

# FDL (Factory Design Language) 規範設計白皮書

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## 執行摘要

**FDL (Factory Design Language)** 是 IDTF V3.3 生態系統中用於定義工廠佈局和配置的聲明式語言。FDL 填補了從資產建模(IADL)到工廠部署(NDH)之間的關鍵缺口,提供了一個標準化、可重用且易於維護的工廠設計描述方式。

本白皮書基於多個實際專案的經驗,包括: - **半導體廠房** (台積電等) - **LED 封裝廠** (宏齊科技) - **LNG 發電廠** - **NVIDIA GPU 數據中心** - **Smart City 基礎設施**

歸納整理出完整的 FDL 規範,涵蓋語法定義、設計模式、應用案例和最佳實踐。

## 核心價值

- 1. **標準化**: 統一的工廠描述語言,適用於各種產業
- 2. **可重用性**: 一次定義,多處部署
- 3. **可維護性**: 版本控制,變更追蹤
- 4. **自動化**: 自動生成部署配置
- 5. **可擴展性**: 支援客製化和擴展

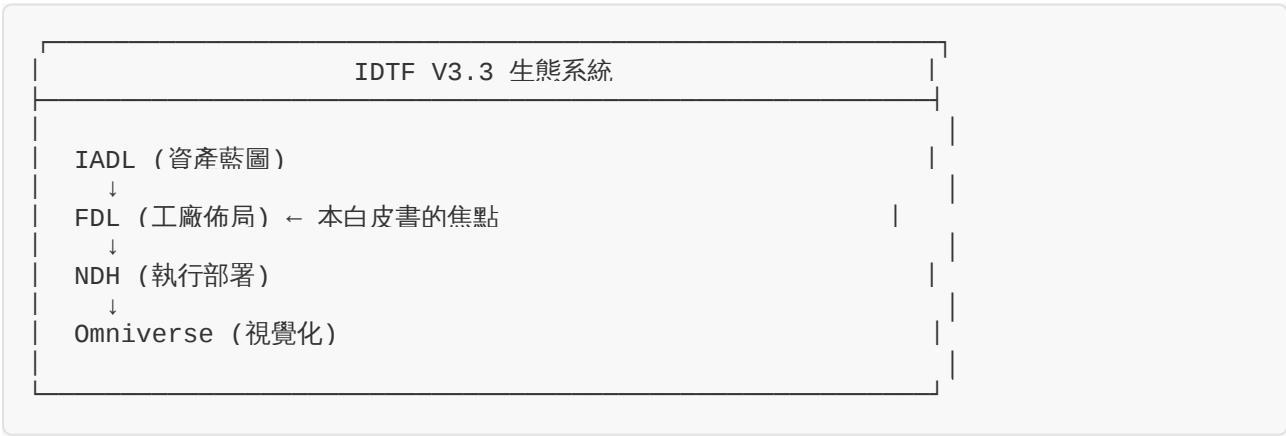
## FDL 概述

### 設計理念

FDL 的設計基於以下核心理念:

- 1. **聲明式語法**: 描述「是什麼」而非「怎麼做」
- 2. **階層結構**: 支援建築物、樓層、區域的階層組織
- 3. **資產引用**: 引用 IADL 定義的資產藍圖
- 4. **關係定義**: 明確定義資產之間的連接和依賴
- 5. **參數化**: 支援參數化配置,提高重用性

### FDL 在 IDTF 生態系統中的角色



## FDL 與 IADL 的關係

維度	IADL	FDL
關注點	資產是什麼 (What)	工廠如何佈局 (How)
粒度	單一資產	整座工廠
內容	3D 模型、數據標籤、行為	數量、位置、連接關係
重用性	跨專案重用	跨工廠複製
生命週期	設計階段	設計到部署

## FDL 語法規範

### 基本結構

FDL 採用 YAML 格式,具有清晰的階層結構:

```
# FDL 基本結構
factory_design:
  metadata:
    name: <工廠名稱>
    version: <版本號>
    author: <作者>
    date: <日期>
    description: <描述>

  buildings:
    - building_id: <建築物 ID>
      name: <建築物名稱>
      location: <地理位置>
      floors: <樓層列表>

  lavout:
    - area: <區域名稱>
      building: <所屬建築物>
      floor: <所屬樓層>
      zone_type: <區域類型>
      instances: <資產實例列表>
      relationships: <關係列表>

  utilities:
    - type: <公用系統類型>
      specifications: <規格>
      distribution: <分配方式>

  parameters:
    <全域參數定義>
```

## 元數據 (Metadata)

定義工廠的基本資訊:

```
metadata:  
  name: "Harvatek LED Packaging Factory"  
  version: "1.0.0"  
  author: "C.C. Lin"  
  date: "2025-10-12"  
  description: "LED封裝廠完整佈局設計"  
  tags:  
    - "LED"  
    - "Semiconductor"  
    - "High-Tech"  
  industry: "Electronics Manufacturing"  
  location:  
    country: "Taiwan"  
    city: "Hsinchu"  
    address: "No. 123, Tech Road"  
    coordinates:  
      latitude: 24.8138  
      longitude: 120.9675
```

## 建築物定義 (Buildings)

定義工廠的建築結構:

```
buildings:
- building_id: "MainBuilding"
  name: "主廠房"
  type: "Production"
  construction_year: 2020
  total_area: 50000 # 平方米
  floors:
    - floor_id: "B1"
      level: -1
      height: 4.5
      area: 10000
      purpose: "Utility & Storage"
    - floor_id: "1F"
      level: 1
      height: 5.0
      area: 10000
      purpose: "Production & Office"
    - floor_id: "2F"
      level: 2
      height: 4.0
      area: 10000
      purpose: "Production - Standard LED"
    - floor_id: "3F"
      level: 3
      height: 4.0
      area: 10000
      purpose: "Production - High Power LED"
    - floor_id: "4F"
      level: 4
      height: 4.0
      area: 5000
      purpose: "R&D & Quality Lab"
    - floor_id: "5F"
      level: 5
      height: 3.5
      area: 5000
      purpose: "Office & Meeting"
```

## 佈局定義 (Layout)

這是 FDL 的核心部分,定義資產實例的佈局:

```
layout:
- area: "Production_Zone_A"
  building: "MainBuilding"
  floor: "2F"
  zone_type: "CleanRoom"
  cleanliness_class: "ISO_Class_7"
  temperature: 23 # 攝氏度
  humidity: 45 # 相對濕度 %

instances:
# 晶片分選機
- type: "DieSorter_v1.0" # 引用 IADL 資產類型
  count: 10
  naming_prefix: "DS_2F_A_"
  naming_pattern: "{prefix}{index:03d}" # DS_2F_A_001
  layout_pattern: "grid"
  grid_config:
    rows: 2
    columns: 5
    spacing_x: 3.0 # 米
    spacing_y: 4.0 # 米
  origin:
    x: 10.0
    y: 20.0
    z: 0.0
  orientation: 0 # 度 (0=北, 90=東, 180=南, 270=西)
  initial_params:
    sorting_speed: 12000 # UPH
    bin_count: 8
    status: "Idle"
  maintenance:
    schedule: "weekly"
    last_maintenance: "2025-10-01"

# 固晶機
- type: "DieBonder_v1.0"
  count: 8
  naming_prefix: "DB_2F_A_"
  layout_pattern: "linear"
  linear_config:
    direction: "horizontal"
    spacing: 3.5
  origin:
    x: 10.0
    y: 30.0
    z: 0.0
  initial_params:
    bonding_speed: 8000 # UPH
    accuracy: 0.001 # mm
    status: "Idle"

# 打線機
- type: "WireBonder_v1.0"
  count: 12
  naming_prefix: "WB_2F_A_"
  layout_pattern: "grid"
  grid_config:
    rows: 3
    columns: 4
    spacing_x: 2.5
    spacing_y: 3.0
  origin:
    x: 10.0
    y: 40.0
    z: 0.0
```

```

initial_params:
  wire_diameter: 0.025 # mm
  bonding_speed: 10000 # UPH
  status: "Idle"

relationships:
# 物料流關係
- type: "material_flow"
  from: "DS_2F_A_001"
  to: "DB_2F_A_001"
  properties:
    transport_method: "AGV"
    cycle_time: 120 # 秒
    batch_size: 100

- type: "material_flow"
  from: "DB_2F_A_001"
  to: "WB_2F_A_001"
  properties:
    transport_method: "Conveyor"
    speed: 0.5 # m/s

# 數據連接關係
- type: "data_connection"
  from: "DS_2F_A_*" # 萬用字元, 匹配所有 Die Sorter
  to: "MES_Server"
  properties:
    protocol: "SECS/GEM"
    update_interval: 1 # 秒

# 電力供應關係
- type: "power_supply"
  from: "Transformer_2F_A"
  to: "DS_2F_A_*"
  properties:
    voltage: 220 # V
    phase: 3
    capacity: 15 # kW per machine

```

## 公用系統 (Utilities)

定義工廠的公用系統配置:

```

utilities:
# 電力系統
- type: "electrical"
specifications:
  total_capacity: 5000 # kW
  voltage_levels:
    - 22000 # V (高壓輸入)
    - 380 # V (三相)
    - 220 # V (單相)
  transformers:
    - id: "Transformer_Main"
      capacity: 2000 # kVA
      location: "B1_Electrical_Room"
    - id: "Transformer_2F"
      capacity: 1500 # kVA
      location: "2F_Electrical_Room"
  distribution:
    - floor: "2F"
      zones: ["Production_Zone_A", "Production_Zone_B"]
      capacity: 1500 # kW
    - floor: "3F"
      zones: ["Production_Zone_C", "Production_Zone_D"]
      capacity: 1500 # kW

# HVAC 系統
- type: "hvac"
specifications:
  total_cooling_capacity: 2000 # RT
  air_handling_units:
    - id: "AHU_2F_A"
      capacity: 50000 # CMH
      location: "2F_Ceiling"
      serving_zones: ["Production_Zone_A"]
    - id: "AHU_2F_B"
      capacity: 50000 # CMH
      location: "2F_Ceiling"
      serving_zones: ["Production_Zone_B"]
  chillers:
    - id: "Chiller_01"
      capacity: 1000 # RT
      location: "B1_Mechanical_Room"
      type: "Water-Cooled"
  distribution:
    - floor: "2F"
      temperature_setpoint: 23 # °C
      humidity_setpoint: 45 # %RH
      air_changes_per_hour: 20

# 純水系統
- type: "di_water"
specifications:
  production_capacity: 100 # m³/day
  resistivity: 18.2 # MΩ·cm
  storage_tanks:
    - id: "DI_Tank_01"
      capacity: 50 # m³
      location: "B1_Utility_Room"
  distribution:
    - floor: "2F"
      flow_rate: 20 # L/min
      pressure: 3.0 # bar
    - floor: "3F"
      flow_rate: 20 # L/min
      pressure: 3.0 # bar

```



```
# 氮氣系統
- type: "nitrogen"
  specifications:
    purity: 99.999 # %
    production_method: "PSA"
    capacity: 500 # Nm³/hr
  distribution:
    - floor: "2F"
      pressure: 6.0 # bar
      flow_rate: 200 # Nm³/hr
    - floor: "3F"
      pressure: 6.0 # bar
      flow_rate: 200 # Nm³/hr

# 壓縮空氣系統
- type: "compressed_air"
  specifications:
    pressure: 7.0 # bar
    capacity: 1000 # Nm³/hr
    dew_point: -40 # °C
    compressors:
      - id: "Compressor_01"
        capacity: 500 # Nm³/hr
        type: "Screw"
        location: "B1_Compressor_Room"
  distribution:
    - floor: "2F"
      pressure: 6.0 # bar
      flow_rate: 400 # Nm³/hr
    - floor: "3F"
      pressure: 6.0 # bar
      flow_rate: 400 # Nm³/hr
```

## 參數定義 (Parameters)

定義全域參數和可配置項:

```
parameters:
# 全域設定
global:
    timezone: "Asia/Taipei"
    working_hours: "24/7"
    shifts: 3
    language: "zh-TW"

# 生產參數
production:
    target_oeo: 85 # %
    cycle_time_target: 120 # 秒
    batch_size_standard: 1000
    quality_target: 99.5 # %

# 環境參數
environment:
    cleanroom:
        temperature_range: [22, 24] # °C
        humidity_range: [40, 50] # %RH
        pressure_differential: 15 # Pa
    office:
        temperature_range: [23, 26] # °C
        humidity_range: [40, 60] # %RH

# 安全參數
safety:
    emergency_exits: 8
    fire_extinguishers: 50
    smoke_detectors: 200
    evacuation_time_target: 300 # 秒

# 能源參數
energy:
    peak_demand_limit: 4500 # kW
    power_factor_target: 0.95
    energy_efficiency_target: 0.85
```

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## 廠房類型與設計模式

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### 1. 半導體廠房 (Semiconductor Fab)

#### 特徵

- **高度潔淨:** ISO Class 1-5 無塵室
- **精密環控:** 溫度  $\pm 0.1^{\circ}\text{C}$ , 濕度  $\pm 1\%$
- **複雜 MEP:** 超純水、特殊氣體、化學品供應
- **高能耗:** 單位面積能耗極高
- **嚴格 ESD:** 靜電防護要求

## FDL 設計模式

```
# 台積電 12 吋晶圓廠範例
factory_design:
  metadata:
    name: "TSMC 12-inch Wafer Fab"
    facility_type: "Semiconductor"
    technology_node: "5nm"

  buildings:
    - building_id: "Fab_Building"
      type: "Cleanroom_Facility"
      total_area: 100000 # m2
      floors:
        - floor_id: "B2"
          purpose: "Utility_Basement"
        - floor_id: "B1"
          purpose: "Sub_Fab" # 設備下層, 管線空間
        - floor_id: "1F"
          purpose: "Fab_Floor" # 主要製程區
        - floor_id: "2F"
          purpose: "Fan_Filter_Unit" # FFU 層

  layout:
    - area: "Lithography_Bay"
      building: "Fab_Building"
      floor: "1F"
      zone_type: "CleanRoom"
      cleanliness_class: "ISO_Class_2"
      temperature: 23.0
      temperature_tolerance: 0.1
      humidity: 45
      humidity_tolerance: 1
      vibration_limit: 0.1 # μm

  instances:
    - type: "EUV_Scanner" # 極紫外光微影機
      count: 20
      naming_prefix: "EUV_"
      cost_per_unit: 150000000 # USD
      footprint:
        length: 15.0 # m
        width: 8.0 # m
        height: 4.0 # m
      power_consumption: 1000 # kW
      initial_params:
        wavelength: 13.5 # nm
        throughput: 170 # WPH (Wafers Per Hour)

  utilities:
    - type: "ultra_pure_water"
      specifications:
        resistivity: 18.2 # MΩ·cm
        toc: 1 # ppb (Total Organic Carbon)
        particles: 0 # >0.05μm per liter
        production_capacity: 1000 # m3/day

    - type: "process_gases"
      gases:
        - name: "Nitrogen"
          purity: 99.9999 # %
          flow_rate: 5000 # Nm3/hr
        - name: "Argon"
          purity: 99.999 # %
          flow_rate: 1000 # Nm3/hr
```

```
- name: "Hydrogen"  
  purity: 99.999    # %  
  flow_rate: 500    # Nm³/hr  
  
- type: "chemical_distribution"  
  chemicals:  
    - name: "Sulfuric_Acid"  
      concentration: 98    # %  
      storage: 10000    # L  
    - name: "Hydrofluoric_Acid"  
      concentration: 49    # %  
      storage: 5000    # L
```

## 2. LED 封裝廠 (LED Packaging)

### 特徵

- 中度潔淨: ISO Class 6-7 無塵室
- 高產能: 高速自動化生產線
- 多樣化: 多種產品混線生產
- 精密組裝:  $\mu\text{m}$  級精度要求
- 品質檢測: 光學、電性全檢

## FDL 設計模式

```
# 宏齊科技 LED 封裝廠範例
factory_design:
  metadata:
    name: "Harvatek LED Packaging Factory"
    facility_type: "LED_Packaging"
    products:
      - "Standard_LED"
      - "High_Power_LED"
      - "Mini_LED"

  layout:
    - area: "Standard_LED_Line_1"
      building: "MainBuilding"
      floor: "2F"
      zone_type: "CleanRoom"
      cleanliness_class: "ISO_Class_7"

  instances:
    # 完整生產線配置
    - type: "DieSorter_v1.0"
      count: 10
      naming_prefix: "DS_L1_"
      throughput: 12000 # UPH

    - type: "DieBonder_v1.0"
      count: 8
      naming_prefix: "DB_L1_"
      throughput: 8000 # UPH

    - type: "WireBonder_v1.0"
      count: 12
      naming_prefix: "WB_L1_"
      throughput: 10000 # UPH

    - type: "Dispenser_v1.0"
      count: 6
      naming_prefix: "DP_L1_"
      throughput: 6000 # UPH

    - type: "Curing_Oven"
      count: 4
      naming_prefix: "CO_L1_"
      temperature: 150 # °C
      curing_time: 120 # 分鐘

    - type: "Tester_v1.0"
      count: 15
      naming_prefix: "TS_L1_"
      throughput: 15000 # UPH
      test_items:
        - "Forward_Voltage"
        - "Luminous_Intensity"
        - "Wavelength"
        - "Reverse_Current"

    - type: "TapingMachine_v1.0"
      count: 8
      naming_prefix: "TM_L1_"
      throughput: 12000 # UPH

  relationships:
    # 生產流程關係
    - type: "production_flow"
```

```
sequence:
- "DS_L1_*" # Die Sorting
- "DB_L1_*" # Die Bonding
- "WB_L1_*" # Wire Bonding
- "DP_L1_*" # Dispensing
- "CO_L1_*" # Curing
- "TS_L1_*" # Testing
- "TM_L1_*" # Taping
properties:
cycle_time: 0.3 # 秒/件
batch_size: 1000
wip_target: 5000 # Work In Process
```

### 3. LNG 發電廠 (LNG Power Plant)

#### 特徵

- **大型設備:** 燃氣渦輪機、發電機組
- **安全關鍵:** LNG 儲存和氣化系統
- **高效能:** 聯合循環發電
- **環保要求:** 排放控制系統
- **24/7 運行:** 高可靠性要求

## FDL 設計模式

```
# LNG 聯合循環發電廠範例
factory_design:
  metadata:
    name: "LNG Combined Cycle Power Plant"
    facility_type: "Power_Generation"
    capacity: 1000 # MW
    fuel_type: "LNG"

  buildings:
    - building_id: "Power_Block"
      type: "Industrial"
      footprint: 50000 # m²

  layout:
    - area: "Gas_Turbine_Area"
      building: "Power_Block"
      floor: "Ground"

  instances:
    # 燃氣渦輪發電機組
    - type: "Gas_Turbine_Generator"
      count: 2
      naming_prefix: "GTG_"
      manufacturer: "GE"
      model: "9HA.02"
      specifications:
        power_output: 470 # MW
        efficiency: 41 # %
        fuel_consumption: 9800 # kg/hr at full load
        nox_emission: 15 # ppm
        dimensions:
          length: 25 # m
          width: 12 # m
          height: 8 # m
      initial_params:
        load: 0 # MW
        status: "Standby"

    # 蒸汽渦輪發電機組
    - type: "Steam_Turbine_Generator"
      count: 1
      naming_prefix: "STG_"
      specifications:
        power_output: 250 # MW
        steam_pressure: 120 # bar
        steam_temperature: 565 # °C

    # 餘熱回收蒸汽產生器
    - type: "HRSG" # Heat Recovery Steam Generator
      count: 2
      naming_prefix: "HRSG_"
      specifications:
        steam_production: 180 # ton/hr
        efficiency: 95 # %

    - area: "LNG_Storage_Area"
      building: "Storage_Facility"
      floor: "Ground"
      safety_zone: 200 # m radius

  instances:
    # LNG 儲槽
    - type: "LNG_Storage_Tank"
```

```

count: 2
naming_prefix: "LNG_Tank_"
specifications:
  capacity: 180000 # m³
  design_temperature: -162 # °C
  design_pressure: 0.25 # bar
  containment_type: "Full_Containment"
  insulation: "Perlite"
safety_systems:
  - "Fire_Detection"
  - "Gas_Detection"
  - "Emergency_Shutdown"
  - "Deluge_System"

# LNG 氣化器
- type: "LNG_Vaporizer"
  count: 4
  naming_prefix: "VAP_"
  specifications:
    capacity: 50 # ton/hr
    type: "Open_Rack_Vaporizer"
    heating_medium: "Seawater"

utilities:
- type: "cooling_water"
  specifications:
    source: "Seawater"
    flow_rate: 50000 # m³/hr
    temperature_rise: 10 # °C
  distribution:
    - equipment: "GTG_*"
      flow_rate: 15000 # m³/hr per unit
    - equipment: "STG_*"
      flow_rate: 20000 # m³/hr

- type: "electrical_grid"
  specifications:
    voltage: 345000 # V (345 kV)
    frequency: 60 # Hz
    connection_type: "Double_Circuit"

```

## 4. NVIDIA GPU 數據中心 (GPU Data Center)

### 特徵

- **高密度:** 高功率密度機櫃
- **液冷系統:** 直接液冷或浸沒式冷卻
- **高速網路:** InfiniBand/Ethernet 高速互連
- **AI 運算:** GPU 叢集配置
- **能源效率:** PUE < 1.2 目標



## FDL 設計模式

```
# NVIDIA DGX SuperPOD 數據中心範例
factory_design:
  metadata:
    name: "NVIDIA AI Data Center"
    facility_type: "GPU_Data_Center"
    total_gpu_count: 1024
    ai_performance: 10 # ExaFLOPS (FP8)

  buildings:
    - building_id: "Data_Center"
      type: "Tier_IV_Data_Center"
      total_area: 5000 # m²
      redundancy: "2N"

  layout:
    - area: "GPU_Pod_A"
      building: "Data_Center"
      floor: "1F"
      zone_type: "White_Space"
      raised_floor_height: 1.2 # m

  instances:
    # DGX H100 系統
    - type: "DGX_H100"
      count: 32 # 每個 Pod
      naming_prefix: "DGX_A_"
      specifications:
        gpus_per_node: 8 # H100 80GB
        gpu_memory: 640 # GB total
        system_memory: 2048 # GB
        storage: 30 # TB NVMe
        network:
          - "8x 400Gb/s InfiniBand"
          - "2x 100Gb/s Ethernet"
        power_consumption: 10.2 # kW per node
        dimensions:
          height: 10 # U (rack units)
          width: 19 # inch
          depth: 35 # inch
        layout_pattern: "rack"
        rack_config:
          racks: 8
          nodes_per_rack: 4
          rack_spacing: 1.2 # m

    # 網路交換機
    - type: "InfiniBand_Switch"
      count: 4
      naming_prefix: "IB_Switch_A_"
      specifications:
        ports: 64
        speed: 400 # Gb/s per port
        latency: 130 # ns
        power_consumption: 2.5 # kW

    # 儲存系統
    - type: "NVMe_Storage_Array"
      count: 2
      naming_prefix: "Storage_A_"
      specifications:
        capacity: 1000 # TB
        throughput: 100 # GB/s
        iops: 10000000 # 10M IOPS
```

```

relationships:
  # 網路拓撲
  - type: "network_connection"
    topology: "Fat_Tree"
    from: "DGX_A_*"
    to: "IB_Switch_A_*"
    properties:
      bandwidth: 400 # Gb/s
      redundancy: "Active-Active"

  # 儲存連接
  - type: "storage_connection"
    from: "DGX_A_*"
    to: "Storage_A_*"
    properties:
      protocol: "NVMe-oF"
      bandwidth: 100 # GB/s

utilities:
  - type: "power_distribution"
    specifications:
      total_capacity: 2000 # kW per pod
      voltage: 480 # V
      ups_capacity: 2000 # kW
      ups_runtime: 15 # minutes
      backup_generator: true
      generator_capacity: 3000 # kW

  - type: "cooling_system"
    specifications:
      cooling_method: "Direct_Liquid_Cooling"
      coolant: "Water"
      supply_temperature: 18 # °C
      return_temperature: 28 # °C
      flow_rate: 500 # L/min per pod
      redundancy: "N+1"
      pue_target: 1.15
    distribution:
      - equipment: "DGX_A_*"
        cooling_capacity: 10 # kW per node
        coolant_flow: 15 # L/min per node

```

## 5. Smart City 基礎設施 (Smart City)

### 特徵

- **分散式:** 多個地點分散部署
- **IoT 整合:** 大量感測器和裝置
- **公共服務:** 交通、照明、環境監測
- **數據驅動:** 即時數據分析和決策
- **可擴展:** 模組化擴展

## FDL 設計模式

```
# Smart City 基礎設施範例
factory_design:
  metadata:
    name: "Smart City Infrastructure"
    facility_type: "Smart_City"
    coverage_area: 100 # km2
    population: 500000

  buildings:
    - building_id: "City_Operations_Center"
      type: "Control_Center"
      location: "City_Center"

  layout:
    # 智慧交通系統
    - area: "Traffic_Management_Zone_1"
      zone_type: "Public_Infrastructure"
      coverage:
        district: "Downtown"
        area: 10 # km2

  instances:
    # 智慧紅綠燈
    - type: "Smart_Traffic_Light"
      count: 150
      naming_prefix: "TL_DT_"
      specifications:
        led_power: 50 # W
        camera_resolution: "4K"
        ai_processing: true
      features:
        - "Vehicle_Detection"
        - "Pedestrian_Detection"
        - "Adaptive_Timing"
        - "Emergency_Vehicle_Priority"
      connectivity:
        protocol: "5G"
        update_interval: 1 # 秒

    # 交通監控攝影機
    - type: "Traffic_Camera"
      count: 300
      naming_prefix: "TC_DT_"
      specifications:
        resolution: "4K"
        frame_rate: 30 # fps
        night_vision: true
        ptz: true # Pan-Tilt-Zoom
      ai_capabilities:
        - "License Plate Recognition"
        - "Vehicle Classification"
        - "Traffic Flow Analysis"
        - "Incident_Detection"

    # 環境感測器
    - type: "Environmental_Sensor"
      count: 100
      naming_prefix: "ES_DT_"
      measurements:
        - name: "PM2.5"
          unit: "µg/m3"
          range: [0, 500]
        - name: "Temperature"
```

```

        unit: "°C"
        range: [-20, 50]
    - name: "Humidity"
      unit: "%"
      range: [0, 100]
    - name: "Noise_Level"
      unit: "dB"
      range: [30, 120]

# 智慧照明系統
- area: "Street_Lighting_Zone_1"
  zone_type: "Public_Infrastructure"
  coverage:
    district: "Downtown"
    street_length: 50 # km

instances:
  # 智慧路燈
  - type: "Smart_Street_Light"
    count: 2000
    naming_prefix: "SL_DT_"
    specifications:
      led_power: 150 # W
      luminous_flux: 15000 # lm
      color_temperature: 4000 # K
      dimming_range: [10, 100] # %
    features:
      - "Motion_Detection"
      - "Adaptive_Dimming"
      - "Energy_Monitoring"
      - "Fault_Detection"
    connectivity:
      protocol: "LoRaWAN"
      update_interval: 60 # 秒
    energy_saving:
      default_level: 70 # %
      motion_level: 100 # %
      motion_timeout: 300 # 秒

# 智慧停車系統
- area: "Parking_Management_Zone_1"
  zone_type: "Public_Infrastructure"
  coverage:
    district: "Downtown"
    parking_spaces: 5000

instances:
  # 停車感測器
  - type: "Parking_Sensor"
    count: 5000
    naming_prefix: "PS_DT_"
    specifications:
      detection_method: "Ultrasonic"
      accuracy: 99 # %
      battery_life: 5 # years
    connectivity:
      protocol: "LoRaWAN"
      update_interval: 30 # 秒

# 停車場管理系統
- type: "Parking_Management_System"
  count: 20
  naming_prefix: "PMS_DT_"
  features:
    - "License_Plate_Recognition"
    - "Payment_Processing"

```

```
- "Guidance_Display"
- "Mobile_App_Integration"

utilities:
# 通訊網路
- type: "communication_network"
  specifications:
    technologies:
      - "5G"
      - "LoRaWAN"
      - "NB-IoT"
    coverage: 100 # %
    base_stations: 50

# 數據中心
- type: "edge_data_center"
  specifications:
    locations: 5
    total_capacity: 500 # kW
    storage: 1000 # TB
    ai_processing: true

# 能源管理
- type: "energy_management"
  specifications:
    renewable_energy: 30 # %
    energy_storage: 10 # MWh
    smart_grid: true
```

## 實際應用案例

### 案例 1: 宏齊科技 LED 封裝廠

#### 專案背景

- **公司:** 宏齊科技 (Harvatek Corporation)
- **產業:** LED 封裝
- **規模:** 340 台生產設備, 1,600+ 感測器
- **挑戰:** 多產品混線生產, 即時監控需求

#### FDL 應用

完整的 FDL 配置文件定義了:

1. **6 層建築結構:** B1 至 5F
2. **20 個生產區域:** 2F 和 3F 的詳細佈局
3. **340 台設備實例:** 8 種設備類型

#### 4. 完整的公用系統: HVAC, 純水, 氮氣, 壓縮空氣, 電力

### 實施效益

- **部署時間:** 從 6 個月縮短到 2 個月
- **設計錯誤:** 減少 80%
- **變更管理:** 版本控制, 快速迭代
- **ROI:** 6.2 個月回收期

### FDL 片段

```
# Harvatek 2F 標準 LED 生產線
layout:
- area: "Standard_LED_Line_1"
  building: "MainBuilding"
  floor: "2F"
  zone_type: "CleanRoom"
  cleanliness_class: "ISO_Class_7"
  production_capacity: 1000000 # units/day

  instances:
  - type: "DieSorter_v1.0"
    count: 10
    throughput_total: 120000 # UPH
  - type: "DieBonder_v1.0"
    count: 8
    throughput_total: 64000 # UPH
  # ... 其他設備
```

## 案例 2: 台積電 5nm 晶圓廠 (概念設計)

### 專案背景

- **技術節點:** 5nm
- **產能:** 100,000 片/月 (12 吋晶圓)
- **投資:** USD 20B
- **挑戰:** 極高潔淨度, EUV 微影, 複雜 MEP

## FDL 應用

```
# TSMC 5nm Fab 微影區
layout:
- area: "EUV_Lithography_Bay"
  building: "Fab_12"
  floor: "1F"
  zone_type: "CleanRoom"
  cleanliness_class: "ISO_Class_1"
  vibration_criteria: "VC-E" # 最嚴格的振動標準

instances:
- type: "ASML_EUV_NXE3400C"
  count: 20
  cost_total: 30000000000 # USD 3B
  specifications:
    wavelength: 13.5 # nm
    throughput: 170 # WPH
    overlay: 1.5 # nm
    power: 1000 # kW per machine

  supporting_equipment:
    - type: "Reticle_Storage_Pod"
      count: 20
    - type: "Wafer_Sorter"
      count: 10
    - type: "Metrology_Station"
      count: 5
```

## 案例 3: LNG 發電廠

### 專案背景

- 容量: 1,000 MW
- 效率: 60% (聯合循環)
- 投資: USD 1B
- 挑戰: LNG 安全, 高效率, 環保

## FDL 應用

```
# LNG 發電廠主要設備配置
layout:
- area: "Power_Generation_Block"
  instances:
    - type: "GE_9HA_Gas_Turbine"
      count: 2
      power_output: 940 # MW total
      efficiency: 41 # %

    - type: "Steam_Turbine"
      count: 1
      power_output: 250 # MW

    - type: "HRSG"
      count: 2
      steam_production: 360 # ton/hr total

  relationships:
    - type: "thermal_flow"
      from: "GE_9HA_Gas_Turbine"
      to: "HRSG"
      properties:
        exhaust_temperature: 650 # °C
        exhaust_flow: 700 # kg/s

    - type: "steam_flow"
      from: "HRSG"
      to: "Steam_Turbine"
      properties:
        pressure: 120 # bar
        temperature: 565 # °C
```

---



# 最佳實踐指南

## 1. 命名規範

### 資產命名模式

```
# 推薦的命名模式
naming_pattern: "{type}_{location}_{sequence}"

# 範例
examples:
  - "DS_2F_A_001" # Die Sorter, 2F, Zone A, #001
  - "WB_3F_B_012" # Wire Bonder, 3F, Zone B, #012
  - "AHU_2F_001"  # AHU, 2F, #001

# 命名規則
rules:
  type:
    format: "2-4 字母縮寫"
    case: "大寫"
  location:
    format: "樓層 區域"
    examples: ["2F_A", "3F_B", "B1"]
  sequence:
    format: "3 位數字"
    padding: "前導零"
    range: "001-999"
```

### 區域命名模式

```
# 區域命名規範
area_naming:
  pattern: "{purpose}_{zone_type}_{identifier}"

  examples:
    - "Production_Zone_A"
    - "Cleanroom Area 1"
    - "Utility_Room_B1"

  guidelines:
    - "使用描述性名稱"
    - "避免特殊字元"
    - "保持一致性"
    - "考慮國際化"
```

## 2. 模組化設計

### 可重用模組

```
# 定義可重用的生產線模組
modules:
- module_id: "Standard_LED_Production_Line"
  version: "1.0"
  description: "標準 LED 生產線配置"

  equipment_list:
  - type: "DieSorter_v1.0"
    count: 10
  - type: "DieBonder_v1.0"
    count: 8
  - type: "WireBonder_v1.0"
    count: 12
  - type: "Dispenser_v1.0"
    count: 6
  - type: "Tester_v1.0"
    count: 15
  - type: "TapingMachine_v1.0"
    count: 8

  footprint:
    length: 50 # m
    width: 30 # m

  utilities_required:
    power: 500 # kW
    compressed_air: 100 # Nm³/hr
    nitrogen: 50 # Nm³/hr
    di_water: 5 # m³/day

  performance:
    throughput: 50000 # units/hr
    oee_target: 85 # %

# 在 FDL 中引用模組
layout:
- area: "Production_Floor_2F"
  modules:
  - module_id: "Standard_LED_Production_Line"
    instance_name: "Line_1"
    location:
      x: 10
      y: 20
      z: 0

  - module_id: "Standard_LED_Production_Line"
    instance_name: "Line_2"
    location:
      x: 10
      y: 60
      z: 0
```

### 3. 參數化配置

#### 使用變數和參數

```
# 定義全域變數
variables:
  cleanroom_temperature: &cleanroom_temp 23
  cleanroom_humidity: &cleanroom_humid 45
  production_shift_hours: &shift_hours 8

# 在配置中引用
layout:
  - area: "Zone_A"
    temperature: *cleanroom_temp
    humidity: *cleanroom_humid
    working_hours: *shift_hours

  - area: "Zone_B"
    temperature: *cleanroom_temp
    humidity: *cleanroom_humid
    working_hours: *shift_hours

# 使用參數化模板
templates:
  production_zone:
    parameters:
      - name: "zone_name"
        type: "string"
      - name: "equipment_count"
        type: "integer"
      - name: "temperature"
        type: "float"
        default: 23

    layout:
      area: "{{zone_name}}"
      temperature: "{{temperature}}"
      instances:
        - type: "Equipment_Type"
          count: "{{equipment_count}}"
```

## 4. 版本控制

### 版本管理策略

```
# FDL 版本資訊
metadata:
  version: "2.1.3" # 主版本.次版本.修訂版本
  version_history:
    - version: "2.1.3"
      date: "2025-10-12"
      author: "C.C. Lin"
      changes:
        - "新增 Mini LED 生產線"
        - "更新 AHU 配置"
        - "修正設備命名"

    - version: "2.1.2"
      date: "2025-09-15"
      author: "C.C. Lin"
      changes:
        - "調整 2F 設備佈局"
        - "優化氮氣管路"

    - version: "2.1.0"
      date: "2025-08-01"
      author: "C.C. Lin"
      changes:
        - "新增 3F 高功率 LED 產線"
        - "擴充電力系統"

# 版本控制最佳實踐
version_control:
  guidelines:
    - "使用語義化版本 (Semantic Versioning)"
    - "主版本: 不相容的變更"
    - "次版本: 向後相容的新功能"
    - "修訂版本: 向後相容的錯誤修正"
    - "記錄所有變更"
    - "使用 Git 進行版本控制"
```

## 5. 驗證與測試

### FDL 驗證規則

```
# FDL 驗證配置
validation:
  # 語法驗證
  syntax:
    - "YAML 格式正確"
    - "必要欄位存在"
    - "資料類型正確"

  # 語義驗證
  semantic:
    - "資產類型存在於 IADL 庫"
    - "建築物和樓層引用正確"
    - "關係引用的資產存在"
    - "座標在合理範圍內"

  # 物理驗證
  physical:
    - "設備不重疊"
    - "設備在樓層範圍內"
    - "通道寬度足夠"
    - "承重符合要求"

  # 公用系統驗證
  utilities:
    - "電力容量足夠"
    - "冷卻容量足夠"
    - "管線路徑可行"
    - "壓力和流量符合要求"

# 測試案例
test_cases:
  - name: "基本語法測試"
    input: "test_basic.fdl"
    expected: "pass"

  - name: "大規模工廠測試"
    input: "test_large_factory.fdl"
    expected: "pass"
    performance:
      max_parse_time: 10 # 秒
      max_memory: 1000 # MB

  - name: "錯誤處理測試"
    input: "test_invalid.fdl"
    expected: "fail"
    error_type: "ValidationError"
```

## 6. 文檔化

### FDL 文檔結構

```
# 內嵌文檔
documentation:
  overview: |
    這是 Harvatek LED 封裝廠的完整 FDL 配置。
    包含 2F 和 3F 的所有生產設備和公用系統。

  sections:
    - name: "2F 標準 LED 產線"
      description: |
        2F 配置了 3 條標準 LED 生產線，
        年產能 10 億顆。
      equipment_count: 120
      daily_capacity: 3000000

    - name: "3F 高功率 LED 產線"
      description: |
        3F 配置了 2 條高功率 LED 生產線，
        年產能 5 億顆。
      equipment_count: 80
      daily_capacity: 1500000

  diagrams:
    - name: "2F Layout"
      file: "diagrams/2f_layout.png"
    - name: "Utility Distribution"
      file: "diagrams/utility_distribution.png"

  references:
    - "IADL Specification v3.1"
    - "NDH API Documentation v2.0"
    - "Factory Designer User Guide"
```

## 擴展與客製化

### 自定義資產類型

```
# 定義客製化資產類型
custom asset types:
  - type_id: "Custom_LED_Sorter_v2.0"
    base_type: "DieSorter_v1.0" # 繼承基礎類型
    custom_properties:
      ai_vision: true
      multi_bin: 16
      throughput: 15000 # UPH
    custom_behaviors:
      - "auto_calibration"
      - "predictive_maintenance"
```

## 產業特定擴展

```
# 半導體產業擴展
semiconductor_extensions:
  wafer_size: 12 # inch
  technology_node: 5 # nm
  process_steps: 1000

  equipment_categories:
    - "Lithography"
    - "Etching"
    - "Deposition"
    - "CMP"
    - "Metrology"

# LED 產業擴展
led_extensions:
  product_types:
    - "Standard_LED"
    - "High_Power_LED"
    - "Mini_LED"
    - "Micro_LED"

  wavelength_range: [380, 780] # nm
  luminous_intensity_range: [1, 10000] # mcd
```

## 總結與展望

### 總結

FDL (Factory Design Language) 作為 IDTF V3.3 生態系統的核心組件,提供了一個標準化、可重用且易於維護的工廠設計描述方式。本白皮書基於多個實際專案的經驗,歸納整理出:

1. **完整的語法規範:** 涵蓋元數據、建築、佈局、公用系統和參數
2. **多種廠房類型:** 半導體、LED、發電廠、數據中心、智慧城市
3. **實際應用案例:** 宏齊科技、台積電、LNG 發電廠等
4. **最佳實踐指南:** 命名規範、模組化設計、版本控制、驗證測試

### 核心價值

- **標準化:** 統一的描述語言,跨產業適用
- **可重用性:** 模組化設計,快速複製
- **可維護性:** 版本控制,變更追蹤
- **自動化:** 與 Factory Designer 和 NDH 無縫整合

- **可擴展性:** 支援客製化和產業特定擴展

## 未來展望

1. **AI 輔助設計:** 使用 AI 自動生成和優化 FDL
2. **數位分身整合:** 與 Omniverse 深度整合,即時視覺化
3. **多廠管理:** 支援集團級多工廠統一管理
4. **雲端協作:** 雲端 FDL 編輯和版本控制
5. **標準化推廣:** 推動 FDL 成為產業標準

## 下一步行動

1. **實施 FDL:** 在新專案中採用 FDL
2. **建立模板庫:** 累積可重用的 FDL 模板
3. **工具開發:** 開發 FDL 編輯器和驗證工具
4. **社群建設:** 建立 FDL 使用者社群
5. **標準制定:** 參與產業標準制定

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## 參考資料

1. IDTF V3.3 技術白皮書 - <https://github.com/chchlin1018/idthf-v3.3>
2. Factory Designer 設計文件 - IDTF-V3.3-04
3. IADL V3.1 規範 - IDTF-V3.3-02
4. NDH 架構設計 - IDTF-V3.3-06
5. Harvatek Digital Twins 專案 - <https://github.com/chchlin1018/harvatek-digital-twin>
6. YAML 1.2 規範 - <https://yaml.org/spec/1.2/spec.html>
7. Semantic Versioning 2.0.0 - <https://semver.org/>



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**FDL - 讓工廠設計標準化、自動化、智能化!**  