Development of an AGV Algorithm for Parking Lot

Implementation of an AGV Control Algorithm and Verification via Simulation

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Definition of AGV

- **What is the AGV?**

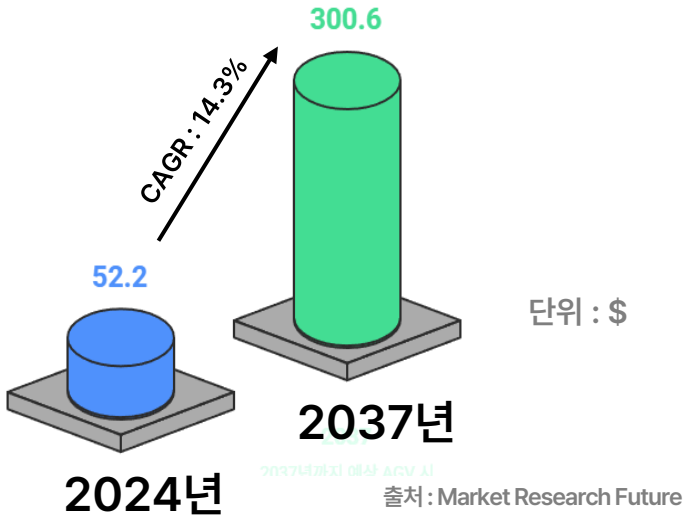
  ➢ Automated Guided Vehicle (무인 운반차)

  – 정해진 경로를 따라 자체 동력으로만 자재를 운반하는 목적을 가진 자동화 차량

출처 : Stiles Machinery

AGV Market Size

- **Present Market size and its projected future growth.**
  - ➢ 2024년 AGV시장규모, 약52억 2천만 달러로 평가
  - ➢ 2037년 약 300억 6천만 달러 예상
  - ➢ 연평균 성장률 약 14.3% 예측



Utilization of AGV Control System

- **Parking Robot**

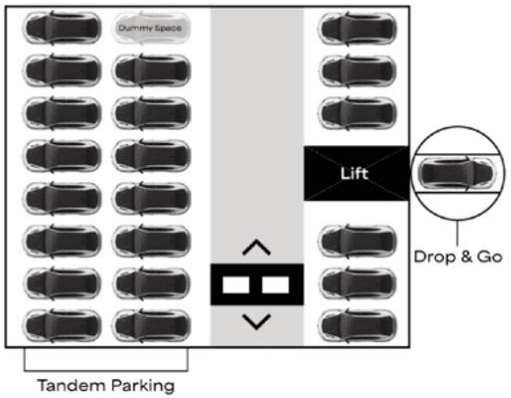
➢ 현대위아 vs HL만도, 주차로봇 대결 막 올랐다.

현대위아와 HL만도의 주차로봇 (사진=각사)

출처 - ZD코리아

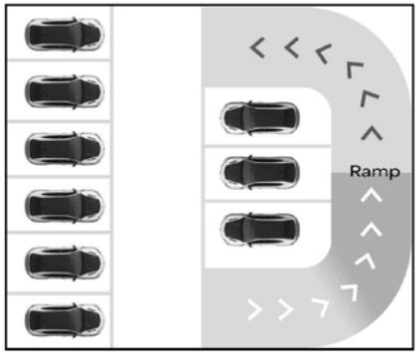
Necessity of AGV In Parking lot

- **주차장 공간 효율성 증가**
  - ➢ 차량 사이 간격 최소화로 주차 밀도 향상
  - ➢ 기존의 주차 도로를 주차공간으로 활용 가능



MPSystem

25 Spaces ↑



Conventional Parking

8 Spaces

출처 : 삼표

Necessity of AGV In Parking lot

- **사고 예방**
  - ➢ 인적 오류로 인한 충돌 사고 제거
  - ➢ 알고리즘 기반 안전 주행으로 차량 손상 방지
  - ➢ 2023년 주차장 사고 건수 1542건, 하루 평균 4.2건 꼴로 발생 (출처 : 경찰청)

2023년 주차장 사고 건수

1542건

하루평균 4.2건의 주차장 사고 발생

Necessity of AGV In Parking lot

- **환경 오염 감소**
  - ➢ 주차장 무인화에 따른 차량 주행 배기가스 배출 '0mg'
  - ➢ 주차장 주변 환경의 공기질 개선

<지하주차장의 평균 일산화탄소 농도>

$$K = \frac{0.06 \cdot X \cdot M \cdot L}{V \cdot Q}$$

단, K : 지하주차장의 평균 일산화탄소 농도 [m^3/m^3]

X : 자동차 출입대수 [대/h]

M : 주행시 일산화탄소 평균배출량 [$m^3/min \cdot 대$]

L : 평균주행거리 [m/대]

V : 평균주행속도 [$km/h \cdot 대$]

Q : 환기량 [m^3/h]

여기서, 0.06 은 환산계수이다.

Multi-Agent Path Finding [MAPF]

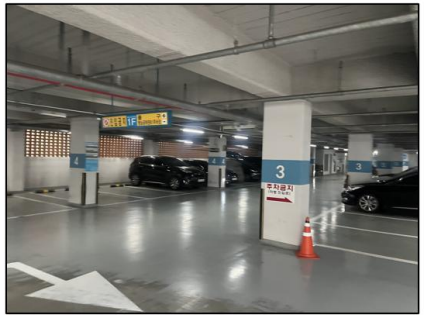
- **Definition of MAPF**
  - ➢ 여러 에이전트가 공유된 환경에서 충돌없이 이동하는 경로 집합을 찾는 문제
- **Key Components of MAPF**
  - ➢ Agents
  - ➢ Environment
  - ➢ Start / Goal
  - ➢ Time
- **Collision Types**
  - ➢ 정점 충돌 [Vertex Confilct]
    - 동일 시간에 동일 정점[위치] 차지

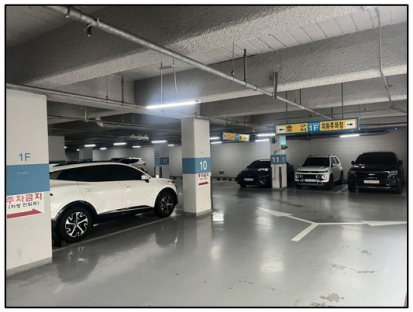
  - ➢ 간선 충돌 [Edge Conflict]
    - 동일 시간 사이에 동일 간선[경로]를 교차하여 통과

Environment : 형남공학관 주차장

- **형남공학관 주차장**

  ➢ 형남공학관 주차장 지하2층 전경

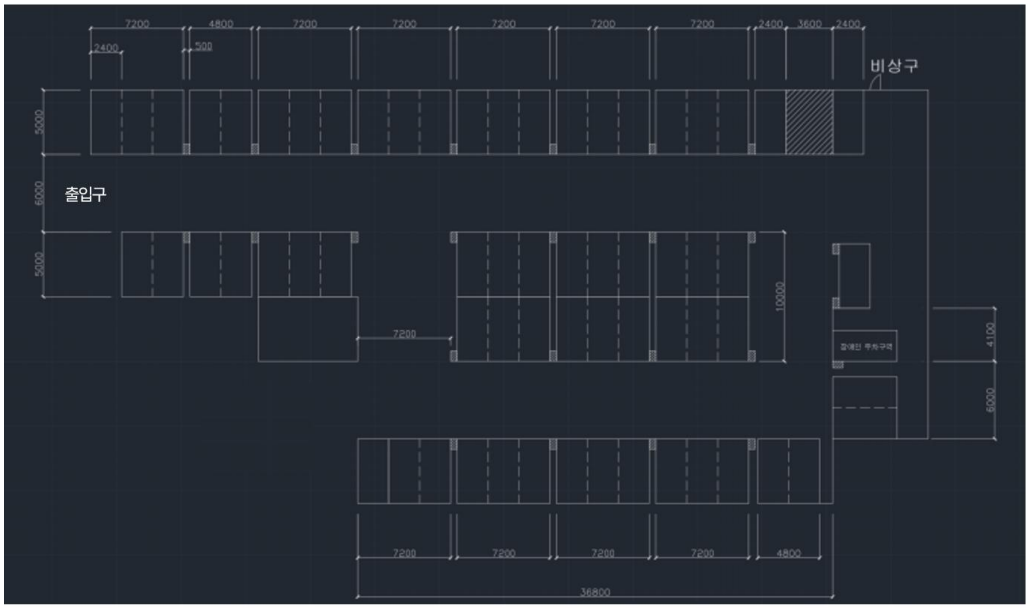




Environment : 형남공학관 주차장

- **형남공학관 주차장**

  ➢ 형남공학관 주차장 지하2층 도면



[0] Priority System : Score / Stuck Boost

- **Priority Score**
  - ➢ $\text{Priority}(A) = (Base \times 100) + StuckBoost - A.id$
  - ➢ 출차 [RETURNING_WITH_CAR] : 3
  - ➢ 충천 필요 [GOING_TO_CHARGE] : 2
  - ➢ 주차 / 차량 수거 [GOING_TO PARK / GOING TO COLLECT] : 1
  - ➢ 대기 / 충전 중 / 기지로 복귀 [IDLE / CHARGING / RETURNING_HOME] : 0

- **Stuck Boost Mechanism**
  - ➢ $StuckBoost = \begin{cases} 1000 & if\ A.stuck \geq DEADLOCK\_THRESHOLD \\ A.Stuck \times 10 & otherwise \end{cases}$

- **Tie-Breaking Mechanism**
  - ➢ AGENT ID = $A.id$ [ex. A > B > C]

[0] Priority System : pseudo-code

- **Pseudo-code[의사코드]**

➢

```
// basic priority based on agent.state
p = base(state)

//Stuck Boost
if (stuck_steps >= deadlock_threshold)
   p += stuck_boost_hard
else if (stuck_steps > 0)
   p += stuck_steps * stuck_boost_mult

// Tie-breaking mechanism
tie_break(A.id)

// plan and application
plan_step() → reservation → move → stuck update→ (metrics_notify_all)
```

[1] A *algorithm : Definition

- **What is the A*algorithm?**

➢ A* algorithm

- 그래프 기반 최단 경로 탐색에서 가장 널리 쓰이는 알고리즘
- Shortest Path = Path with Min[$f(n)$]

➢ $g(n)$

- 출발 노드부터 현재 노드까지 실제 소요 비용

➢ $h(n)$ [Manhattan Distance]

- $h(n) = |x_n - x_{goal}| + |y_n - y_{goal}|$
- 현재 노드부터 목표 노드까지 예상 비용
- 휴리스틱 함수 활용 추정치

➢ $f(n)$

- 총 예상 비용 [Total Estimated Cost]
- $f(n) = g(n) + h(n)$

[1] A *algorithm : pseudo-code / Diagram

- pseudo-code

```
function plan_astar(agents, map):
  next_pos = get_current_positions(all_agents)
  sorted_agents = sort_by_priority(agents)

  for agent in sorted_agents:
    if agent.is_waiting(rotation or action) then
      continue

    temp_obstacles =
    get_higher_priority_moves(agent, next_pos) +
    get_lower_priority_positions(agent, agents)
    temp_pathfinder = create_pathfinder(agent.pos,
agent.goal)
    path = compute_path(
          temp_pathfinder, map, temp_obstacles
      )
    desired_move = get_next_step(path)
    destroy_pathfinder(temp_pathfinder)
    next_pos[agent.id] = apply_rotation(agent, desired_move)

resolve_final_conflicts(next_pos, sorted_agents)
return next_pos
```

[2] D* lite algorithm : Definition

- **What is the D*lite algorithm?**

➢ D* lite algorithm

- 동적 환경에서 주로 쓰이는 알고리즘
- 목표에서 역방향으로 모든 지점까지의 최단 경로 비용 계산
- Shortest Path = All Consistent path

➢ $g(s)$

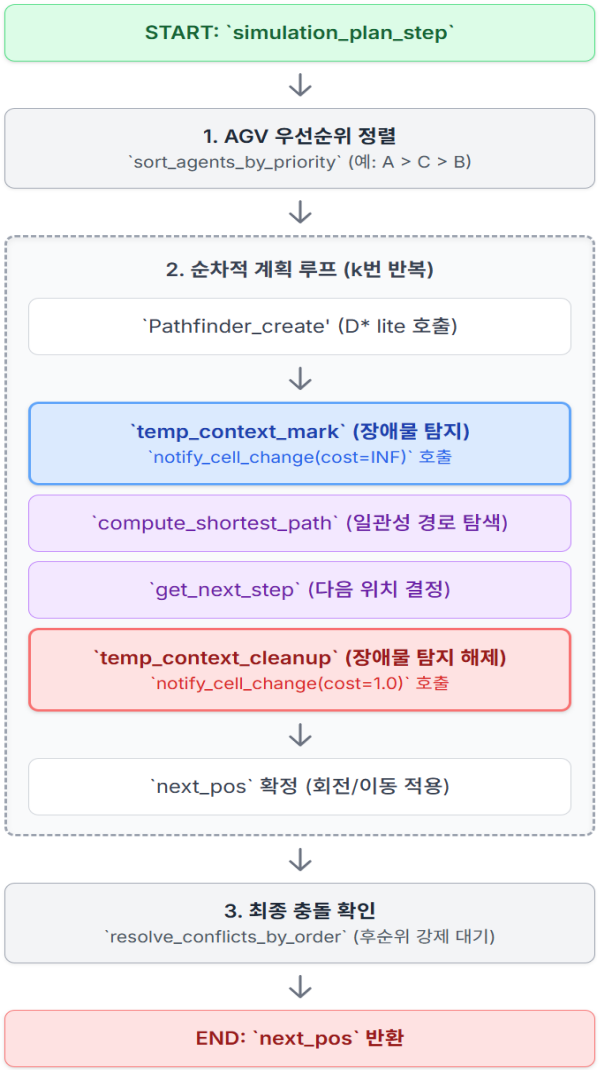
- 목표 노드부터 현재 노드까지 '**알려진**' 추정 소요 비용

➢ $rhs(s)$

- $g(s)$ 의 1- step 예측 값.
- $rhs(s) = \begin{cases} 0 & if\ s = s_{goal} \\ min_{s' \in Succ(s)}(c(s,s') + g(s')) & otherwise \end{cases}$

➢ $C(s, s')$

- S′ -> S 비용



[2] D* lite algorithm : Definition

- **What is the D*lite algorithm?**

➢ *Consistency*

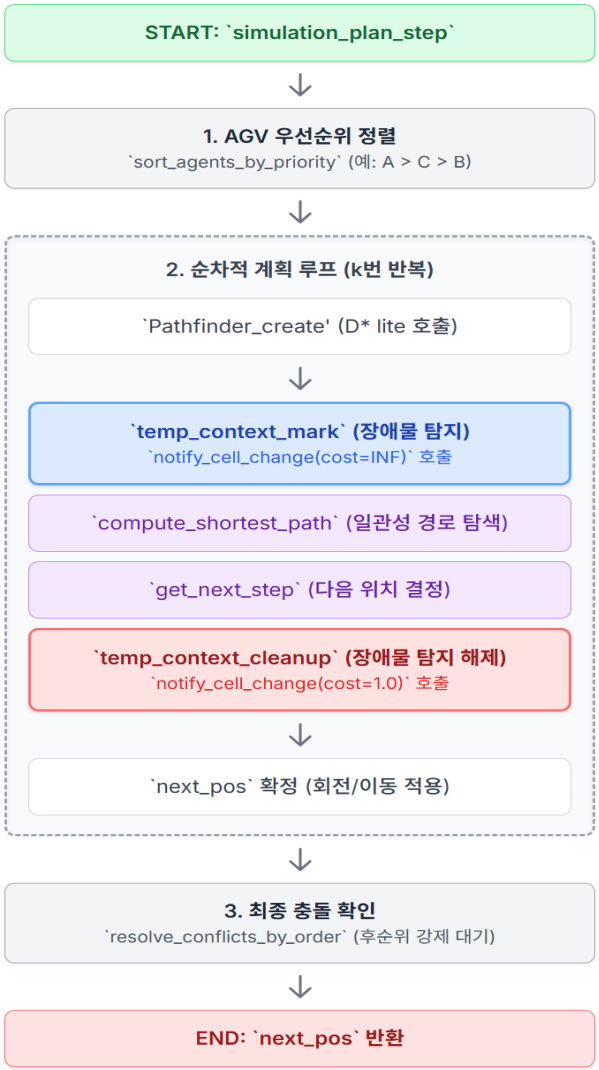
- $g(s) = rhs(s)$: Node 's' is consistent.
- $g(s) \neq rhs(s)$: Node 's' is inconsistent. -> Update Target

➢ *Priority Key*

- $Key(s) = [k_1(s); k_2(s)]$
- 우선순위 큐 사용하여 '비일관성' 노드 갱신 -> 일관성 's' 탐색
- 총 예상 경로 비용 : $k_1(s) = min(g(s), rhs(s)) + h(s_{start}, s) + k_m$
- 현재노드 ~ 목표노드 예상 비용 : $k_2(s) = min(g(s), rhs(s))$

➢ *ComputerShortestpath()*

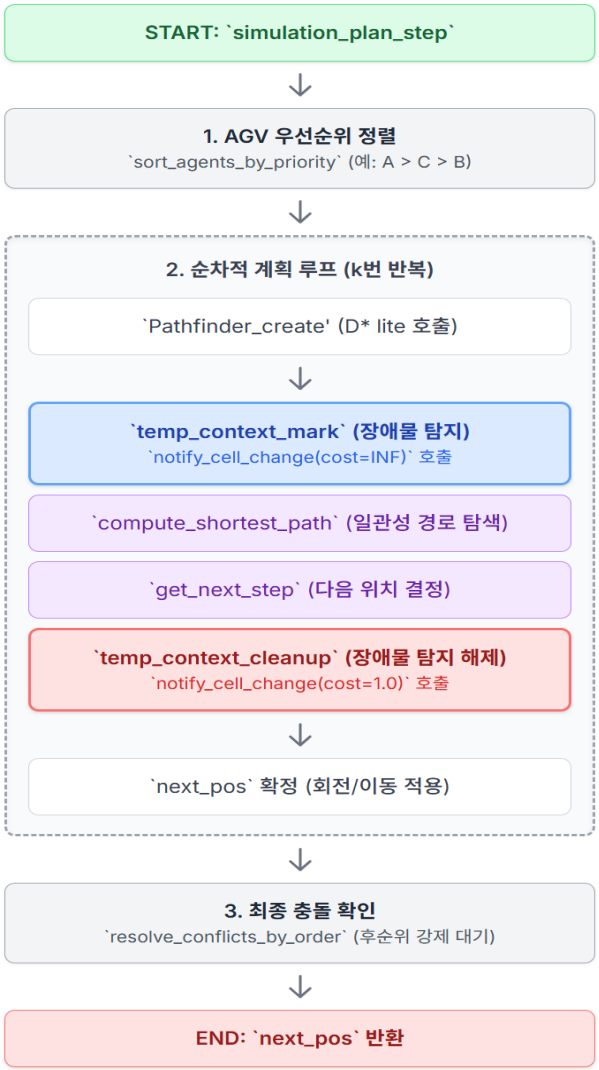
- while $\left(\min_{u \in U} key(u) < key(s_{start})\right)$ or $(rhs(s_{start}) \neq g(s_{start}))$



[2] D* lite algorithm : pseudo-code / Diagram

- pseudo-code

```
function plan_dstar_lite(agents, map):
  next_pos = get_current_positions(all_agents)
  sorted_agents = sort_by_priority(agents)

  for agent in sorted_agents:
    if agent.is_waiting(rotation or action) then
      continue
    ensure_pathfinder_exists(agent)

    temp_obstacles =
      get_higher_priority_moves(agent, next_pos) +
      get_lower_priority_positions(agent, agents)

    notify_obstacles(agent.pathfinder, temp_obstacles)
    path = repair_path(agent.pathfinder, map)
    desired_move = get_next_step(path)
    cleanup_notify_obstacles(agent.pathfinder,
temp_obstacles)
    next_pos[agent.id] = apply_rotation(agent, desired_move)

  resolve_final_conflicts(next_pos, sorted_agents)
  return next_pos
```



[3] D* Lite + WHCA* + WFG/SCC + Partial CBS : WHCA*

- **What is the WHCA* algorithm?**

➢ WHCA* [Windowed Hierarchical Cooperative A*]

- 우선순위, 예약 테이블을 활용한 MAPF 알고리즘

➢ Pathfinder Algorithm

- D* lite : Provides the Ideal route

➢ W : Space-Time Reservation Table

- [time][x][y]의 3차원 예약 테이블 (0 < time < H) *H = Horizon

➢ H [Hierachical]

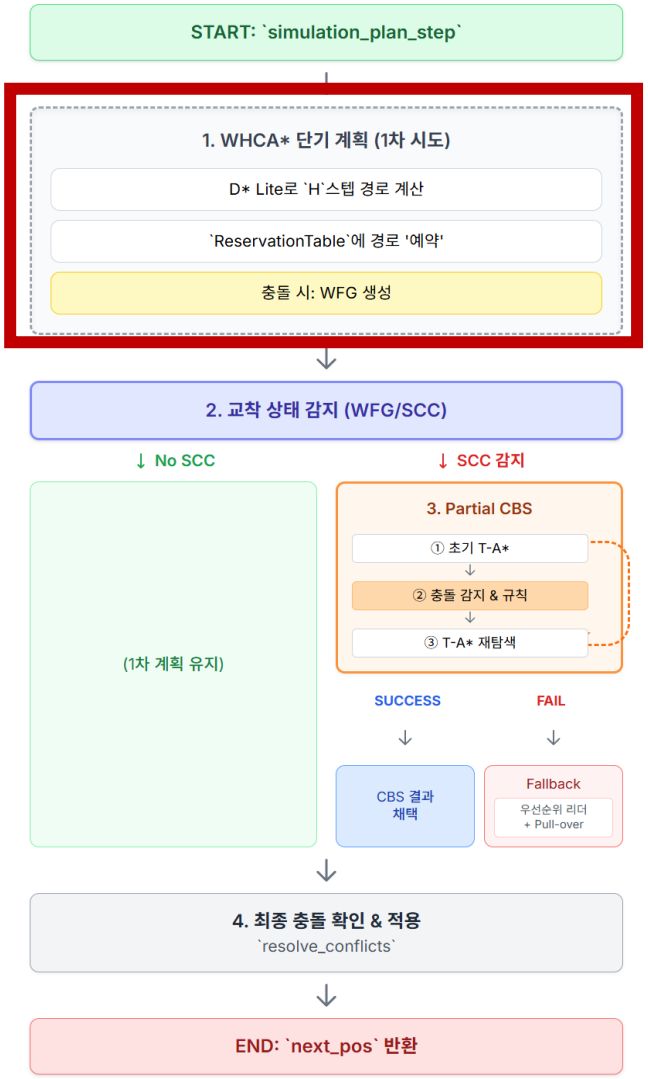
- 우선순위에 따른 순차적 경로 계획

➢ C [Cooperative]

- 타 에이전트 예약 노드 -> 장애물

➢ Limitations

- 우선순위 기반 알고리즘 -> 'Risk of Deadlock'



[3] D* Lite + WHCA* + WFG/SCC + Partial CBS : WFG/SCC

- **What is the WFG?**

➢ WFG [Wait-For Graph]

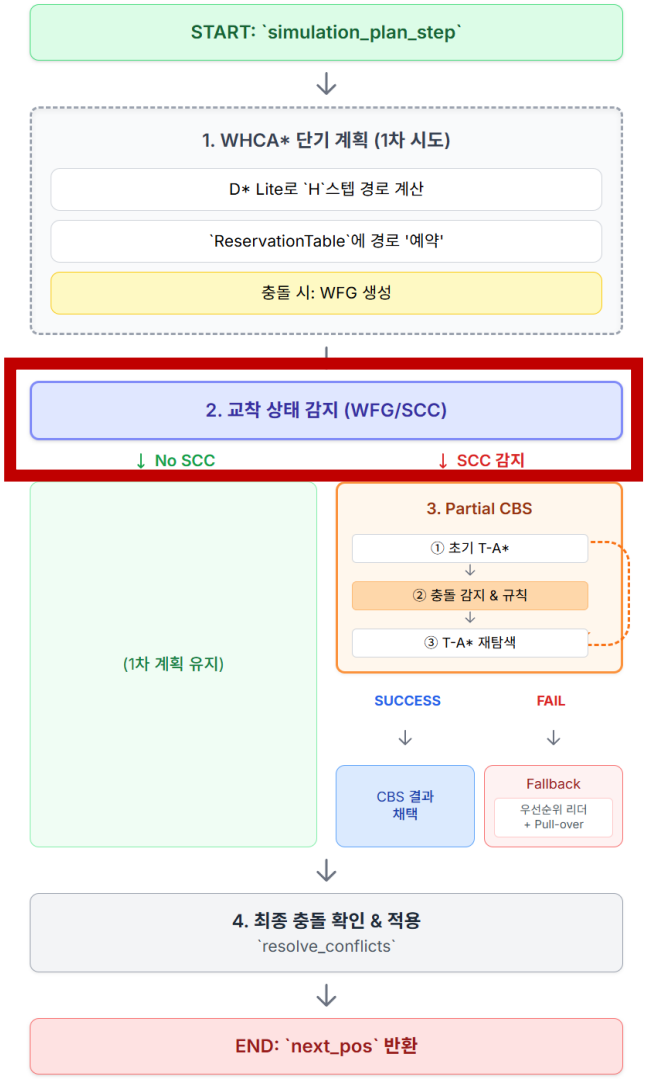
- 현재 시스템 대기 상태 표현하는 자료구조.

➢ Role

- 교착 상태 탐지위한 자료구조

➢ Components

- $G = (V, E)$
- V [Vertex / Node]: 정점의 집합 (운용 AGV: $\{A_1, A_2, \dots\}$)
- E [Edge] : 간선의 집합 (대기 관계: $\{(A_i, A_j) \mid A_i \text{ waits for } A_j\}$)



[3] D* Lite + WHCA* + WFG/SCC + Partial CBS : WFG/SCC

- **What is the SCC?**

➢ SCC [Strongly Connected Compnents]

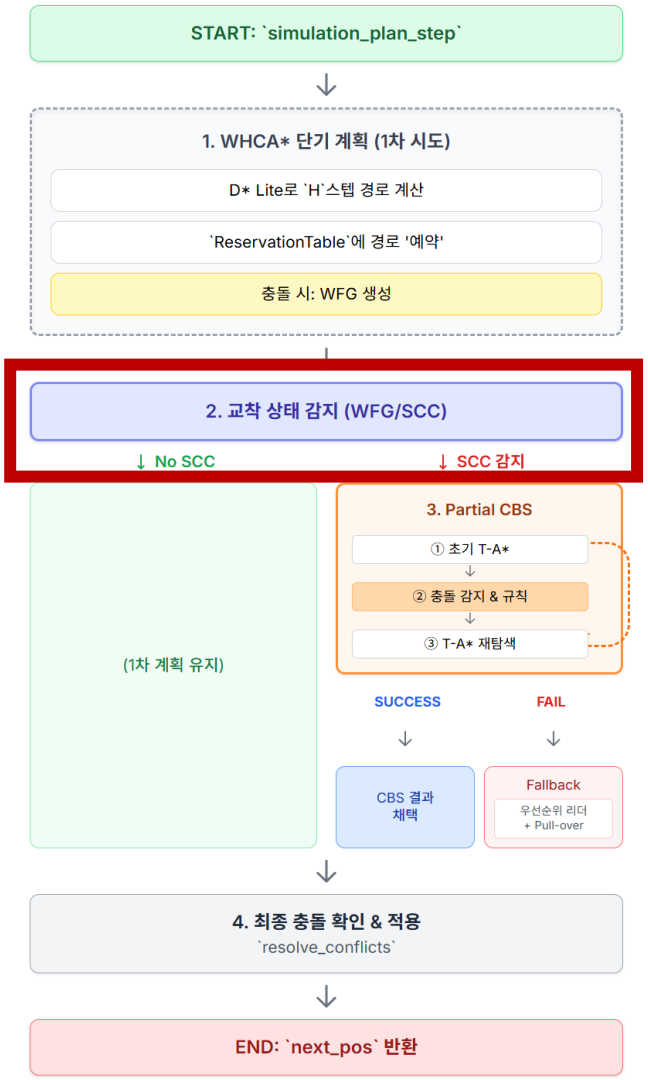
- 그래프 내에서 서로에게 도달 가능한 정점들의 집합
- 크기 2이상 SCC 존재 [ex. $A_i \leftrightarrow A_j$], -> 교착 상태 의미

➢ Role

- 자료구조에서 교착상태 감지

➢ DeadLock Detetction

- Deadlock $\Leftrightarrow \exists$ SCC $C \subseteq V$ s.t. $|C| \geq 2$



[3] D* Lite + WHCA* + WFG/SCC + Partial CBS : CBS

- **What is the CBS algorithm?**

➢ CBS [Conflict – Based Search]

- 지역적 충돌 해소 위한 MAPF 알고리즘
- 소수 에이전트 간의 충돌을 효율적으로 해결함.
- 시스템의 계산 효율성을 향상.

➢ 저수준 [Low – Level] : Time A* -> 개별 경로 탐색기

- [time][x][y] 구조에서 A* 탐색 수행
- State (상태): $s = (x, y, t)$
- 평가 함수 (f-value): $f(s) = g(s) + h(s)$
- $g(s)$: $g(x, y, t) = t$ ($(x_0, y_0, 0)$ -> (x, y, t) : 비용 t)
- $h(s)$: $h(x, y, t) = |x - x_{goal}| + |y - y_{goal}|$

[3] D* Lite + WHCA* + WFG/SCC + Partial CBS : CBS

- **What is the CBS algorithm?**

➢ 고수준 [High – Level] : 충돌 해결 위한 제약 조건 결정

- Cost(N) 가장 낮은 노드 N -> 우선순위 큐에서 선택

$$Cost(N) = \sum_{i \in Agents} PathCost(P_i)$$

- N: 충돌 트리의 노드 [제약 조건의 집합]
- P_i: 노드 N의 제약 조건 & 저수준 탐색 기반 에이전트 i의 경로
- PathCost(P_i): 경로 비용

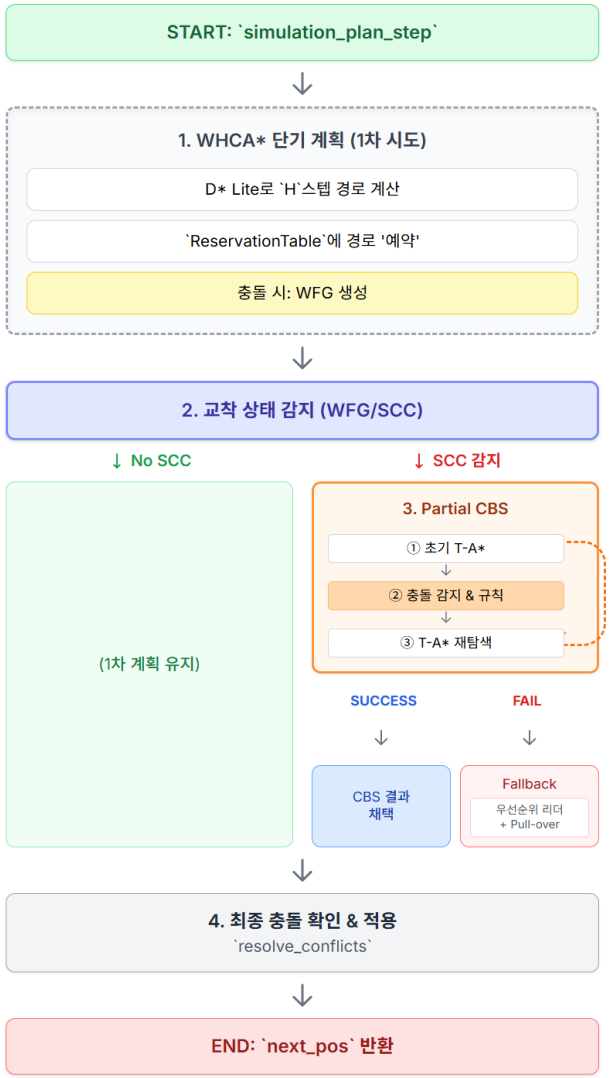
$$\alpha \cdot "\{moves\} + \beta \cdot "\{waits\} + \gamma \cdot h\_\{residual\}$$

➢ 제약 조건 (Constraint) 예시:

- High Level에서 $(Agent\ A, (5,5), t = 3)$ 제약이 내려오면,
- Low Level은 $(5,5,3)$ 상태를 고려하지 않는다.

[3] D* Lite + WHCA* + WFG/SCC + Partial CBS : DeadLock resolve

- **1. 교착 감지**
  - ➢ WFG & SCC 활용하여 교착 상태 식별
- **2. Partical CBS**
  - ➢ SCC 식별 그룹에 Partial CBS 적용
- **3. 우선순위 기반 해결**
  - ➢ CBS 실패할 시, 우선순위 기반 해결
  - ➢ A*, D* lite와 동일한 우선순위 기준
- **4. Pull – over**
  - ➢ Max Stuck value AGV -> Leader AGV
  - ➢ 우선순위 실패할 시, Leader 제외 AGV 한 칸씩 후진.



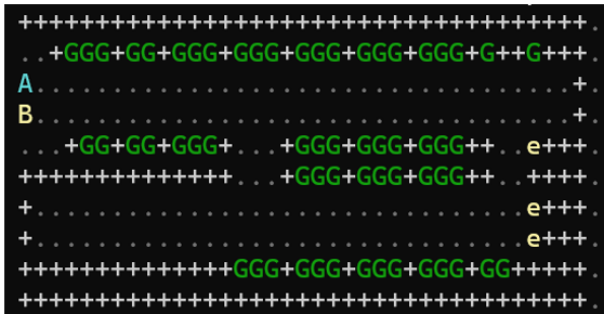
[3] D* Lite + WHCA* + WFG/SCC + Partial CBS : pseudo-code

```
function plan_WHCAstar(agents, map):

 // 1. WHCA* (First attempt)
 rt = create_reservation_table()
 wf_edges = []
 sorted_agents = sort_by_priority(agents)

 for agent in sorted_agents:
// (Plan H_steps using D* Lite)
  path = dstar_find_path(agent.pf, h_steps, rt)

// (Build WFG - Wait-For Graph)
  if has_conflict(path) with other_agent then
   add_wait_edge(wf_edges, agent, other_agent)
   provisional_plan[agent.id] = agent.pos // wait
  else
   reserve_path(rt, path)
   provisional_plan[agent.id] = path[1] // move forward

 // 2. wfg/scc (Deadlock detection)
 sccmask = detect_scc(wf_edges)
```

```
// 3. partial cbs (Deadlock resolution branch)
if sccmask > 0 then
  // (Deadlock occurred)
 deadlocked_group = get_agents_from_mask(sccmask)
  // (Attempt negotiation)
 negotiated_plans, ok
        = run_partial_cbs(deadlocked_group, rt)

  if ok == true then
   // (Negotiation success: Overwrite with CBS results)
    overwrite_next_pos(provisional_plan, negotiated_plans)
  else
// (Negotiation failure: Only leader moves)
    fallback_leader_moves(provisional_plan, deadlocked_group)
// No deadlock. Keep the first-attempt plan
else : (provisional_plan)

 // 4. Final
 resolve_final_conflicts(provisional_plan, sorted_agents)

 return provisional_plan
```

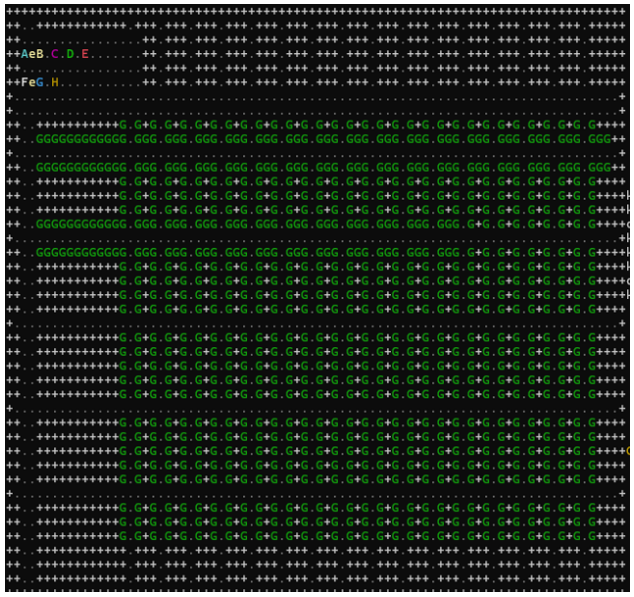
Simulation Map

- **형남공학관 주차장**
  - AGV : 1~4
  - Parking : 61

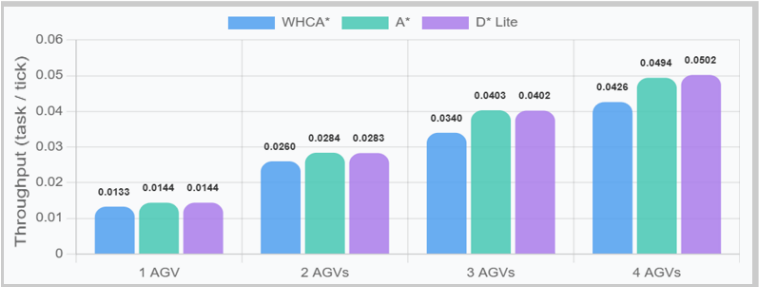
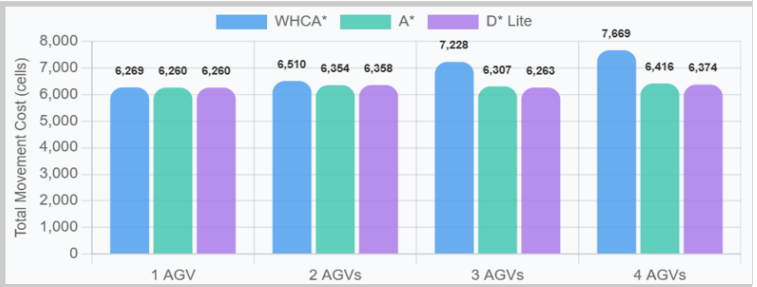
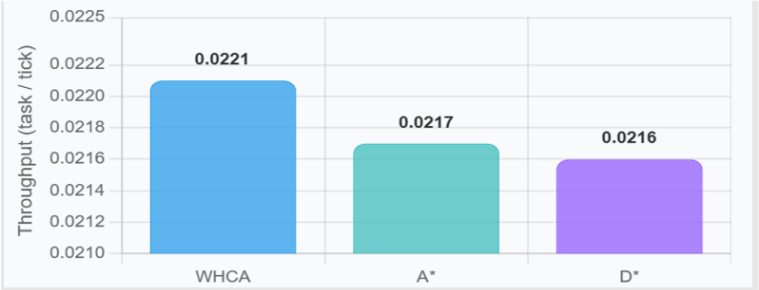
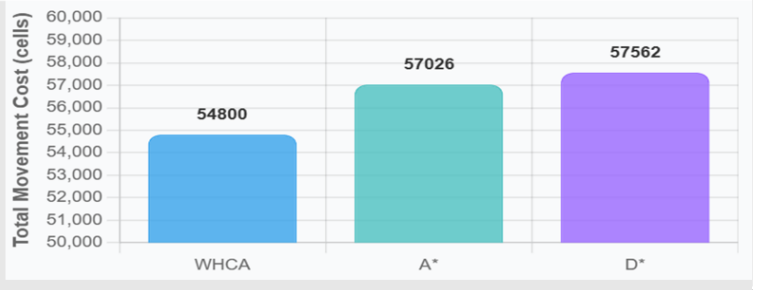
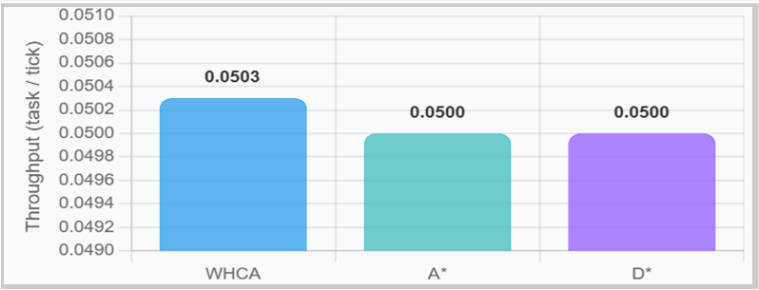
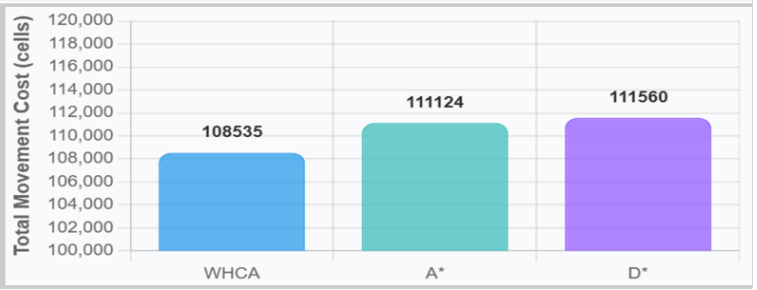


- **MAP2**
  - AGV : 4
  - Parking : 390

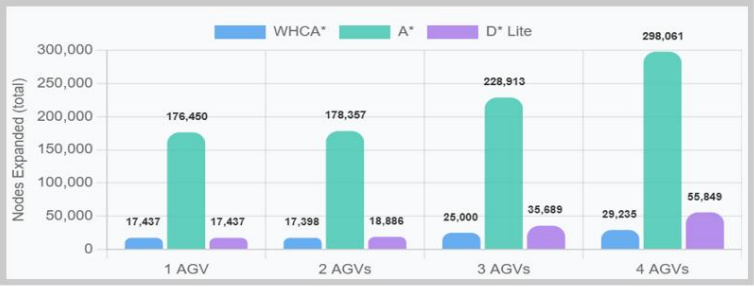
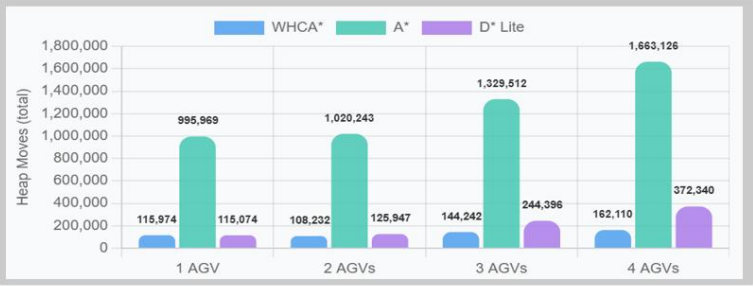
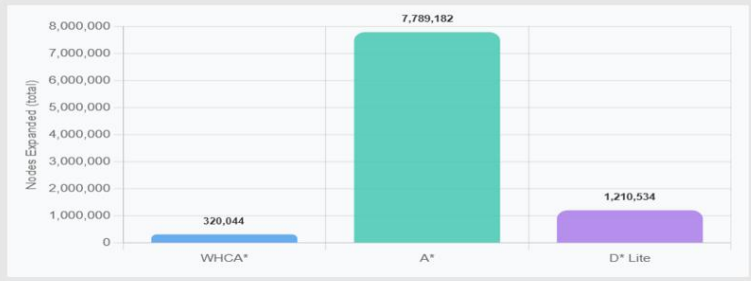
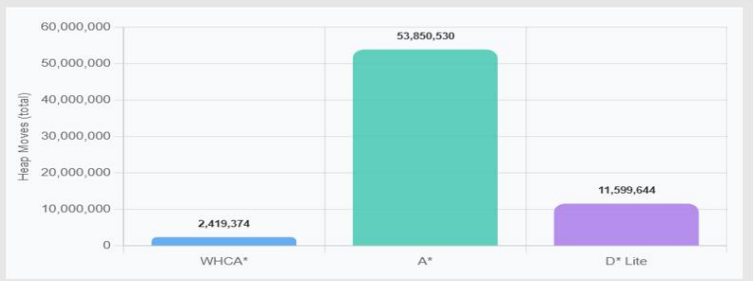
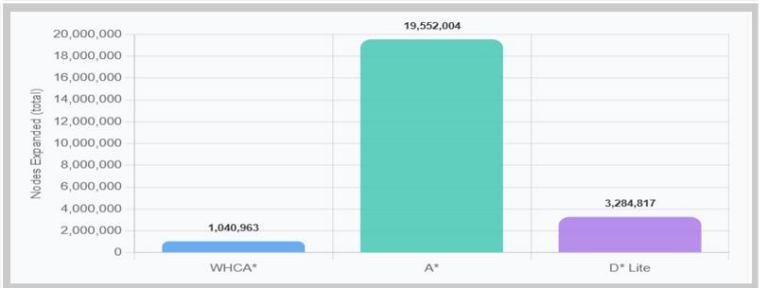
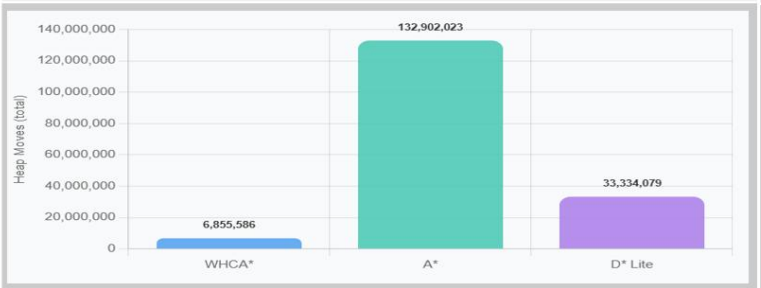
- **MAP3**
  - AGV : 8
  - Parking : 900



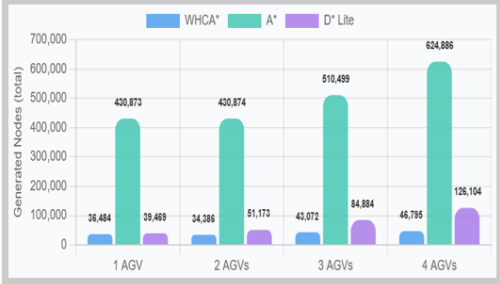
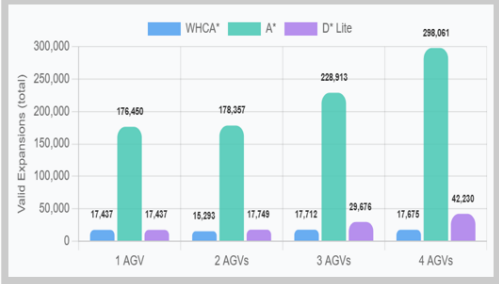
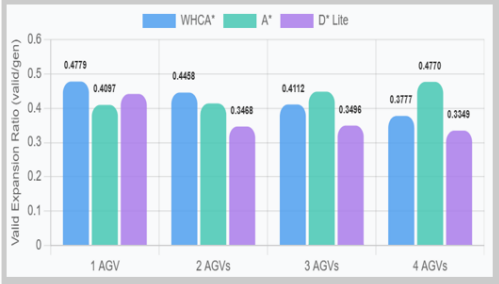
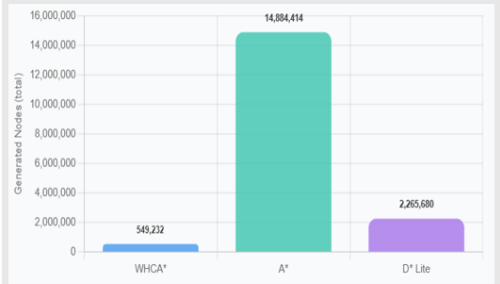
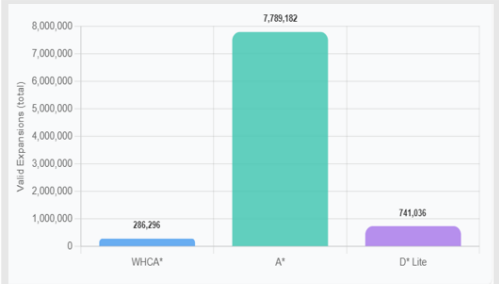
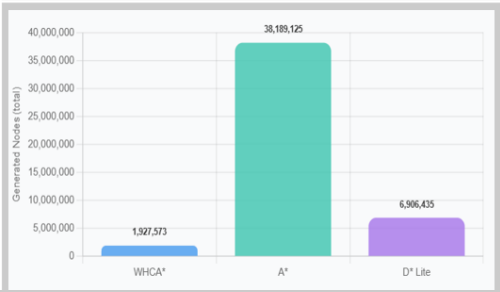
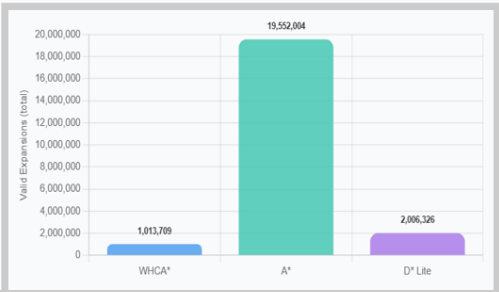
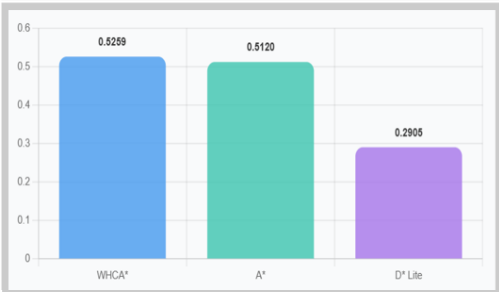
Simulation Result

MAP	Throughput	Total Movement Cost
형남공학관 주차장 Parking : 61		
AGV : 4 Parking : 390		
AGV : 8 Parking : 900		

Simulation Result

MAP	Nodes Expanded	Heap Moves
형남공학관 주차장 Parking : 61		
AGV : 4 Parking : 390		
AGV : 8 Parking : 900		

Simulation Result

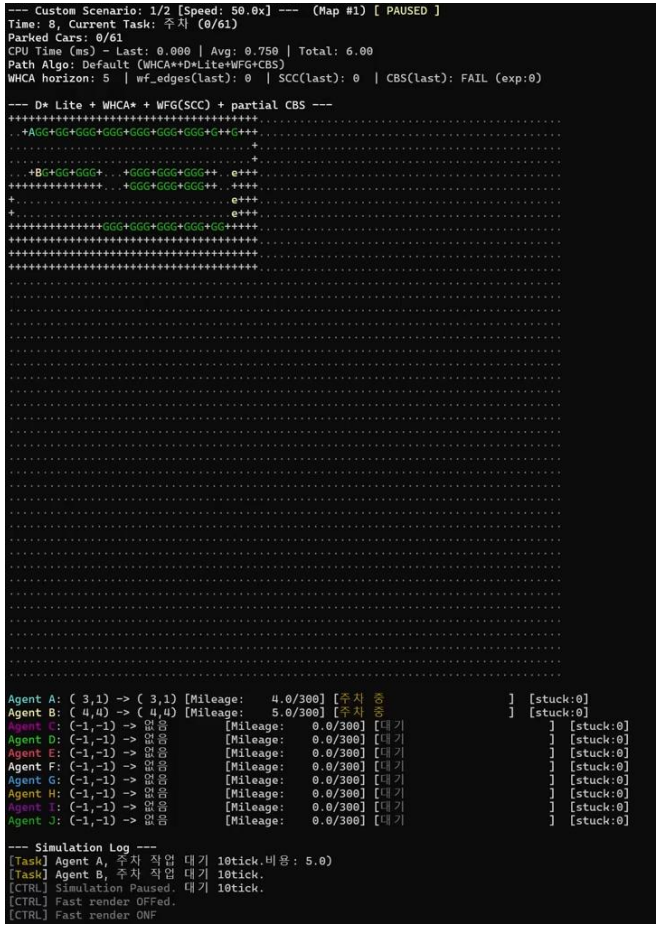
MAP	Generated Noes	Valid Expansions	Valid Expansion Ratio
형남공학관 주차장 Parking : 61			
AGV : 4 Parking : 390			
AGV : 8 Parking : 900			

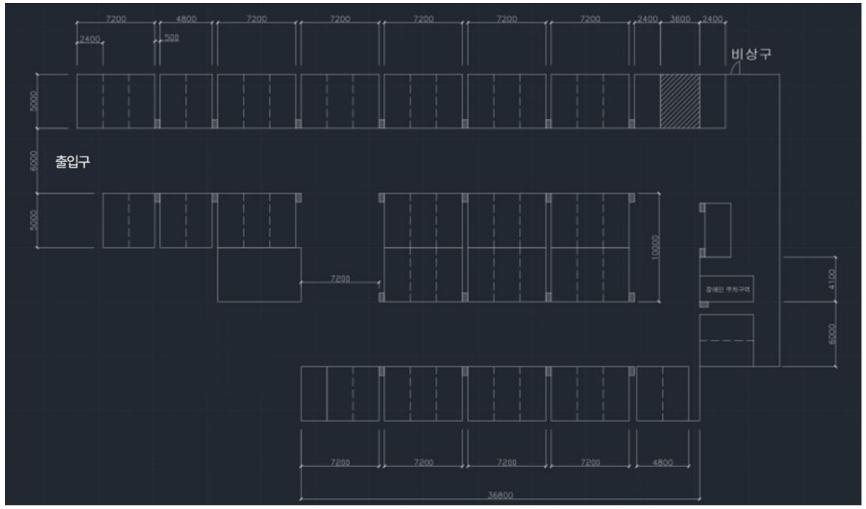
Conclusion

- **Which algorithm has the highest throughput in a low-density environment?**
  - ➢ A* algorithm And D* lite Algorithm
- **Which algorithm has the highest throughput in a High-density environment?**
  - ➢ WHCA* + WFG/SCC + CBS Algorithm
- **Which algorithm requires the least computation under the same conditions?**
  - ➢ 1st : WHCA* + WFG/SCC + CBS Algorithm
  - ➢ 2nd : D* ltie Algorithm
  - ➢ 3rd : A* Algorithm

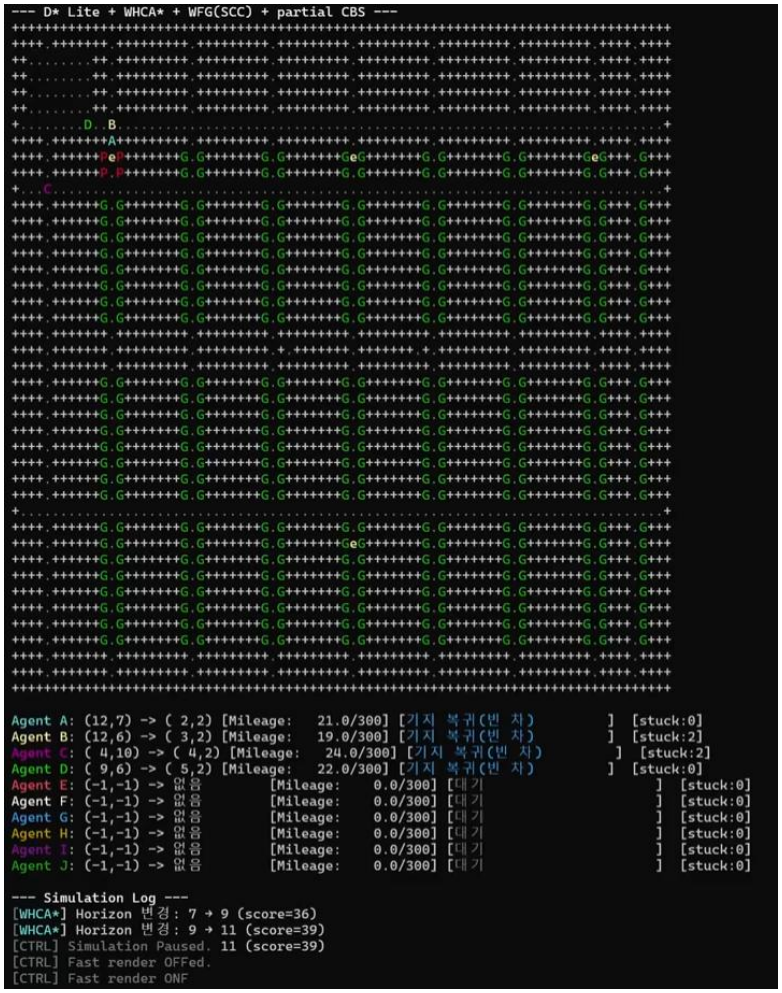
- **"The optimal algorithm varies depending on the context."**

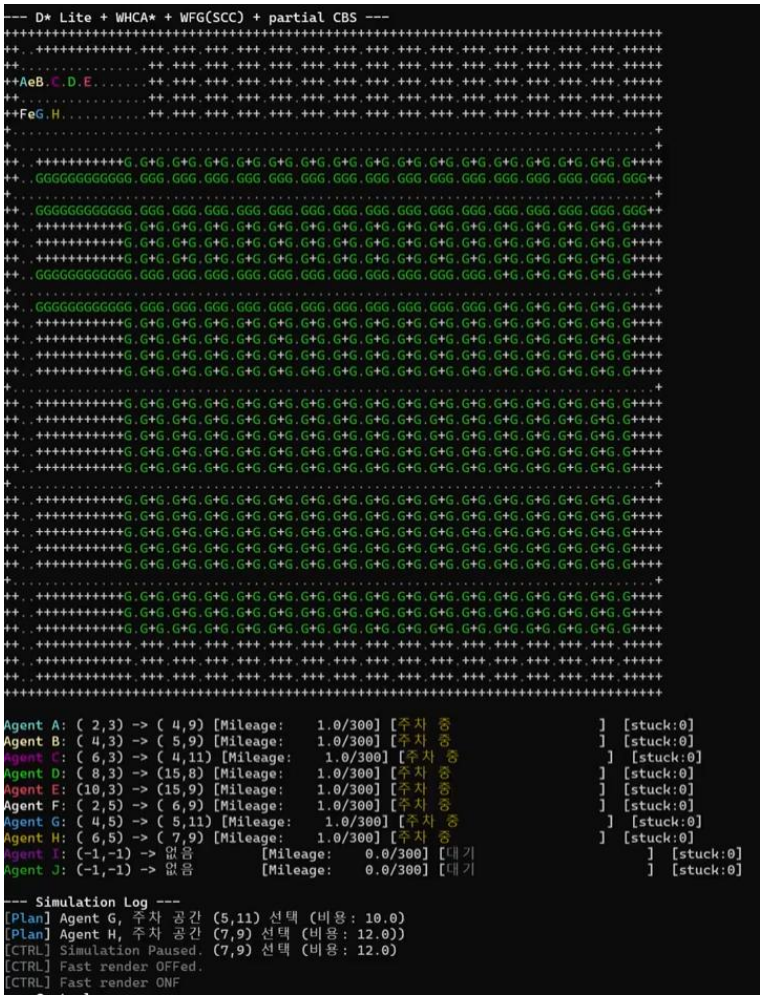
시뮬레이션 영상 [형남 공학관 주차장 + (WHCA*+WFG/SCC +CBS)]





시뮬레이션 영상 [Map2 / Map3]





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