In [1]:

```
# Required Libraries
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns
```

In [2]:

```
# Load the Data
scada_df = pd.read_excel("wtg_scada_dataset.xlsx", sheet_name="wtg_scada_dataset")
wo_df = pd.read_excel("WTG_SAP WO_Dataset.xlsx")
```

In [3]:

```
wo_df
```

Out[3]:

	Created on	Basic start date	Basic finish date	Order	Order Type	Priority text	System status	User Status	Description	Funct
0	2025-03-05	2025-04-04	2025-06-03	80443104	YR02	Within 3 months	CRTD ACAS MACM PRC	CRTD	Replace spinner hatch seal	
1	2025-03-04	2025-03-06	2025-03-06	80442932	YR02	Within 1 month	REL ACAS MSPT PRC	REPL EXSC PPMA	Brake Switch	
2	2025-03-04	2025-03-10	2025-04-02	80443000	YR02	Within 1 month	REL ACAS NMAT PRC	REPL	Replace SRL pull down rope	
3	2025-03-04	2025-03-13	2025-04-03	80443090	YR02	Within 1 month	REL ACAS NMAT PRC	REPL	WOW4 ONS -Rob Dale Scopes 13th March	
4	2025-03-03	2025-03-06	2025-03-06	80442574	YR02	Immediately	REL ACAS NMAT PRC	RERP EXSC	MSI ExtHighl Info X M 1, L 2	
...	...	...	...	...	...	...	...	...	...	
788	2022-05-27	2025-04-07	2025-04-13	80295599	YR02	Within three months	CRTD ACAS CSER MACM PRC	CRTD	TP tetra battries require replacing	WOW03D(
789	2022-04-28	2025-09-08	2025-09-14	80291698	YR02	Within two months	REL ACAS CSER MACM PRC	RERP	Davit top cover requires replacing	WOW03H05X
790	2022-04-24	2025-06-02	2025-06-08	80291098	YR02	Within three	REL ACAS	RERP	Davit top cover	WOW03G03X

	Created on	Basic start date	Basic finish date	Order	Order Type	Priority text	System status	User Status	Description	Funct
						months	CSER MACM PRC		requires replacing	
791	2021-03-08	2025-07-07	2025-07-13	80251472	YR02	Within two months	REL ACAS NMAT PRC	RERP	Davit Pendant Repair	WOV
792	2020-10-02	2025-07-21	2025-07-27	80235942	YR02	Within six months	REL ACAS NMAT PRC	RERP	C06 Davit Slew cover broken	WOV

793 rows × 12 columns

In [4]:

```
wo_df.describe()
```

Out[4]:

	Order	Total planned costs
count	7.930000e+02	793.000000
mean	8.039757e+07	13986.302308
std	3.729229e+04	33173.768714
min	8.023594e+07	0.000000
25%	8.037497e+07	113.290000
50%	8.039881e+07	2016.020000
75%	8.042972e+07	9483.380000
max	8.044310e+07	323266.640000

In [5]:

```
wo_df.isnull().sum()
```

Out[5]:

```
Created on                          0
Basic start date                    0
Basic finish date                   0
Order                               0
Order Type                          0
Priority text                       5
System status                       0
User Status                         0
Description                         0
Functional Location                 0
Description of functional location  0
Total planned costs                 0
dtype: int64
```

In [6]:

```
wo_df.describe(include='all').T
```

```
C:\Users\chinmay\AppData\Local\Temp\ipykernel_10396\2699018485.py:1: FutureWarning: T
reating datetime data as categorical rather than numeric in `.describe` is deprecated
```

```
and will be removed in a future version of pandas. Specify `datetime_is_numeric=True`
to silence this warning and adopt the future behavior now.
  wo_df.describe(include='all').T
```

Out[6]:

	count	unique	top	freq	first	last	mean	std	n
Created on	793	295	2025-02-17 00:00:00	42	2020-10-02	2025-03-05	NaN	NaN	N
Basic start date	793	65	2025-06-23 00:00:00	43	2023-12-06	2026-02-16	NaN	NaN	N
Basic finish date	793	68	2025-06-29 00:00:00	43	2023-12-12	2026-02-22	NaN	NaN	N
Order	793.0	NaN	NaN	NaN	NaT	NaT	80397571.779319	37292.288163	8023594.
Order Type	793	1	YR02	793	NaT	NaT	NaN	NaN	N
Priority text	788	8	Within 3 months	276	NaT	NaT	NaN	NaN	N
System status	793	27	CRTD ACAS NMAT PRC	112	NaT	NaT	NaN	NaN	N
User Status	793	16	RERP	342	NaT	NaT	NaN	NaN	N
Description	793	494	Remove nitrogen bottles from nac	40	NaT	NaT	NaN	NaN	N
Functional Location	793	201	WOW03C01	26	NaT	NaT	NaN	NaN	N
Description of functional location	793	120	Wind Turbine C01_MHIV V164 MK1A 8.0	26	NaT	NaT	NaN	NaN	N
Total planned costs	793.0	NaN	NaN	NaN	NaT	NaT	13986.302308	33173.768714	

In [7]:

```python
wo_df.duplicated()
```

Out[7]:

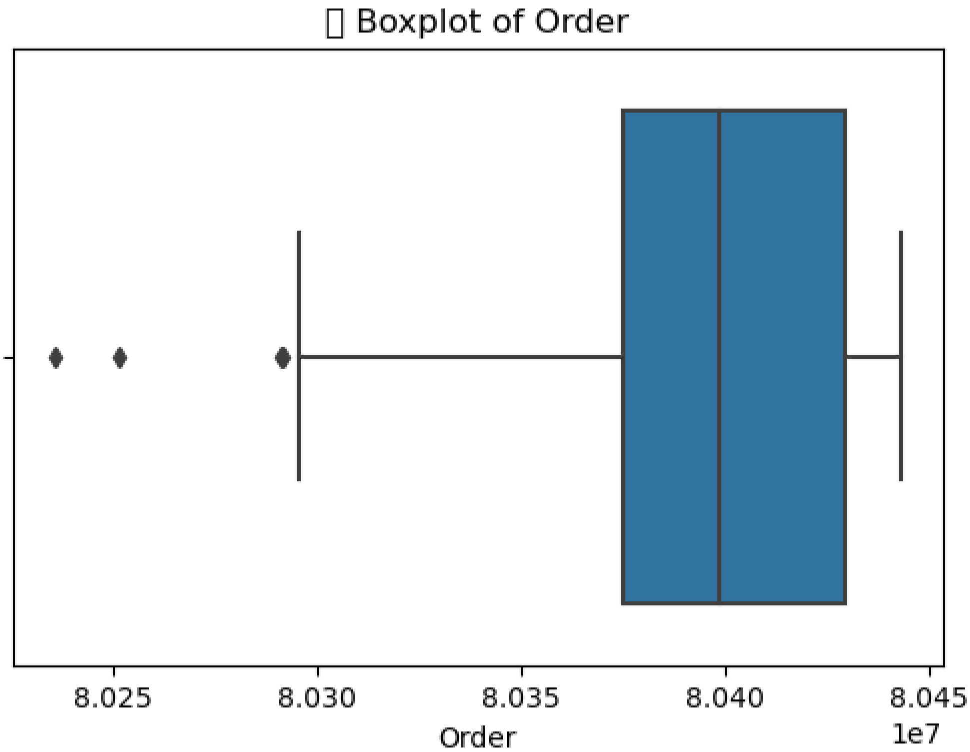
```
0      False
1      False
2      False
3      False
4      False
       ...
788    False
789    False
790    False
791    False
792    False
Length: 793, dtype: bool
```

In [8]:

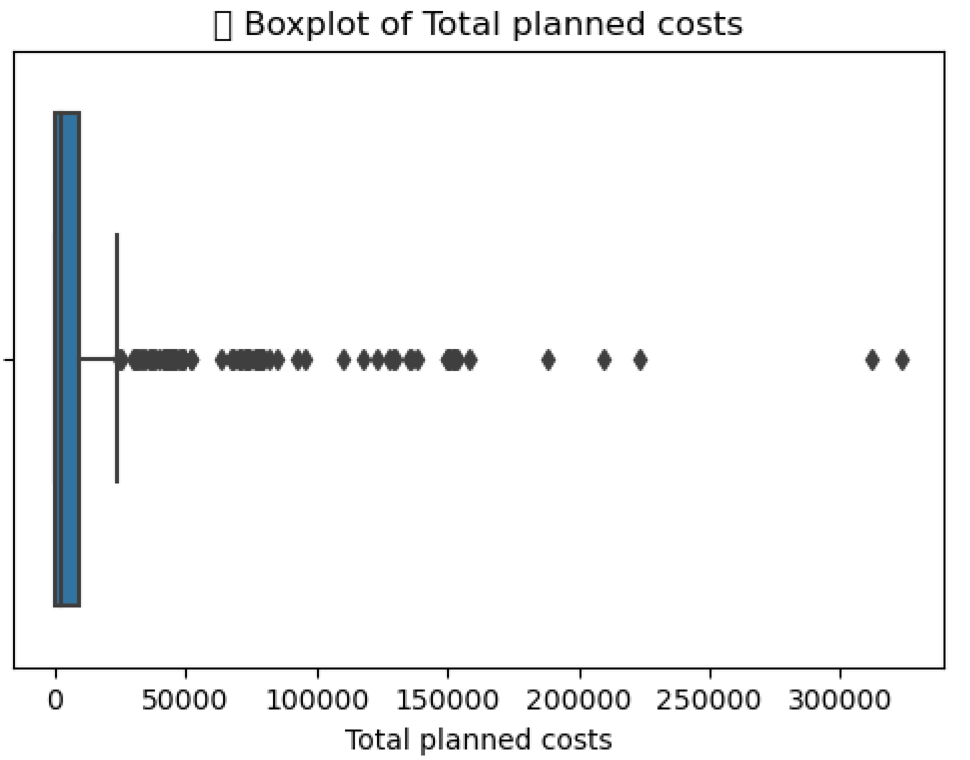
```python
# Boxplots for outlier detection
num_cols = wo_df.select_dtypes(include=np.number).columns
for col in num_cols:
    plt.figure(figsize=(6, 4))
```

```
    sns.boxplot(x=wo_df[col])
    plt.title(f'📦 Boxplot of {col}')
    plt.show()
```

```
C:\Users\chinmay\anaconda3\lib\site-packages\IPython\core\pylabtools.py:152: UserWarn
ing: Glyph 128230 (\N{PACKAGE}) missing from current font.
  fig.canvas.print_figure(bytes_io, **kw)
```




```
C:\Users\chinmay\anaconda3\lib\site-packages\IPython\core\pylabtools.py:152: UserWarn
ing: Glyph 128230 (\N{PACKAGE}) missing from current font.
  fig.canvas.print_figure(bytes_io, **kw)
```

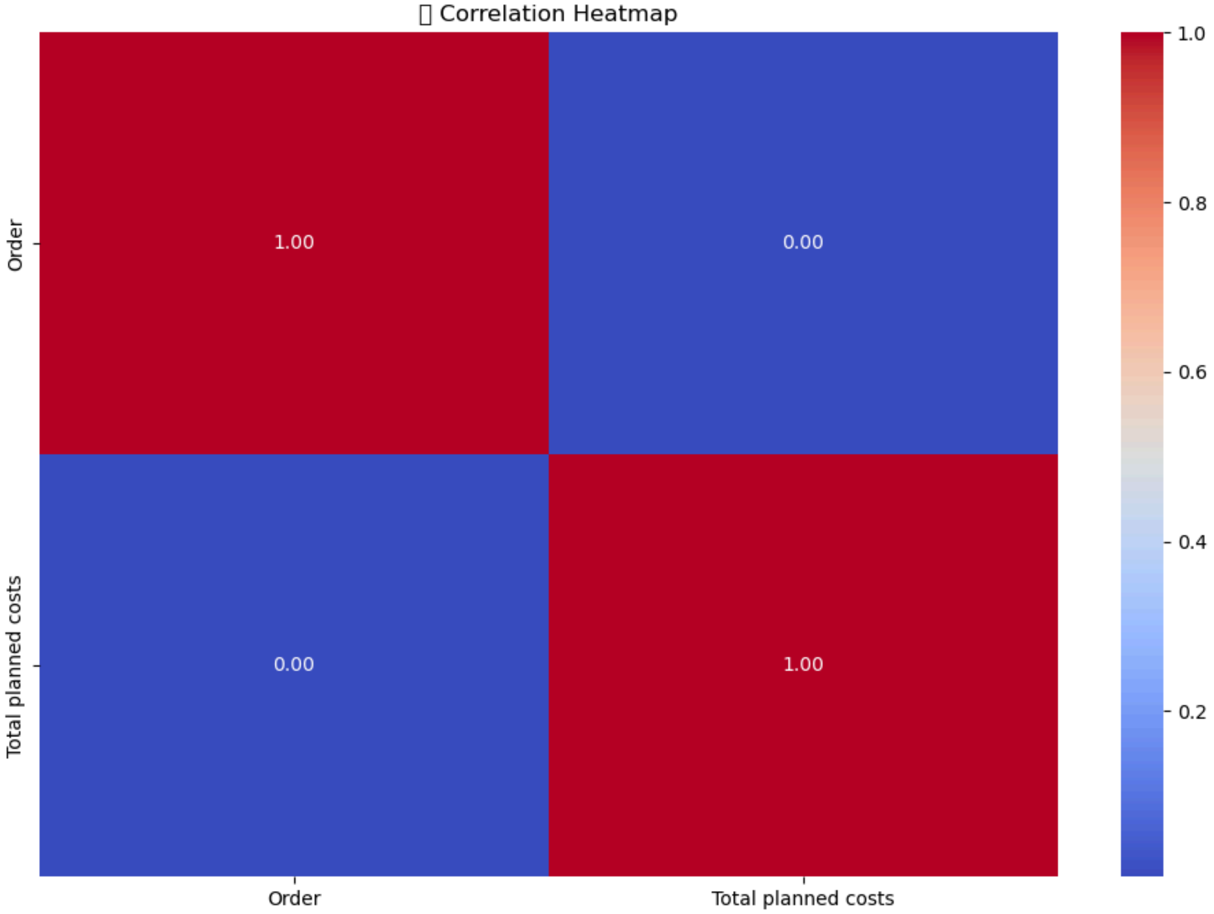


In [9]:

```
# Correlation heatmap (numerical features)
plt.figure(figsize=(12, 8))
sns.heatmap(wo_df.select_dtypes(include='number').corr(), annot=True, fmt='.2f', cma
```

```
plt.title('🔗 Correlation Heatmap')
plt.show()
```

```
C:\Users\chinmay\anaconda3\lib\site-packages\IPython\core\pylabtools.py:152: UserWarn
ing: Glyph 128279 (\N{LINK SYMBOL}) missing from current font.
  fig.canvas.print_figure(bytes_io, **kw)
```



In [10]:

```
scada_df.isnull().sum()
```

Out[10]:

```
timestamp                 0
turbine_id                0
gearbox_temperature_C     0
nacelle_temperature_C     0
hydraulic_pressure_bar    0
cooling_pressure_bar      0
dtype: int64
```

In [11]:

```
# ===============================
# 1. SCADA Risk Score Calculation
# ===============================

# Preprocess SCADA
scada_df['timestamp'] = pd.to_datetime(scada_df['timestamp'])
```

In [12]:

```
scada_df['timestamp']
```

Out[12]:

```
0       2025-03-15 00:00:00
1       2025-03-15 01:00:00
2       2025-03-15 02:00:00
3       2025-03-15 03:00:00
4       2025-03-15 04:00:00
                ...
```

```
29515   2025-04-13 19:00:00
29516   2025-04-13 20:00:00
29517   2025-04-13 21:00:00
29518   2025-04-13 22:00:00
29519   2025-04-13 23:00:00
Name: timestamp, Length: 29520, dtype: datetime64[ns]
```

In [13]:
```python
# Define thresholds
thresholds = {
    'gearbox_temperature_C': 75,
    'nacelle_temperature_C': 60,
    'hydraulic_pressure_bar': 250,
    'cooling_pressure_bar': 200
}
```

In [14]:
```python
# Example: Check if any gearbox temperature exceeds the threshold
if (scada_df['gearbox_temperature_C'] > thresholds['gearbox_temperature_C']).any():
    print("At least one gearbox temperature exceeds the threshold!")
```

```
At least one gearbox temperature exceeds the threshold!
```

In [15]:
```python
# Create threshold flags
for metric, limit in thresholds.items():
    scada_df[f'{metric}_flag'] = (scada_df[metric] > limit).astype(int)
```

In [16]:
```python
  scada_df[f'{metric}_flag']
```

Out[16]:
```
0        0
1        0
2        0
3        0
4        0
        ..
29515    0
29516    0
29517    0
29518    0
29519    0
Name: cooling_pressure_bar_flag, Length: 29520, dtype: int32
```

In [17]:
```python
# Summarize threshold violations per turbine
scada_risk = scada_df.groupby('turbine_id')[
    [f'{metric}_flag' for metric in thresholds]
].sum().reset_index()
```

In [18]:
```python
scada_risk
```

Out[18]:

	turbine_id	gearbox_temperature_C_flag	nacelle_temperature_C_flag	hydraulic_pressure_bar_flag
0	WOW03A01	1	0	2
1	WOW03A02	2	0	6
2	WOW03A03	1	0	1
3	WOW03A04	0	0	2
4	WOW03A05	1	0	7

	turbine_id	gearbox_temperature_C_flag	nacelle_temperature_C_flag	hydraulic_pressure_bar_flag
5	WOW03B01	0	0	7
6	WOW03B02	3	0	9
7	WOW03B03	1	0	3
8	WOW03B04	1	0	4
9	WOW03B05	0	0	6
10	WOW03B06	0	0	4
11	WOW03C01	0	0	5
12	WOW03C02	1	0	6
13	WOW03C03	0	0	4
14	WOW03C04	2	0	5
15	WOW03C05	0	0	7
16	WOW03C06	2	0	4
17	WOW03C07	0	0	5
18	WOW03D01	1	0	5
19	WOW03D02	2	0	3
20	WOW03D03	0	0	6
21	WOW03D04	0	0	4
22	WOW03D05	2	0	4
23	WOW03E01	2	0	4
24	WOW03E02	2	0	4
25	WOW03E03	0	0	7
26	WOW03E04	3	0	7
27	WOW03F01	1	0	3
28	WOW03F02	1	1	6
29	WOW03F03	2	0	5
30	WOW03F04	1	0	5
31	WOW03F05	0	0	5
32	WOW03G01	2	0	9
33	WOW03G02	0	0	6
34	WOW03G03	0	0	6
35	WOW03G04	0	0	10
36	WOW03H01	1	0	4
37	WOW03H02	1	0	0
38	WOW03H03	1	0	6
39	WOW03H04	0	0	5
40	WOW03H05	1	0	2

In [19]:

```
# Total breach count
scada_risk['scada_risk_score_raw'] = scada_risk.drop(columns='turbine_id').sum(axis=
```

In [20]:

```
scada_risk['scada_risk_score_raw']
```

Out[20]:

```
0      4
1      9
2      2
3      2
4      8
5      7
6     12
7      4
8      5
9      6
10     4
11     5
12     7
13     4
14     7
15     7
16     6
17     6
18     6
19     6
20     7
21     4
22     6
23     7
24     6
25     9
26    11
27     4
28     9
29     7
30     7
31     5
32    11
33     6
34     6
35    11
36     5
37     1
38     7
39     5
40     3
Name: scada_risk_score_raw, dtype: int64
```

In [21]:

```
# Normalize to 0-100
scada_risk['scada_risk_score'] = (
    scada_risk['scada_risk_score_raw'] / scada_risk['scada_risk_score_raw'].max()
) * 100
```

In [22]:

```
scada_risk['scada_risk_score']
```

Out[22]:

```
0      33.333333
1      75.000000
```

```
2      16.666667
3      16.666667
4      66.666667
5      58.333333
6     100.000000
7      33.333333
8      41.666667
9      50.000000
10     33.333333
11     41.666667
12     58.333333
13     33.333333
14     58.333333
15     58.333333
16     50.000000
17     50.000000
18     50.000000
19     50.000000
20     58.333333
21     33.333333
22     50.000000
23     58.333333
24     50.000000
25     75.000000
26     91.666667
27     33.333333
28     75.000000
29     58.333333
30     58.333333
31     41.666667
32     91.666667
33     50.000000
34     50.000000
35     91.666667
36     41.666667
37      8.333333
38     58.333333
39     41.666667
40     25.000000
Name: scada_risk_score, dtype: float64
```

In [23]:

```
# ================================
# 2. Work Order (WO) Risk Scoring
# ================================

# Clean column names
wo_df.columns = [col.strip().lower().replace(" ", "_") for col in wo_df.columns]
```

In [24]:

```
wo_df.columns
```

Out[24]:

```
Index(['created_on', 'basic_start_date', 'basic_finish_date', 'order',
       'order_type', 'priority_text', 'system_status', 'user_status',
       'description', 'functional_location',
       'description_of_functional_location', 'total_planned_costs'],
      dtype='object')
```

In [25]:

```
# Extract turbine ID
wo_df['turbine_id'] = wo_df['functional_location'].str.strip()
```

In [26]:

```
wo_df['turbine_id']
```

Out[26]:
```
0                          WOW03H05
1                          WOW03A03
2                          WOW03B03
3                          WOW03X01
4                          WOW03F03
                    ...
788             WOW03D03YAB01UH002
789       WOW03H05XMM80GM001-UM001
790       WOW03G03XMM80GM001-UM001
791                   WOW03E02UMD80
792                   WOW03C06XMM80
Name: turbine_id, Length: 793, dtype: object
```

In [27]:
```
# Priority mapping
priority_map = {
    'Immediately': 3,
    'Within 1 month': 2,
    'Within 3 months': 1
}
wo_df['priority_score'] = wo_df['priority_text'].map(priority_map).fillna(0)
```

In [28]:
```
wo_df['priority_score']
```

Out[28]:
```
0      1.0
1      2.0
2      2.0
3      2.0
4      3.0
      ...
788    0.0
789    0.0
790    0.0
791    0.0
792    0.0
Name: priority_score, Length: 793, dtype: float64
```

In [29]:
```
priority_map
```

Out[29]:
```
{'Immediately': 3, 'Within 1 month': 2, 'Within 3 months': 1}
```

In [30]:
```
# Work order features
wo_summary = wo_df.groupby('turbine_id').agg(
    wo_count=('order', 'count'),
    avg_cost=('total_planned_costs', 'mean'),
    avg_priority=('priority_score', 'mean'),
    recurring_issues=('description', pd.Series.nunique)
).reset_index()
```

In [31]:
```
wo_summary
```

Out[31]:

	turbine_id	wo_count	avg_cost	avg_priority	recurring_issues
0	WOW03A01	25	12836.820400	1.16	23
1	WOW03A01MDX01	1	1320.000000	1.00	1
2	WOW03A01XMM	1	0.000000	2.00	1

	turbine_id	wo_count	avg_cost	avg_priority	recurring_issues
3	WOW03A02	14	9378.748571	1.00	14
4	WOW03A02MDA15	1	987.440000	2.00	1
...	...	...	...	...	...
196	WOW03Z03AAF11	1	0.000000	0.00	1
197	WOW03Z03AAF24	1	0.000000	0.00	1
198	WOW03Z03AAF24WA001-QB001	1	0.000000	2.00	1
199	WOW03Z03CAA01UH001-RB001	1	0.000000	1.00	1
200	WOW03Z03CFU01	1	0.000000	0.00	1

201 rows × 5 columns

In [32]:
```
# Normalize
for col in ['wo_count', 'avg_cost', 'avg_priority', 'recurring_issues']:
    max_val = wo_summary[col].max()
    wo_summary[f'{col}_norm'] = wo_summary[col] / max_val if max_val > 0 else 0
```

In [33]:
```
# Combined WO risk score (average of all normalized)
wo_summary['wo_risk_score_raw'] = wo_summary[
    ['wo_count_norm', 'avg_cost_norm', 'avg_priority_norm', 'recurring_issues_norm']
].mean(axis=1)
wo_summary['wo_risk_score'] = wo_summary['wo_risk_score_raw'] * 100
```

In [34]:
```
  wo_summary[f'{col}_norm']
```

Out[34]:
```
0      0.884615
1      0.038462
2      0.038462
3      0.538462
4      0.038462
         ...
196    0.038462
197    0.038462
198    0.038462
199    0.038462
200    0.038462
Name: recurring_issues_norm, Length: 201, dtype: float64
```

In [35]:
```
wo_summary['wo_risk_score']
```

Out[35]:
```
0      56.813255
1      10.358493
2      18.589744
3      35.981721
4      18.666108
         ...
196     1.923077
197     1.923077
198    18.589744
199    10.256410
200     1.923077
Name: wo_risk_score, Length: 201, dtype: float64
```

In [36]:
```
# ================================
# 3. Combine and Calculate HI Score
# ================================

# Merge datasets
combined = pd.merge(
    scada_risk[['turbine_id', 'scada_risk_score']],
    wo_summary[['turbine_id', 'wo_risk_score']],
    on='turbine_id',
    how='outer'
).fillna(0)
```

In [37]:
```
combined
```

Out[37]:

	turbine_id	scada_risk_score	wo_risk_score
0	WOW03A01	33.333333	56.813255
1	WOW03A02	75.000000	35.981721
2	WOW03A03	16.666667	30.221836
3	WOW03A04	16.666667	33.635383
4	WOW03A05	66.666667	32.401302
...	...	...	...
197	WOW03Z03AAF11	0.000000	1.923077
198	WOW03Z03AAF24	0.000000	1.923077
199	WOW03Z03AAF24WA001-QB001	0.000000	18.589744
200	WOW03Z03CAA01UH001-RB001	0.000000	10.256410
201	WOW03Z03CFU01	0.000000	1.923077

202 rows × 3 columns

In [38]:
```
# Health Index Score
combined['health_index_score'] = 100 - (
    0.5 * combined['scada_risk_score'] + 0.5 * combined['wo_risk_score']
)
```

In [39]:
```
combined['health_index_score']
```

Out[39]:
```
0      54.926706
1      44.509140
2      76.555748
3      74.848975
4      50.466015
         ...
197    99.038462
198    99.038462
199    90.705128
200    94.871795
201    99.038462
Name: health_index_score, Length: 202, dtype: float64
```

In [40]:
```
# Sort by health index
combined_sorted = combined.sort_values('health_index_score')
```

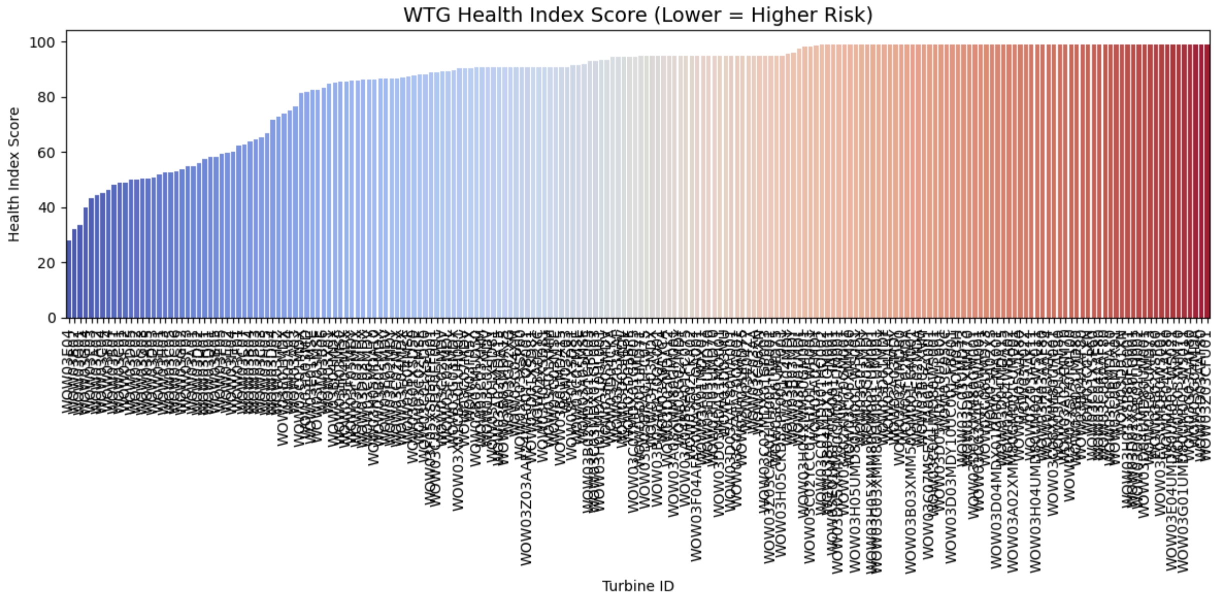
In [41]:
```
combined_sorted
```

Out[41]:

	turbine_id	scada_risk_score	wo_risk_score	health_index_score
26	WOW03E04	91.666667	52.156333	28.088500
6	WOW03B02	100.000000	35.768185	32.115908
32	WOW03G01	91.666667	41.523963	33.404685
35	WOW03G04	91.666667	28.453201	39.940066
25	WOW03E03	75.000000	38.188145	43.405928
...	...	...	...	...
156	WOW03G01UMD80UM001-WS011	0.000000	1.923077	99.038462
160	WOW03G03AAF80	0.000000	1.923077	99.038462
166	WOW03G04MDA	0.000000	1.923077	99.038462
113	WOW03D03AAF80	0.000000	1.923077	99.038462
201	WOW03Z03CFU01	0.000000	1.923077	99.038462

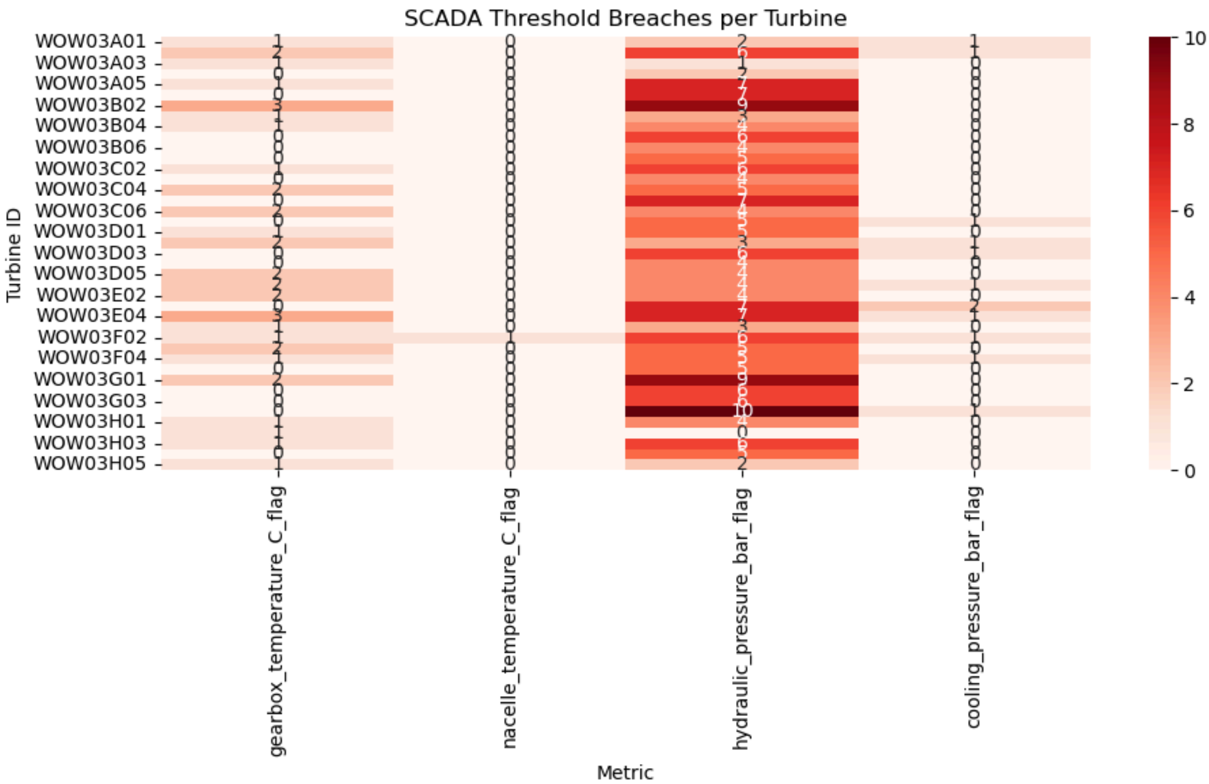
202 rows × 4 columns

In [42]:
```
# ================================
# 4. Visualizations
# ================================

# Barplot of Health Index
plt.figure(figsize=(12, 6))
sns.barplot(data=combined_sorted, x='turbine_id', y='health_index_score', palette='c
plt.title('WTG Health Index Score (Lower = Higher Risk)', fontsize=14)
plt.xlabel('Turbine ID')
plt.ylabel('Health Index Score')
plt.xticks(rotation=90)
plt.tight_layout()
plt.show()
```



In [43]:

```python
# Heatmap of SCADA risks
scada_heatmap = scada_risk.set_index('turbine_id')[
    [f'{metric}_flag' for metric in thresholds]
]

plt.figure(figsize=(10, 6))
sns.heatmap(scada_heatmap, cmap='Reds', annot=True, fmt='d')
plt.title('SCADA Threshold Breaches per Turbine')
plt.ylabel('Turbine ID')
plt.xlabel('Metric')
plt.tight_layout()
plt.show()
```



In [44]:

```python
# Top 10 Risky Turbines
top_risky = combined_sorted.head(10)
print("⚠️ Top 10 Most At-Risk WTGs (Lowest Health Index):")
print(top_risky[['turbine_id', 'scada_risk_score', 'wo_risk_score', 'health_index_sc
```

```
🔺 Top 10 Most At-Risk WTGs (Lowest Health Index):
   turbine_id  scada_risk_score  wo_risk_score  health_index_score
26   WOW03E04         91.666667      52.156333           28.088500
6    WOW03B02        100.000000      35.768185           32.115908
32   WOW03G01         91.666667      41.523963           33.404685
35   WOW03G04         91.666667      28.453201           39.940066
25   WOW03E03         75.000000      38.188145           43.405928
1    WOW03A02         75.000000      35.981721           44.509140
14   WOW03C04         58.333333      51.786545           44.940061
30   WOW03F04         58.333333      49.313718           46.176474
5    WOW03B01         58.333333      45.830768           47.917949
11   WOW03C01         41.666667      60.478054           48.927640
```

In [45]:

```
top_risky
```

Out[45]:

	turbine_id	scada_risk_score	wo_risk_score	health_index_score
26	WOW03E04	91.666667	52.156333	28.088500
6	WOW03B02	100.000000	35.768185	32.115908
32	WOW03G01	91.666667	41.523963	33.404685
35	WOW03G04	91.666667	28.453201	39.940066
25	WOW03E03	75.000000	38.188145	43.405928
1	WOW03A02	75.000000	35.981721	44.509140
14	WOW03C04	58.333333	51.786545	44.940061
30	WOW03F04	58.333333	49.313718	46.176474
5	WOW03B01	58.333333	45.830768	47.917949
11	WOW03C01	41.666667	60.478054	48.927640

In [46]:

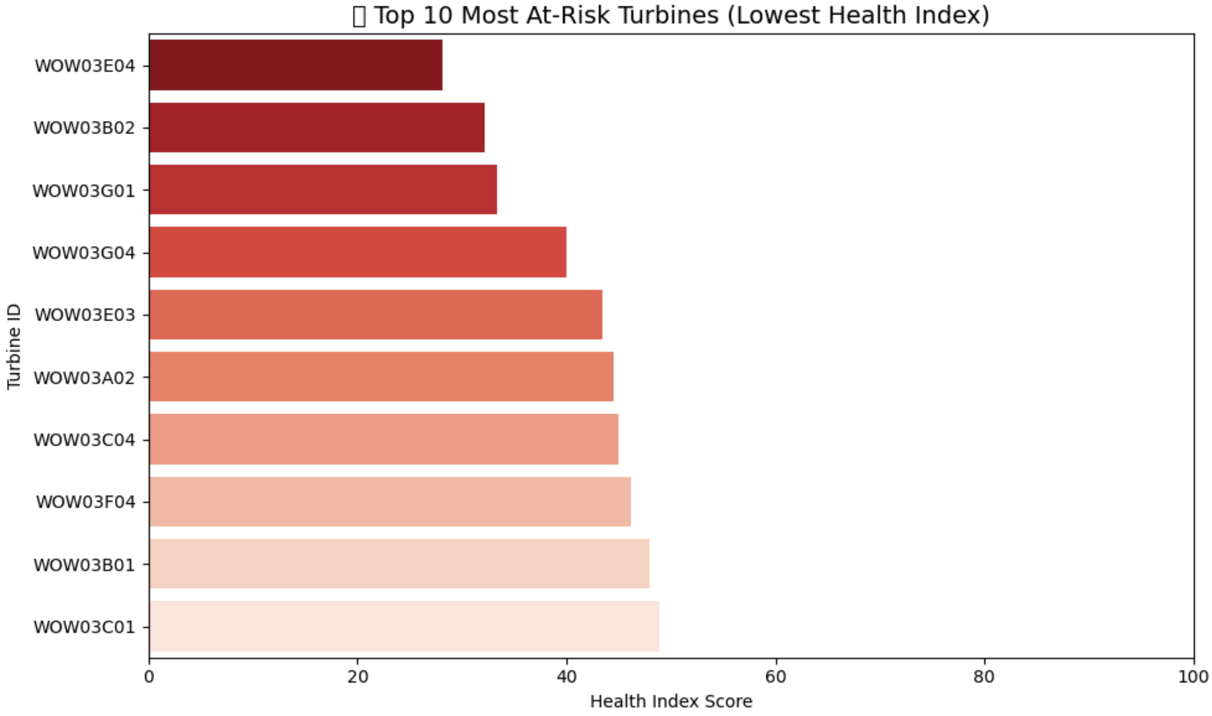
```
# Ensure combined and combined_sorted are created
# If not already defined, recreate them here

# Sort combined scores for visualization
combined_sorted = combined.sort_values('health_index_score').reset_index(drop=True)

# Define top and bottom turbines for plots
top10 = combined_sorted.head(10)
bottom10 = combined_sorted.tail(10)
```

In [47]:

```
# Plot 1: Horizontal Barplot - Top 10 Risky Turbines
plt.figure(figsize=(10, 6))
sns.barplot(data=top10, y='turbine_id', x='health_index_score', palette='Reds_r')
plt.title('🔺 Top 10 Most At-Risk Turbines (Lowest Health Index)', fontsize=14)
plt.xlabel('Health Index Score')
plt.ylabel('Turbine ID')
plt.xlim(0, 100)
plt.tight_layout()
plt.show()
```

```
C:\Users\chinmay\AppData\Local\Temp\ipykernel_10396\2835192681.py:8: UserWarning: Gly
ph 128314 (\N{UP-POINTING RED TRIANGLE}) missing from current font.
  plt.tight_layout()
C:\Users\chinmay\anaconda3\lib\site-packages\IPython\core\pylabtools.py:152: UserWarn
```

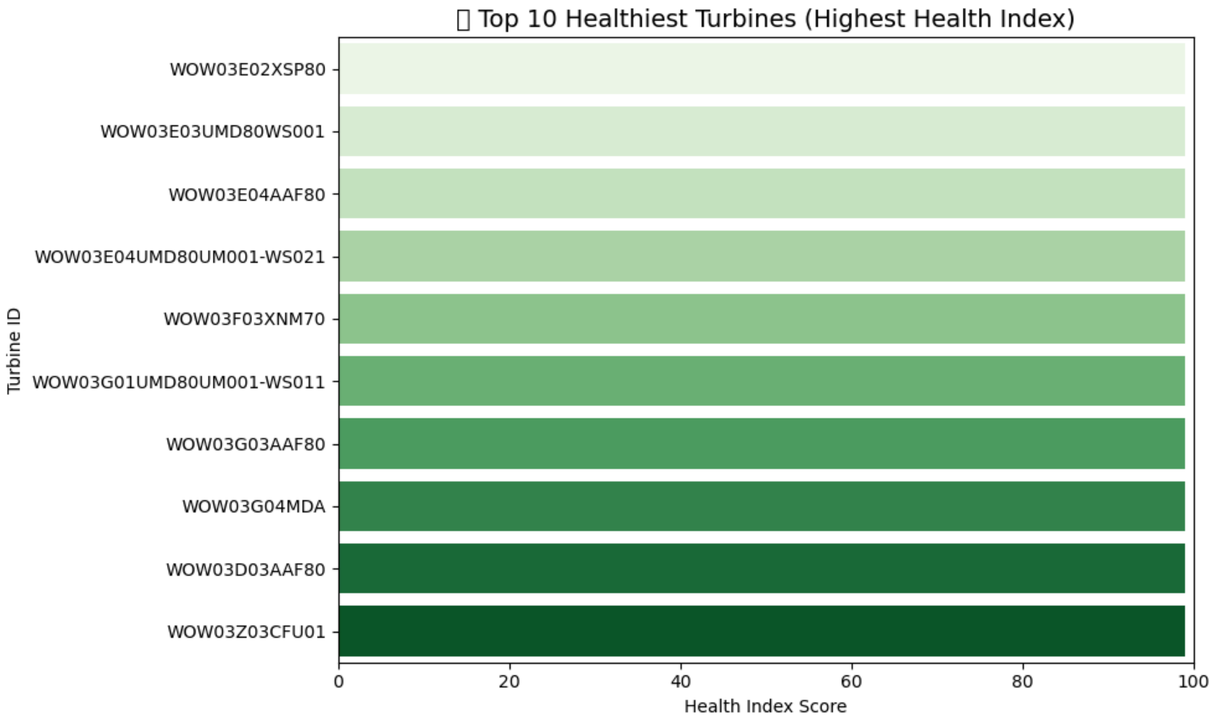
```
ing: Glyph 128314 (\N{UP-POINTING RED TRIANGLE}) missing from current font.
  fig.canvas.print_figure(bytes_io, **kw)
```



In [48]:

```
# Plot 2: Horizontal Barplot - Top 10 Healthiest Turbines
plt.figure(figsize=(10, 6))
sns.barplot(data=bottom10, y='turbine_id', x='health_index_score', palette='Greens')
plt.title('🟢 Top 10 Healthiest Turbines (Highest Health Index)', fontsize=14)
plt.xlabel('Health Index Score')
plt.ylabel('Turbine ID')
plt.xlim(0, 100)
plt.tight_layout()
plt.show()
```

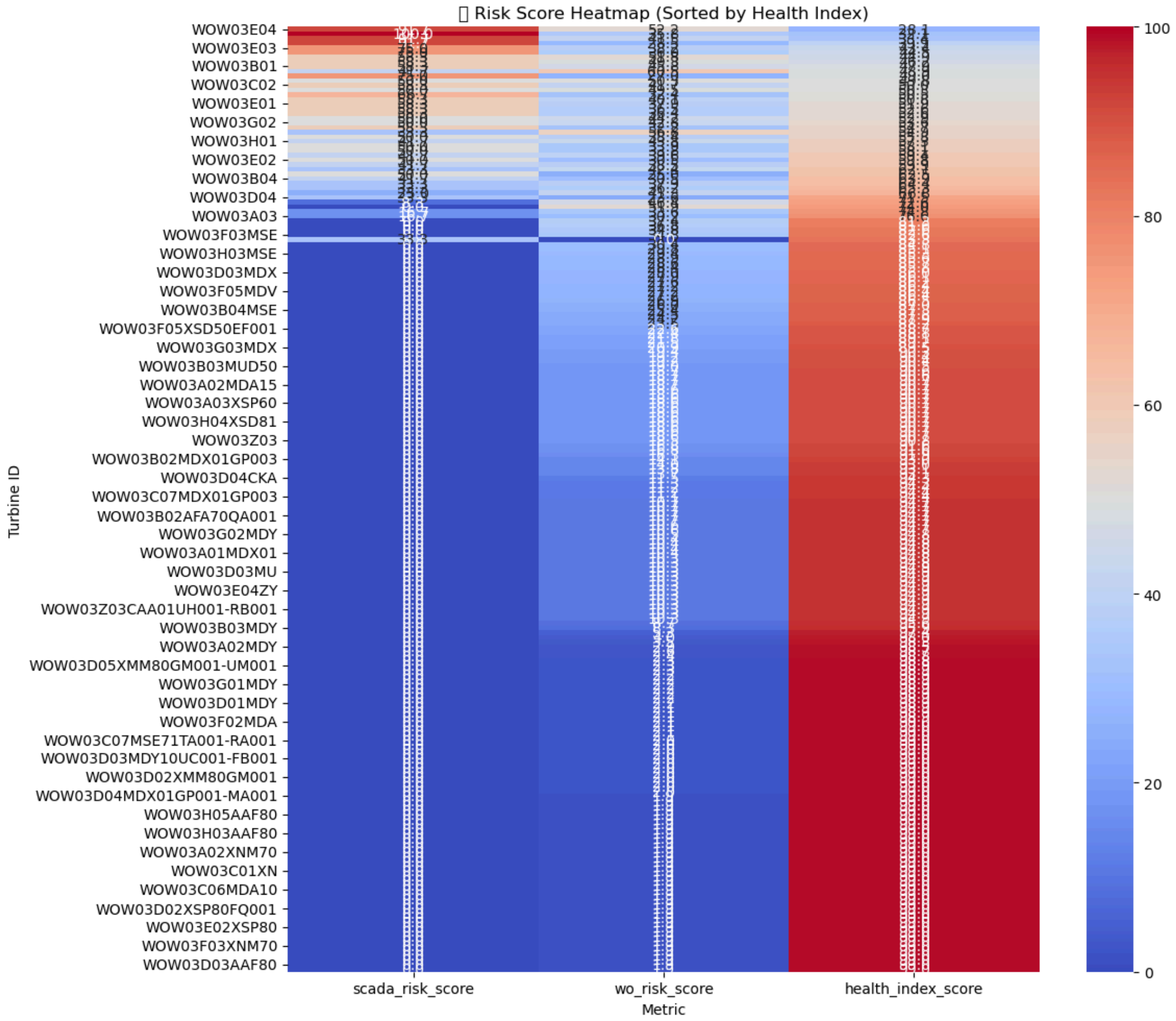
```
C:\Users\chinmay\AppData\Local\Temp\ipykernel_10396\14481383.py:8: UserWarning: Glyph
128994 (\N{LARGE GREEN CIRCLE}) missing from current font.
  plt.tight_layout()
C:\Users\chinmay\anaconda3\lib\site-packages\IPython\core\pylabtools.py:152: UserWarn
ing: Glyph 128994 (\N{LARGE GREEN CIRCLE}) missing from current font.
  fig.canvas.print_figure(bytes_io, **kw)
```



In [49]:

```
# Plot 3: Risk Score Heatmap
risk_matrix = combined.set_index('turbine_id')[['scada_risk_score', 'wo_risk_score',

plt.figure(figsize=(12, 10))
sns.heatmap(risk_matrix.sort_values('health_index_score', ascending=True), annot=Tru
plt.title('📊 Risk Score Heatmap (Sorted by Health Index)')
plt.xlabel('Metric')
plt.ylabel('Turbine ID')
plt.tight_layout()
plt.show()
```

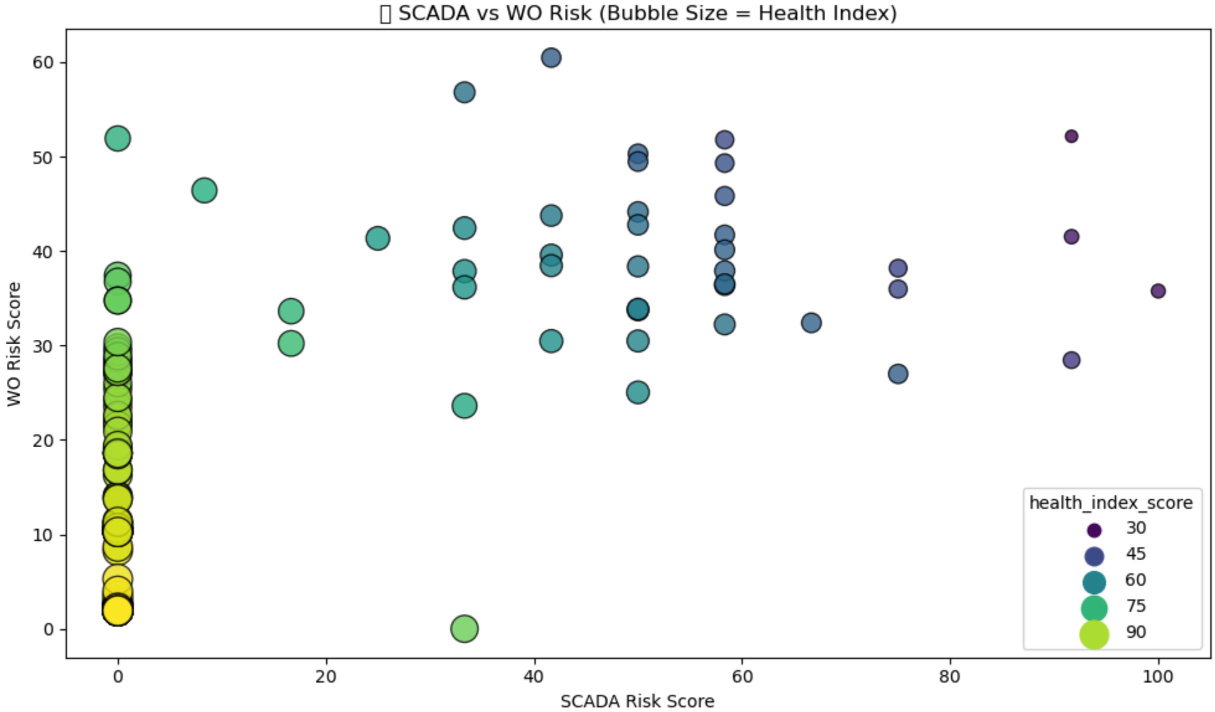
```
C:\Users\chinmay\AppData\Local\Temp\ipykernel_10396\1643960804.py:9: UserWarning: Gly
ph 128202 (\N{BAR CHART}) missing from current font.
  plt.tight_layout()
C:\Users\chinmay\anaconda3\lib\site-packages\IPython\core\pylabtools.py:152: UserWarn
ing: Glyph 128202 (\N{BAR CHART}) missing from current font.
  fig.canvas.print_figure(bytes_io, **kw)
```



In [50]:

```python
# Plot 4: SCADA vs WO Risk Bubble Chart
plt.figure(figsize=(10, 6))
sns.scatterplot(
    data=combined,
    x='scada_risk_score',
    y='wo_risk_score',
    size='health_index_score',
    hue='health_index_score',
    sizes=(50, 300),
    palette='viridis',
    alpha=0.8,
    edgecolor="black"
)
plt.title('🧮 SCADA vs WO Risk (Bubble Size = Health Index)')
plt.xlabel('SCADA Risk Score')
plt.ylabel('WO Risk Score')
plt.tight_layout()
plt.show()
```

```
C:\Users\chinmay\AppData\Local\Temp\ipykernel_10396\2512330493.py:17: UserWarning: Gl
yph 129518 (\N{ABACUS}) missing from current font.
  plt.tight_layout()
C:\Users\chinmay\anaconda3\lib\site-packages\IPython\core\pylabtools.py:152: UserWarn
ing: Glyph 129518 (\N{ABACUS}) missing from current font.
  fig.canvas.print_figure(bytes_io, **kw)
```



In [ ]:

In [ ]:

Work Order Prioritization Logic

To prioritize work orders effectively, we incorporate multiple dimensions beyond cost and count. The weighted scoring model includes:

- **Severity (1-5):** Impact level on asset performance
- **Failure Mode Criticality (1-5):** Based on historical failure consequence
- **Recurrence (1-5):** Frequency of similar failures
- **Lost Production Potential (1-5):** Downtime impact on power generation
- **Safety Risk (1-5):** Risk to personnel
- **Estimated Cost (normalized)**
- **Lead Time (in days, normalized)**

The total WO risk score is a weighted combination of the above factors.

In [51]:

```
print(wo_df.columns)
```

```
Index(['created_on', 'basic_start_date', 'basic_finish_date', 'order',
       'order_type', 'priority_text', 'system_status', 'user_status',
       'description', 'functional_location',
       'description_of_functional_location', 'total_planned_costs',
       'turbine_id', 'priority_score'],
      dtype='object')
```

In [52]:

```
# Ensure datetime format
wo_df['basic_start_date'] = pd.to_datetime(wo_df['basic_start_date'])
wo_df['basic_finish_date'] = pd.to_datetime(wo_df['basic_finish_date'])
```

```
# Calculate lead time
wo_df['lead_time_days'] = (wo_df['basic_finish_date'] - wo_df['basic_start_date']).d

# Normalize cost and lead time
wo_df['normalized_cost'] = (wo_df['total_planned_costs'] - wo_df['total_planned_cost
wo_df['normalized_lead_time'] = (wo_df['lead_time_days'] - wo_df['lead_time_days'].m

# Risk score using available data
wo_df['WO_risk_score'] = (
    wo_df['priority_score'] * 0.6 +
    wo_df['normalized_cost'] * 0.2 +
    wo_df['normalized_lead_time'] * 0.2
)
```

In [53]:

```
wo_df['basic_start_date']
```

Out[53]:

```
0      2025-04-04
1      2025-03-06
2      2025-03-10
3      2025-03-13
4      2025-03-06
          ...
788    2025-04-07
789    2025-09-08
790    2025-06-02
791    2025-07-07
792    2025-07-21
Name: basic_start_date, Length: 793, dtype: datetime64[ns]
```

In [54]:

```
wo_df['basic_finish_date']
```

Out[54]:

```
0      2025-06-03
1      2025-03-06
2      2025-04-02
3      2025-04-03
4      2025-03-06
          ...
788    2025-04-13
789    2025-09-14
790    2025-06-08
791    2025-07-13
792    2025-07-27
Name: basic_finish_date, Length: 793, dtype: datetime64[ns]
```

In [55]:

```
wo_df['lead_time_days']
```

Out[55]:

```
0       60
1        0
2       23
3       21
4        0
        ..
788      6
789      6
790      6
791      6
792      6
Name: lead_time_days, Length: 793, dtype: int64
```

In [56]:

```
wo_df['normalized_cost']
```

Out[56]:
```
0      0.004316
1      0.006279
2      0.006125
3      0.023479
4      0.012250
         ...
788    0.000000
789    0.009648
790    0.009648
791    0.008167
792    0.012250
Name: normalized_cost, Length: 793, dtype: float64
```

In [57]:
```
wo_df['normalized_lead_time']
```

Out[57]:
```
0      0.181818
1      0.000000
2      0.069697
3      0.063636
4      0.000000
         ...
788    0.018182
789    0.018182
790    0.018182
791    0.018182
792    0.018182
Name: normalized_lead_time, Length: 793, dtype: float64
```

In [58]:
```
wo_df['WO_risk_score']
```

Out[58]:
```
0      0.637227
1      1.201256
2      1.215164
3      1.217423
4      1.802450
         ...
788    0.003636
789    0.005566
790    0.005566
791    0.005270
792    0.006086
Name: WO_risk_score, Length: 793, dtype: float64
```

Data Understanding & Feature Engineering

We can leverage multiple data sources to assess asset health:

- **SCADA:** Sensor data (e.g., temperature, pressure). Feature engineering includes:
  - Rolling means/variances
  - Anomaly detection using thresholds or ML
- **CMMS (WO data):** Frequency and type of failures
- **Vibration Sensors:** Harmonic signatures for bearing faults
- **Alarm Logs:** Frequency and type of alarms
- **Maintenance Logs:** Previous repairs and effectiveness

Useful features:

- Time since last failure

- Time to failure (MTBF)
- Frequency of anomalies per asset

Dynamic Health Index

To make the Health Index dynamic:

- **Time Decay:** Older events have less weight
- **Weighted Updates:** Critical failures impact the index more than minor issues
- **Feedback Loops:** Completed maintenance can improve the score

Implementation example (conceptual):

```
HI = α * Current_Score + β * New_Events - γ * Resolved_Issues
```

Where:

- α, β, γ are tunable decay/weighting constants
- Resolved issues (e.g., successful maintenance) reduce the overall risk

Assumptions & Limitations

- Sensor thresholds are reliable and standardized
- Data is complete and up-to-date
- Equal weighting may not reflect true risk impact (tunable)
- Historical failure mode criticality is based on limited records

Data Quality Issues:

- Missing or erroneous data
- Sensor drift or calibration errors
- Inconsistent WO descriptions

Mitigation:

- Data imputation
- Anomaly detection on sensor data
- NLP for work order standardization

Decision-Making & Action Plan

The scores drive prioritization by:

- Scheduling immediate inspections for turbines with **Health Index > 80**
- **High WO Risk** WOs are resolved within 7 days
- **Medium Risk** WOs scheduled based on resource availability

Resource Allocation:

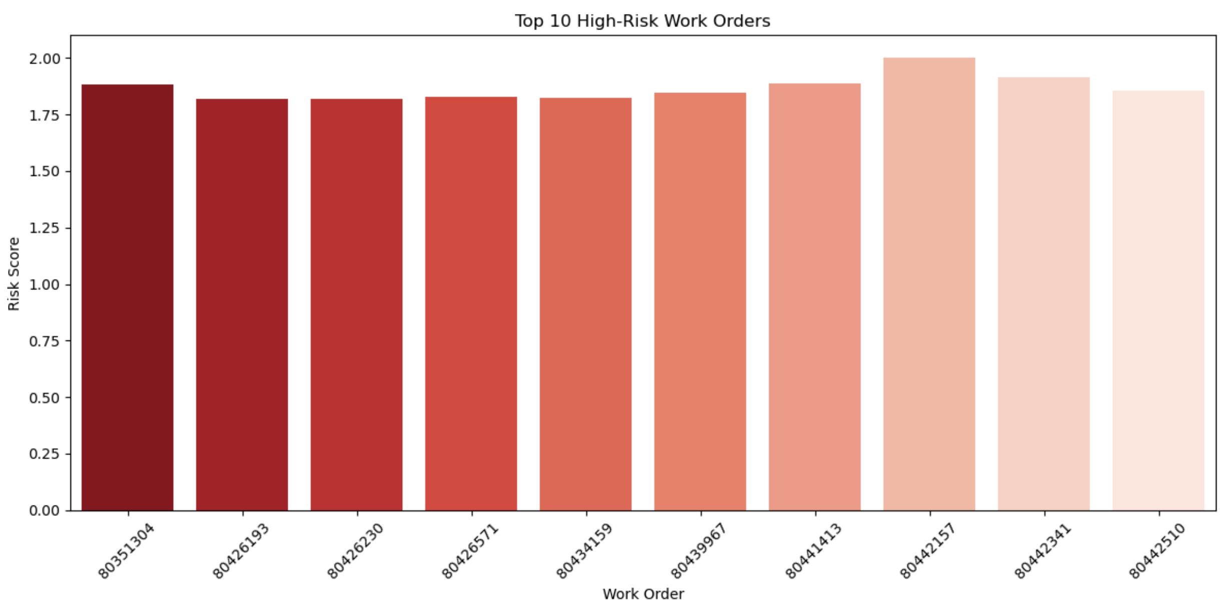
- Teams dispatched to turbines with highest cumulative risk
- Budget assigned to high-cost, high-impact failures

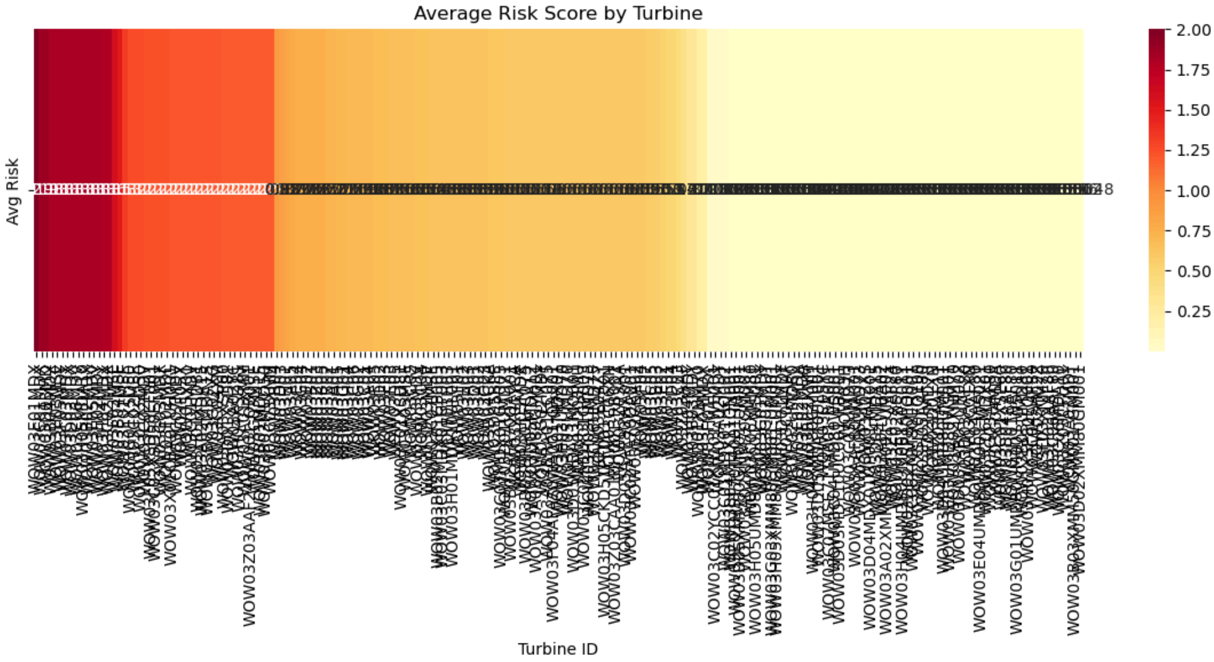
Example Rules:

```
if WO_risk_score > 4.5:
    schedule_urgent_repair()
elif Health_Index > 80:
    trigger_inspection()
```

In [59]:

```
import matplotlib.pyplot as plt
import seaborn as sns

# Recalculate lead time and risk score (if needed)
wo_df['basic_start_date'] = pd.to_datetime(wo_df['basic_start_date'])
wo_df['basic_finish_date'] = pd.to_datetime(wo_df['basic_finish_date'])
wo_df['lead_time_days'] = (wo_df['basic_finish_date'] - wo_df['basic_start_date']).d

wo_df['normalized_cost'] = (wo_df['total_planned_costs'] - wo_df['total_planned_cost
wo_df['normalized_lead_time'] = (wo_df['lead_time_days'] - wo_df['lead_time_days'].m

wo_df['WO_risk_score'] = (
    wo_df['priority_score'] * 0.6 +
    wo_df['normalized_cost'] * 0.2 +
    wo_df['normalized_lead_time'] * 0.2
)

# Bar chart for top 10 high-risk WOs
top_wos = wo_df.sort_values(by='WO_risk_score', ascending=False).head(10)
plt.figure(figsize=(12, 6))
sns.barplot(data=top_wos, x='order', y='WO_risk_score', palette='Reds_r')
plt.title("Top 10 High-Risk Work Orders")
plt.xticks(rotation=45)
plt.xlabel("Work Order")
plt.ylabel("Risk Score")
plt.tight_layout()
plt.show()

# Optional: Heatmap of turbine risk (if turbine_id is available)
turbine_risk = wo_df.groupby('turbine_id')['WO_risk_score'].mean().sort_values(ascen
plt.figure(figsize=(12, 6))
sns.heatmap([turbine_risk['WO_risk_score']], cmap="YlOrRd", annot=True, cbar=True, x
plt.title("Average Risk Score by Turbine")
plt.xlabel("Turbine ID")
plt.tight_layout()
plt.show()
```





In [ ]:

In [ ]:

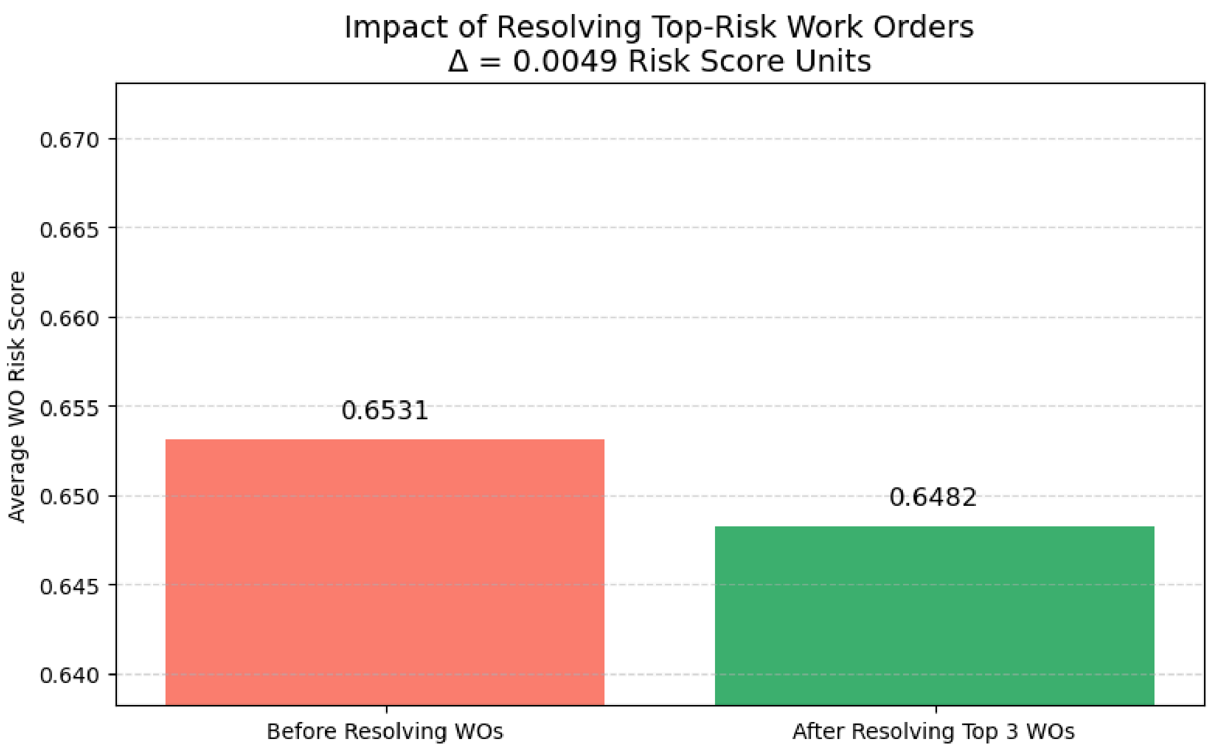
In [60]:

```
# Recalculate WO risk score if needed
wo_df['lead_time_days'] = (wo_df['basic_finish_date'] - wo_df['basic_start_date']).d
wo_df['normalized_cost'] = (wo_df['total_planned_costs'] - wo_df['total_planned_cost
wo_df['normalized_lead_time'] = (wo_df['lead_time_days'] - wo_df['lead_time_days'].m

wo_df['WO_risk_score'] = (
    wo_df['priority_score'] * 0.6 +
    wo_df['normalized_cost'] * 0.2 +
    wo_df['normalized_lead_time'] * 0.2
)

# ✅ Identify top unique high-risk work orders (averaged across duplicates)
top_orders = (
    wo_df.groupby('order')['WO_risk_score']
    .mean()
    .sort_values(ascending=False)
    .head(3)
    .index.tolist()
)

# ✅ Remove all rows that belong to those high-risk orders
resolved_df = wo_df[~wo_df['order'].isin(top_orders)]

# ✅ Compare average scores
health_before = wo_df['WO_risk_score'].mean()
health_after = resolved_df['WO_risk_score'].mean()

print(f"Average Risk Score Before Resolution: {health_before:.4f}")
print(f"Average Risk Score After Resolving Top 3 High-Risk WOs: {health_after:.4f}")
```

```
Average Risk Score Before Resolution: 0.6531
Average Risk Score After Resolving Top 3 High-Risk WOs: 0.6482
```

In [61]:

```
import matplotlib.pyplot as plt

# Labels and values
labels = ['Before Resolving WOs', 'After Resolving Top 3 WOs']
scores = [health_before, health_after]
delta = scores[0] - scores[1]

# Bar plot
plt.figure(figsize=(8, 5))
bars = plt.bar(labels, scores, color=['salmon', 'mediumseagreen'])

# Annotate bars
for i, score in enumerate(scores):
    plt.text(i, score + 0.001, f"{score:.4f}", ha='center', va='bottom', fontsize=12

# Add delta info
plt.title(f"Impact of Resolving Top-Risk Work Orders\nΔ = {delta:.4f} Risk Score Uni
plt.ylabel("Average WO Risk Score")
plt.ylim(min(scores) - 0.01, max(scores) + 0.02)
plt.grid(axis='y', linestyle='--', alpha=0.5)
plt.tight_layout()
plt.show()
```



In [62]:

```
# Step 1: Compute SCADA Anomaly Score per Turbine

# Define failure thresholds
thresholds = {
    "gearbox_temperature_C": 75,
    "nacelle_temperature_C": 60,
    "hydraulic_pressure_bar": 250,
    "cooling_pressure_bar": 200
}

# Count how often each turbine exceeds any threshold
def compute_anomaly_score(df, thresholds):
    df = df.copy()
    for col, threshold in thresholds.items():
        df[f"{col}_exceed"] = df[col] > threshold
```

```
    exceed_cols = [f"{col}_exceed" for col in thresholds]
    df["anomaly_count"] = df[exceed_cols].sum(axis=1)
    return df

scada_df_scored = compute_anomaly_score(scada_df, thresholds)

# Aggregate anomaly score per turbine
scada_anomaly_score = scada_df_scored.groupby("turbine_id")["anomaly_count"].sum().r
scada_anomaly_score.rename(columns={"anomaly_count": "scada_risk_score"}, inplace=Tr

# Normalize to 0-100
scada_anomaly_score["scada_risk_score_norm"] = (
    100 * scada_anomaly_score["scada_risk_score"] / scada_anomaly_score["scada_risk_
)

scada_anomaly_score.head()
```

Out[62]:

	turbine_id	scada_risk_score	scada_risk_score_norm
0	WOW03A01	4	33.333333
1	WOW03A02	9	75.000000
2	WOW03A03	2	16.666667
3	WOW03A04	2	16.666667
4	WOW03A05	8	66.666667

In [63]:

```
print(wo_df.columns.tolist())
```

```
['created_on', 'basic_start_date', 'basic_finish_date', 'order', 'order_type', 'prior
ity_text', 'system_status', 'user_status', 'description', 'functional_location', 'des
cription_of_functional_location', 'total_planned_costs', 'turbine_id', 'priority_scor
e', 'lead_time_days', 'normalized_cost', 'normalized_lead_time', 'WO_risk_score']
```

In [64]:

```
# Map priority to weights
priority_weights = {
    "Immediately": 100,
    "Within 1 month": 70,
    "Within 3 months": 40
}

# Clean and prepare
wo_df_clean = wo_df.copy()
wo_df_clean = wo_df_clean[wo_df_clean["functional_location"].str.startswith("WOW")]
wo_df_clean["turbine_id"] = wo_df_clean["functional_location"].str.strip()
wo_df_clean["priority_score"] = wo_df_clean["priority_text"].map(priority_weights).f

# Calculate weighted work order score
wo_df_clean["wo_score"] = wo_df_clean["priority_score"] * wo_df_clean["total_planned

# Aggregate per turbine
wo_agg = wo_df_clean.groupby("turbine_id").agg({
    "wo_score": "sum",
    "order": "count"
}).reset_index().rename(columns={"Order": "wo_count"})

# Normalize score
wo_agg["wo_score_norm"] = 100 * wo_agg["wo_score"] / wo_agg["wo_score"].max()
wo_agg.head()
```

Out[64]:

	turbine_id	wo_score	order	wo_score_norm
0	WOW03A01	15006820.0	25	46.422421
1	WOW03A01MDX01	52800.0	1	0.163333
2	WOW03A01XMM	0.0	1	0.000000
3	WOW03A02	7479531.5	14	23.137344
4	WOW03A02MDA15	69120.8	1	0.213820

In [65]:

```
# Assume SCADA = 60%, WO = 40%
scada_scores = scada_anomaly_score[["turbine_id", "scada_risk_score_norm"]]
wo_scores = wo_agg[["turbine_id", "wo_score_norm"]]

# Merge
health_df = pd.merge(scada_scores, wo_scores, on="turbine_id", how="outer").fillna(0

# Calculate Health Index Score
health_df["health_index_score"] = (
    0.6 * health_df["scada_risk_score_norm"] + 0.4 * health_df["wo_score_norm"]
)

# Round for presentation
health_df["health_index_score"] = health_df["health_index_score"].round(2)

# Sort descending (highest risk first)
health_df_sorted = health_df.sort_values(by="health_index_score", ascending=False)

# Display top 10
health_df_sorted.head(10)
```

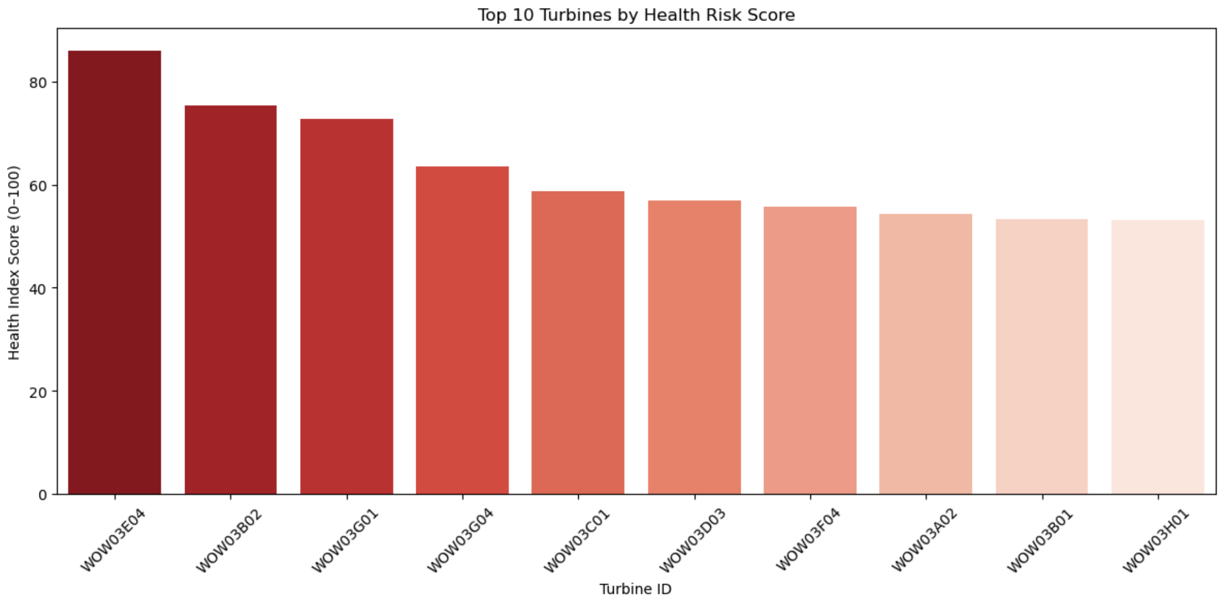
Out[65]:

	turbine_id	scada_risk_score_norm	wo_score_norm	health_index_score
26	WOW03E04	91.666667	77.494297	86.00
6	WOW03B02	100.000000	38.153299	75.26
32	WOW03G01	91.666667	44.132927	72.65
35	WOW03G04	91.666667	21.314501	63.53
11	WOW03C01	41.666667	84.506255	58.80
20	WOW03D03	58.333333	54.726587	56.89
30	WOW03F04	58.333333	51.750448	55.70
1	WOW03A02	75.000000	23.137344	54.25
5	WOW03B01	58.333333	45.892492	53.36
36	WOW03H01	41.666667	70.218093	53.09

In [66]:

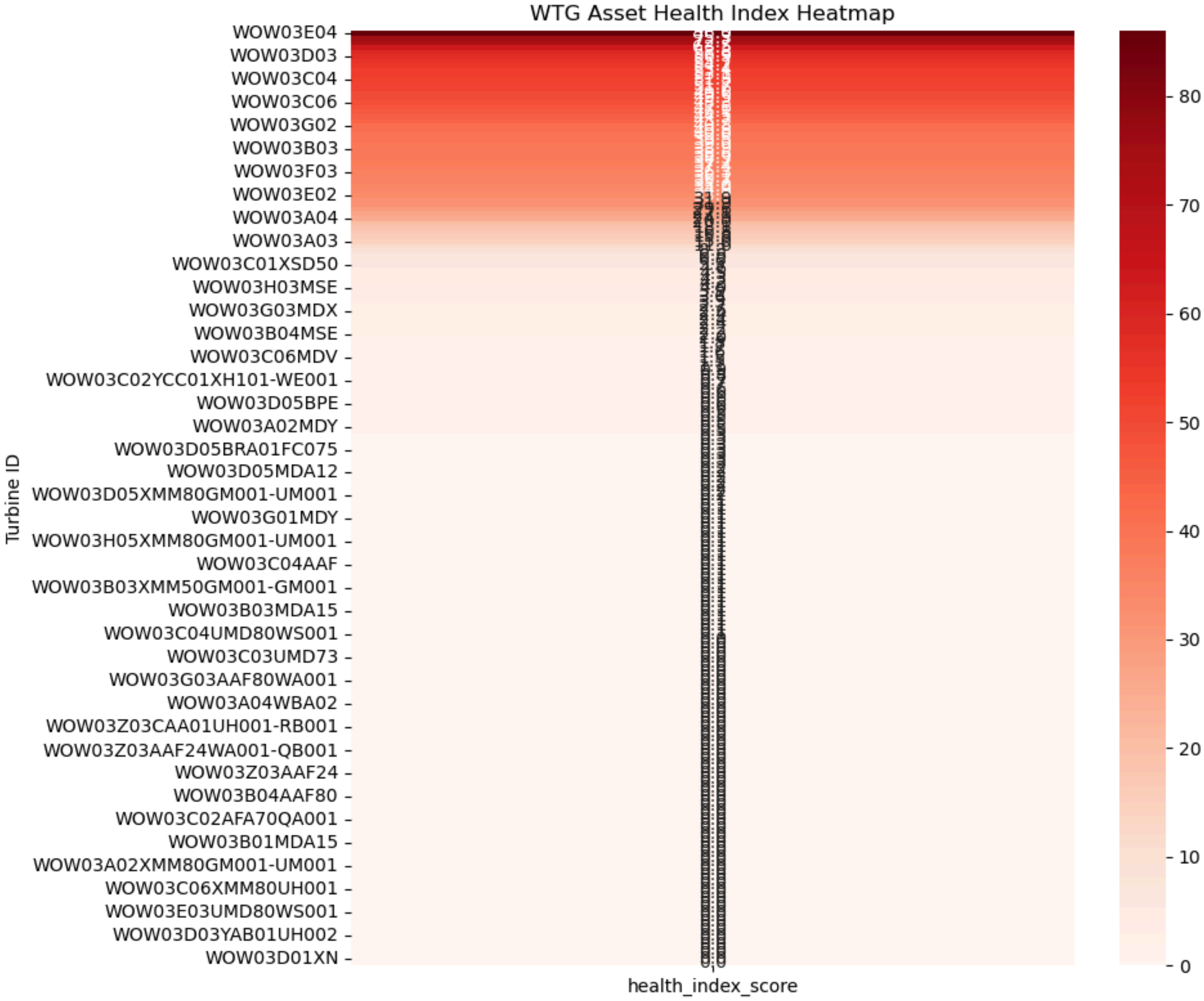
```
import matplotlib.pyplot as plt
import seaborn as sns

# Set up figure
plt.figure(figsize=(12, 6))
top_10 = health_df_sorted.head(10)

# Plot
sns.barplot(
```

```
    data=top_10,
    x="turbine_id",
    y="health_index_score",
    palette="Reds_r"
)
plt.title("Top 10 Turbines by Health Risk Score")
plt.ylabel("Health Index Score (0-100)")
plt.xlabel("Turbine ID")
plt.xticks(rotation=45)
plt.tight_layout()
plt.show()
```



In [67]:

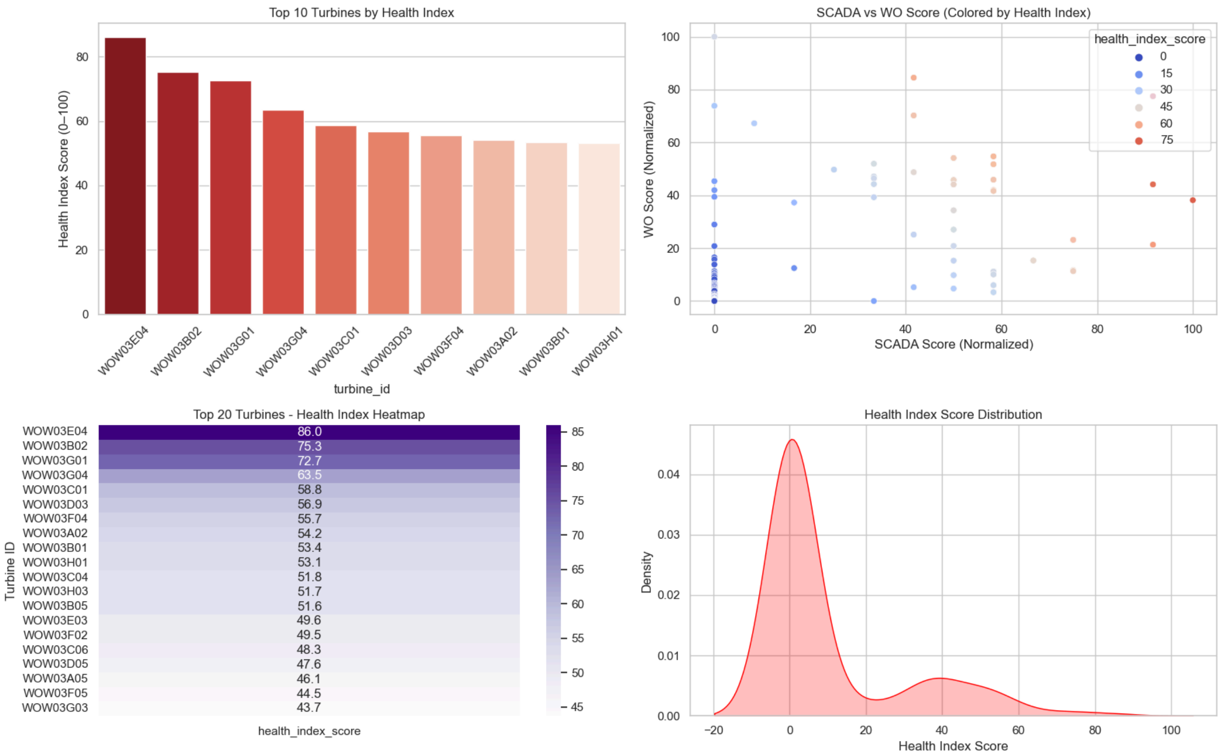
```
# Convert to matrix format for heatmap (if more turbines exist)
plt.figure(figsize=(10, 8))
heatmap_data = health_df_sorted.set_index("turbine_id")[["health_index_score"]]

sns.heatmap(heatmap_data, annot=True, cmap="Reds", fmt=".1f")
plt.title("WTG Asset Health Index Heatmap")
plt.ylabel("Turbine ID")
plt.tight_layout()
plt.show()
```



In [68]:

```
# Ensure clean aesthetics
sns.set(style="whitegrid")

# Select top turbines
top_turbines = health_df_sorted.head(10).copy()

# Create subplots layout
fig, axes = plt.subplots(2, 2, figsize=(16, 10))

# 1. Barplot - Top 10 Turbines by Health Index
sns.barplot(data=top_turbines, x="turbine_id", y="health_index_score", ax=axes[0, 0]
axes[0, 0].set_title("Top 10 Turbines by Health Index")
axes[0, 0].tick_params(axis='x', rotation=45)
axes[0, 0].set_ylabel("Health Index Score (0–100)")

# 2. Scatter Plot - SCADA vs WO Scores
sns.scatterplot(
    data=health_df_sorted,
    x="scada_risk_score_norm",
    y="wo_score_norm",
    hue="health_index_score",
    palette="coolwarm",
    ax=axes[0, 1]
)
axes[0, 1].set_title("SCADA vs WO Score (Colored by Health Index)")
axes[0, 1].set_xlabel("SCADA Score (Normalized)")
axes[0, 1].set_ylabel("WO Score (Normalized)")

# 3. Heatmap - Top 20 Turbines by Risk
heatmap_data = health_df_sorted.set_index("turbine_id")[["health_index_score"]]
sns.heatmap(heatmap_data.head(20), annot=True, cmap="Purples", fmt=".1f", ax=axes[1,
```

```
axes[1, 0].set_title("Top 20 Turbines - Health Index Heatmap")
axes[1, 0].set_xlabel("")
axes[1, 0].set_ylabel("Turbine ID")

# 4. KDE Plot - Distribution of Health Scores
sns.kdeplot(data=health_df_sorted["health_index_score"], fill=True, color="red", ax=
axes[1, 1].set_title("Health Index Score Distribution")
axes[1, 1].set_xlabel("Health Index Score")
axes[1, 1].set_ylabel("Density")

plt.tight_layout()
plt.show()
```



In [69]:

```
# List of different SCADA/WO weight combinations to test
weight_scenarios = [
    (0.2, 0.8),
    (0.4, 0.6),
    (0.5, 0.5),
    (0.6, 0.4),
    (0.8, 0.2)
]

# Collect results
sensitivity_results = []

for scada_w, wo_w in weight_scenarios:
    # Recalculate health index for each weight combination
    health_df["health_index_score"] = (
        scada_w * health_df["scada_risk_score_norm"] +
        wo_w * health_df["wo_score_norm"]
    )
    avg_score = health_df["health_index_score"].mean()
    max_score = health_df["health_index_score"].max()
    sensitivity_results.append({
        "SCADA Weight": scada_w,
        "WO Weight": wo_w,
        "Average Health Index": avg_score,
        "Max Health Index": max_score
    })
```

```python
# Convert to DataFrame
sensitivity_df = pd.DataFrame(sensitivity_results)

# Plot sensitivity trend
import seaborn as sns
import matplotlib.pyplot as plt

plt.figure(figsize=(10, 6))
sns.lineplot(data=sensitivity_df, x="SCADA Weight", y="Average Health Index", marker
sns.lineplot(data=sensitivity_df, x="SCADA Weight", y="Max Health Index", marker="s"
plt.title("Sensitivity of Health Index to SCADA vs WO Weights")
plt.ylabel("Health Index Score")
plt.xlabel("SCADA Weight (1 - WO Weight)")
plt.legend()
plt.grid(True)
plt.show()

# Also show data
sensitivity_df
```

Out[69]:

	SCADA Weight	WO Weight	Average Health Index	Max Health Index
0	0.2	0.8	9.937766	80.328771
1	0.4	0.6	10.072962	83.163245
2	0.5	0.5	10.140559	84.580482
3	0.6	0.4	10.208157	85.997719
4	0.8	0.2	10.343352	88.832193

In [ ]:

```python

```

In [70]:

```python
!jupyter nbconvert --to html "Offshore Wind Turbine Health Index and Work Order Prio
```

```
[NbConvertApp] Converting notebook Offshore Wind Turbine Health Index and Work Order Prioritization.ipynb to html
[NbConvertApp] Writing 3030747 bytes to Offshore Wind Turbine Health Index and Work Order Prioritization.html
```

In [ ]: