 5.73 hours
Port_Entry_Exit = 2.0 hours

Fixed_Time = 3.3333 + 5.73 + 5.73 + 2.0 = 16.7933 hours
```

Step 3: Per-Vessel Components

```
Per_Vessel_Time = 1.0 + 2.0 + 5.0 = 8.0 hours
Total_Vessel_Time = 1 vessel × 8.0 hours = 8.0 hours
```

Step 4: Total Cycle Duration

```
Cycle_Duration = 16.7933 + 8.0 = 24.7933 hours
```

CSV Verification: `Cycle_Duration_hr = 24.7933` [PASS]

4.2.4 Example: 15,000 m3 Shuttle

Step 1: Vessels per Trip

```
Vessels_per_Trip = floor(15000 / 5000) = 3 vessels
```

Step 2: Fixed Components

```
Shore_Loading = 15000 / 1500 = 10.0 hours
Travel_Out = 5.73 hours
```

```
Travel_Return = 5.73 hours
Port_Entry_Exit = 2.0 hours

Fixed_Time = 10.0 + 5.73 + 5.73 + 2.0 = 23.46 hours
```

Step 3: Per-Vessel Components

```
Total_Vessel_Time = 3 vessels × 8.0 hours = 24.0 hours
```

Step 4: Total Cycle Duration

```
Cycle_Duration = 23.46 + 24.0 = 47.46 hours
```

CSV Verification: `Cycle_Duration_hr = 47.46` [PASS]

4.3 Annual Capacity Calculation

4.3.1 Formula

```
Annual_Cycles_Max = Max_Annual_Hours / Cycle_Duration
                  = 8000 / Cycle_Duration

Annual_Supply_m3 = Annual_Cycles_Max × Shuttle_Size
Ships_Per_Year = Annual_Cycles_Max × Vessels_per_Trip
```

4.3.2 Verification Table

Shuttle (m3)	Vessels/Trip	Cycle (hr)	Annual Cycles	Ships/Year	CSV Match
5,000	1	24.79	322.67	322.67	[PASS]
10,000	2	36.13	221.44	442.89	[PASS]
15,000	3	47.46	168.56	505.69	[PASS]

4.4 Cost Verification

4.4.1 Shuttle CAPEX

10,000 m3 Shuttle:

```
CAPEX = 61,500,000 × (10000 / 40000)^0.75
      = 61,500,000 × (0.25)^0.75
      = 61,500,000 × 0.3536
      = $21,746,430
```

5,000 m3 Shuttle:

```
CAPEX = 61,500,000 × (5000 / 40000)^0.75
      = 61,500,000 × (0.125)^0.75
      = 61,500,000 × 0.2102
      = $12,927,300
```

4.4.2 Annualized CAPEX

Shuttle (m3)	CAPEX	Annualized CAPEX/yr
5,000	$12,927,300	$1,193,053
10,000	$21,746,430	$2,007,330
15,000	$29,631,149	$2,735,075

4.5 Shuttle Size Comparison

4.5.1 Comparison Table (1000 m3/h Pump)

Metric	5,000 m3	10,000 m3	15,000 m3
NPC Total	$754.93M	**$747.18M**	$803.67M
LCOAmmonia	$3.20/ton	**$3.17/ton**	$3.41/ton
Cycle Duration	24.79 hr	36.13 hr	47.46 hr
Vessels per Trip	1	2	3
Annual Cycles	322.67	221.44	168.56
Ships per Year	322.67	442.89	505.69
Time Utilization	100%	100%	100%

4.5.2 Cost Breakdown Comparison

Cost Component	5,000 m3	10,000 m3	15,000 m3
Annualized Shuttle CAPEX	$268.47M	$335.12M	$399.82M
Annualized Bunkering CAPEX	$14.65M	$14.95M	$16.30M
Shuttle Fixed OPEX	$145.45M	$181.56M	$216.61M
Bunkering Fixed OPEX	$7.93M	$8.10M	$8.83M
Shuttle Variable OPEX	$305.93M	$194.95M	$149.59M
Bunkering Variable OPEX	$12.51M	$12.51M	$12.51M
NPC Total	**$754.93M**	**$747.18M**	**$803.67M**

4.5.3 Why 10,000 m3 is Optimal

1. **Economies of batch**: 2 vessels/trip reduces travel cost per vessel by 50%
2. **CAPEX efficiency**: Larger shuttle amortized over more vessels

3. **Sweet spot**: Balances cycle time increase vs vessels served

The 5,000 m3 shuttle has lower CAPEX but very high variable OPEX ($305.93M) due to many trips. The 15,000 m3 shuttle serves more vessels but has diminishing returns on cycle efficiency.

4.6 Full Scenario Results

Shuttle (m3)	NPC (M)|LCO(/t)	Cycle (hr)	Vessels/Trip	Utilization	
2,500	1024.99	4.35	23.13	1	100%
5,000	754.93	3.20	24.79	1	100%
10,000	**747.18**	**3.17**	**36.13**	**2**	100%
15,000	803.67	3.41	47.46	3	100%
20,000	904.15	3.84	58.79	4	100%
25,000	962.45	4.08	70.13	5	100%
30,000	1043.96	4.43	81.46	6	100%
35,000	1124.44	4.77	92.79	7	100%
40,000	1206.75	5.12	104.13	8	100%
45,000	1293.64	5.49	115.46	9	100%
50,000	1366.40	5.80	126.79	10	100%

4.7 Travel Time Impact

Case 2-1 (Yeosu) has the longest travel time among all cases:

Case	Travel Time (one-way)	Round Trip	Impact
Case 1	1.0 hr	2.0 hr	Baseline
Case 2-2	1.67 hr	3.34 hr	+67%
Case 2-1	**5.73 hr**	**11.46 hr**	**+473%**

This explains why Case 2-1 has the highest NPC and LCOAmmonia among all cases.

4.8 Verification Summary

Item	Expected	CSV Result	Status
Optimal Shuttle	10,000 m3	10,000 m3 (min NPC)	[PASS]
Cycle Time (5000)	24.7933 hr	24.7933 hr	[PASS]
Cycle Time (10000)	36.1267 hr	36.1267 hr	[PASS]
Cycle Time (15000)	47.46 hr	47.46 hr	[PASS]
Vessels/Trip (10000)	2	2.0	[PASS]
Annuity Factor	10.8355	10.8355	[PASS]
NPC (10000)	~$747M	$747.18M	[PASS]
LCO (10000)	~$3.17/ton	$3.17/ton	[PASS]