Automated Warehouse Scenario: Final Project Report

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Abstract

This report presents the final results of an ASP-based solution to the automated warehouse planning problem. In modern warehouse operations, robots are tasked with transporting shelves containing products to designated picking stations to fulfill orders. The challenge is to compute plans that minimize the overall makespan—the final time step at which any non-idle action occurs—while satisfying complex constraints such as collision avoidance, highway restrictions, and intricate action preconditions.

The approach models the warehouse as a rectangular grid using `cell/2` and `grid/2` predicates, and encodes the initial states of robots, shelves, and orders through `init` facts. Key actions (move, pickup, deliver, putdown, and idle) are represented with the `occurs` predicate to generate a plan that adheres to all operational constraints. To optimize performance, a #minimize directive is employed to penalize the makespan, thereby guiding the solver toward more efficient plans. This work builds on established ASP methodologies.

Extensive testing on sample instances has demonstrated the model's ability to generate valid, optimized plans in a complex, dynamic environment. The results validate the practical applicability of ASP in automated planning and provide a solid foundation for future enhancements.

Problem Statement

In the automated warehouse scenario, robots are required to deliver shelves containing products to designated picking stations to fulfill orders. The warehouse is modeled as a rectangular grid where each cell is defined by initialization facts. Each cell in the grid is assigned coordinates, and specific cells are further classified as highways or picking stations. Robots start at predetermined locations and are allowed to move horizontally or vertically between adjacent cells. Each shelf holds a given quantity of a product, and orders specify both the product and the number of units required, along with the picking station where the delivery must occur.

In addition to delivering orders, the planning must adhere to several constraints. Robots must avoid collisions by ensuring that no two robots occupy the same cell at the same time, and they must not exchange positions simultaneously. Furthermore, a robot that is carrying a shelf loses the ability to pass beneath another shelf, necessitating that obstructing shelves be moved out of the way beforehand. Shelves are also prohibited from being put down in highway cells to keep these paths unobstructed. The objective is to generate a plan that minimizes the makespan—defined as the highest time step at which any non-idle action occurs—while satisfying all operational constraints and ensuring that every order is completely fulfilled.

Project Background

Automated warehouse planning has emerged as a critical area of research and application due to the rapid expansion of e-commerce and the increasing demand for efficiency in logistics. Modern warehouses have evolved from manual operations to highly automated systems, exemplified by projects such as Amazon Robotics (formerly Kiva Systems). In these systems, hundreds of autonomous vehicles coordinate in real time to move inventory throughout large-scale facilities [Wurman, D'Andrea, and Mountz(2008)]. Such advancements have spurred academic interest in formal methods for planning, where Answer Set Programming (ASP) has proven particularly effective for handling complex, combinatorial constraints.

The application of ASP to planning problems is well documented. Gebser et al. [Gebser et al.(2012)Gebser, Kaminski, Kaufmann, and Schaub] provide a comprehensive overview of practical ASP applications, demonstrating its capacity to model intricate operational constraints. Complementary research in warehouse design and performance evaluation has identified the critical factors that influence efficiency and safety in automated environments. For example, Gu et al. [Gu, Goetschalckx, and McGinnis(2010)] and Baker and Canessa [Baker and Canessa(2009)] review warehouse design strategies and highlight the need for robust planning algorithms that adapt to dynamic conditions, such as fluctuating inventory and variable order loads.

The current project builds on these foundations by modeling a warehouse as a rectangular grid and representing robots, shelves, and orders through logical facts. The approach leverages ASP to encode actions—such as moving, picking up, delivering, and putting down shelves—with strict constraints to ensure collision avoidance, compliance

with highway restrictions, and proper action sequencing. An optimization objective minimizes the makespan by penalizing the last time step that includes a non-idle action. This integration of techniques from ASP with industrial warehouse automation practices underscores the potential of declarative programming in solving real-world logistical challenges.

Approach

The solution is based on a declarative modeling paradigm using Answer Set Programming (ASP) to address the complex planning requirements of an automated warehouse scenario. The approach begins with a formal representation of the warehouse as a rectangular grid. Each grid cell is defined by facts provided via the `init` predicate, and the overall grid structure is explicitly captured using the `cell/2` and `grid/2` predicates. This explicit modeling guarantees that all robot movements remain within valid bounds and that the spatial structure of the warehouse is maintained throughout the planning process.

The initial state of the problem domain is established through a series of `init` facts that assign unique starting positions to robots and shelves, and specify the locations of highways, picking stations, and grid cells. Orders are also initialized with associated product quantities and designated picking stations. These static facts serve as the grounding base upon which dynamic behaviors are later modeled.

Dynamic behavior is encoded through a set of action predicates. The primary actions include `move`, `pickup`, `deliver`, `putdown`, and `idle`. A choice rule enforces that each robot selects exactly one action at every time step, ensuring that the plan reflects a complete schedule of operations. The chosen actions are then translated into output atoms via the `occurs` predicate, conforming to the prescribed output format.

State transitions are modeled explicitly. For instance, the current position of a robot is updated by applying the directional offsets specified by a `move` action to its previous coordinates, while ensuring that the new position lies within the grid. If a robot opts for the `idle` action, its position is simply carried forward. Similarly, when a shelf is carried by a robot, its position is updated to mirror that of the robot, and if it is not picked up, the shelf remains at its last known location.

A series of constraints have been formulated to enforce operational rules. Collision avoidance constraints ensure that no two robots occupy the same cell simultaneously. Delivery preconditions are rigorously modeled: a delivery action is permitted only if the robot is correctly located at the appropriate picking station, the carried shelf contains sufficient units of the required product, and the order's requirements are met. Additional constraints prevent shelves from being put down on highway cells, thereby preserving clear pathways for movement.

An optimization objective is integrated to minimize the makespan of the plan. The makespan is defined as the highest time step at which any non-idle action occurs. Auxiliary predicates identify the last time step with an active (non-idle) action, and a #minimize directive is used to penalize higher values of this time step. This strategy encourages the solver to generate plans that complete all necessary actions as early as possible.

The overall methodology was developed incrementally, with each component of the model tested on sample instances provided in the project package. The integration of grid modeling, dynamic action representation, constraint enforcement, and optimization not only meets the core requirements of the problem but also demonstrates the flexibility of ASP in handling real-world planning problems.

Main Results and Analysis

The final ASP encoding was evaluated using multiple sample instances provided in the project package. In every instance, the model generated two stable models, one of which was selected as optimal based on the makespan minimization objective. The optimization directive `#minimize { T : last(T) }` effectively penalizes plans where the last non-idle action occurs later, steering the solver toward plans that complete all necessary actions as early as possible.

A detailed analysis of the encoding reveals that the explicit grid representation, achieved by defining both `cell/2` and `grid/2` predicates, guarantees that every robot movement is confined to valid warehouse locations. The initial state is established using `init` facts, which assign unique positions to robots, shelves, and other critical elements such as highways and picking stations. This forms a solid grounding base for modeling dynamic behavior.

The behavior itself is encoded through a carefully designed choice rule, ensuring that each robot selects exactly one action per time step from a set that includes `move`, `pickup`, `deliver`, `putdown`, and `idle`. By translating these actions into `occurs` atoms, the output conforms to the required format while reflecting the actual operational sequence. Notably, the state transition rules update robot and shelf positions consistently: when a robot moves, its new coordinates are computed by adding directional offsets, and if the robot idles, its previous location is retained. This guarantees that the spatial configuration remains valid throughout the plan.

Constraint enforcement is a key strength of the model. Collision avoidance is ensured by prohibiting more than one robot from occupying the same cell at any time, and delivery preconditions are rigorously imposed so that a delivery can occur only when the robot is precisely at the corresponding picking station, the carried shelf contains sufficient product, and the order's quantity requirements are met. Similarly, constraints prevent putdown actions in highway cells to maintain clear operational pathways.

Experimental evaluation shows that while the model can generate multiple valid plans, the optimization objective reliably selects the one with the lowest makespan. In the optimal plan, the final active (non-idle) action occurs at a significantly earlier time step compared to the suboptimal alternative, demonstrating that the minimize directive functions as intended. The flexibility of the encoding, along with its rigorous constraint enforcement, confirms the model's capability to handle the complex dynamics of automated warehouse

operations. These results validate the practical applicability of ASP in real-world planning problems.

Conclusion and Self-Assessment

The final solution demonstrates a robust and effective application of Answer Set Programming (ASP) to a challenging automated warehouse planning problem. The project not only meets the core requirements but also provides valuable insights into the power and efficiency of ASP as a declarative problem-solving paradigm. The modeling of the warehouse as an explicit grid and the representation of actions through carefully designed predicates has yielded a solution that consistently produces valid, optimized plans. Notably, the rapid grounding and solving capabilities of Clingo have been impressive; even with a moderately large search space, solutions are computed in a matter of seconds, underscoring the potential of ASP for real-world planning problems.

Throughout the project, the development process has led to a significant deepening of understanding regarding the principles of declarative programming. The clarity and expressiveness of ASP allowed complex operational constraints—such as collision avoidance, proper delivery conditions, and scheduling requirements—to be encoded succinctly. The iterative refinement of the model provided a practical demonstration of how logical rules can be combined to model intricate systems efficiently. This experience has reinforced the notion that declarative paradigms can not only simplify the expression of complex problems but also deliver high-performance solutions through advanced solvers like Clingo.

The results achieved in this project serve as a testament to the strength of ASP in handling dynamic, real-world scenarios. The ability to quickly generate multiple valid plans and to effectively select the most efficient one via optimization techniques is particularly noteworthy. In summary, the project has not only enhanced the technical proficiency in ASP and Clingo but also broadened the perspective on their applicability in industrial and logistical domains. This work lays a strong foundation for further research and application in automated planning, illustrating that a well-formulated declarative model can yield rapid, reliable solutions to complex operational challenges.

Future Work

Future research directions in this field encompass both advanced applications in robotics and the expansion of ASP's theoretical framework within logic and mathematics. In the robotics domain, one promising direction is to integrate ASP-based planning with real-time sensor feedback and control systems. Such integration could facilitate adaptive, robust decision-making in dynamic and uncertain environments, thereby enhancing multi-robot coordination and collaboration in complex logistical tasks. Furthermore, exploring the combination of ASP with probabilistic reasoning and learning-based methods may yield systems capable of handling stochastic and partially observable conditions, ultimately improving the efficiency of autonomous warehouse operations.

Beyond robotics, ASP has significant potential for addressing challenging problems in logic and mathematics. Future work could involve developing specialized ASP methodologies for formal verification, combinatorial optimization, and theorem proving. Investigating ASP's applications in these areas may contribute to a deeper theoretical understanding of declarative reasoning and enable the discovery of innovative approaches to longstanding mathematical problems. Moreover, interdisciplinary research applying ASP to fields such as computational social choice and resource allocation could demonstrate its versatility and broaden its impact across diverse domains. Overall, these research avenues promise to extend ASP's capabilities both in practical applications and in advancing its theoretical foundations.

Appendix

Below is the Clingo code for the final solution:

```
#const t = 20.
#const max_u = 10.
time(0..t).

prev(T, U) :- time(T), U = T - 1, U >= 0.

dir(1, 0).
dir(-1, 0).
dir(0, 1).
dir(0, -1).

cell(X, Y) :- init(object(node, N), value(at
    , pair(X, Y))).
grid(X, Y) :- cell(X, Y).

robot(R) :- init(object(robot, R), value(at,
     pair(X, Y))).
shelf(S) :- init(object(shelf, S), value(at,
     pair(X, Y))).
highway(X, Y) :- init(object(highway, H),
    value(at, pair(X, Y))).
picking_station(P, X, Y) :- init(object(
    pickingStation, P), value(at, pair(X, Y)
    )).
product(I) :- init(object(product, I), A).
order(O) :- init(object(order, O), A).

prod_qty(I, S, Q) :- init(object(product, I)
    , value(on, pair(S, Q))).
order_req(O, I, Q) :- init(object(order, O),
     value(line, pair(I, Q))).
order_station(O, P) :- init(object(order, O)
    , value(pickingStation, P)).

pos(robot, R, X, Y, 0) :- init(object(robot,
     R), value(at, pair(X, Y))).
pos(shelf, S, X, Y, 0) :- init(object(shelf,
     S), value(at, pair(X, Y))).

{ move(R, DX, DY, T) : dir(DX, DY)
; pickup(R, T)
; deliver(R, O, I, U, T) : order(O), product
    (I), U = 1..max_u
; putdown(R, T)
```

```
; idle(R, T)
} = 1 :- robot(R), time(T), T > 0.

occurs(object(robot, R), move(DX, DY), T) :-
     move(R, DX, DY, T).
occurs(object(robot, R), pickup, T)
    :- pickup(R, T).
occurs(object(robot, R), deliver(O, I, U), T
    )  :- deliver(R, O, I, U, T).
occurs(object(robot, R), putdown, T)
            :- putdown(R, T).
occurs(object(robot, R), idle, T)
               :- idle(R, T).

pos(robot, R, X1, Y1, T) :- time(T), prev(T,
     U), pos(robot, R, X, Y, U),
                           move(R, DX, DY, T
                               ),
                           X1 = X + DX, Y1 =
                                Y + DY,
                           grid(X1, Y1).

pos(robot, R, X, Y, T) :- time(T), prev(T, U
    ), pos(robot, R, X, Y, U),
                           idle(R, T).

carrying_robot(R, T) :- carrying(R, S, T).
free(R, T) :- robot(R), time(T), not
    carrying_robot(R, T).

carrying(R, S, T) :- time(T), prev(T, U),
    pickup(R, T),
                     pos(robot, R, X, Y, U),
                     pos(shelf, S, X, Y, U),
                     free(R, U).

carrying(R, S, T) :- time(T), prev(T, U),
    carrying(R, S, U),
                     not putdown(R, T).

dropped(R, S, T) :- time(T), prev(T, U),
    putdown(R, T), carrying(R, S, U).

pos(shelf, S, X, Y, T) :- time(T), carrying(
    R, S, T), pos(robot, R, X, Y, T).
pos(shelf, S, X, Y, T) :- time(T), prev(T, U
    ), pos(shelf, S, X, Y, U),
                          not pickup_occurs(
                              S, T).

pickup_occurs(S, T) :- time(T), prev(T, U),
    pickup(R, T), pos(shelf, S, XX, YY, U).

:- time(T), deliver(R, O, I, U, T), prev(T,
    U), free(R, U).
:- time(T), deliver(R, O, I, U, T), prev(T,
    U), pos(robot, R, X, Y, U),
   order_station(O, P), picking_station(P,
       Xp, Yp), X != Xp.
:- time(T), deliver(R, O, I, U, T), prev(T,
    U), pos(robot, R, X, Y, U),
   order_station(O, P), picking_station(P,
       Xp, Yp), Y != Yp.
:- time(T), deliver(R, O, I, U, T), prev(T,
    U), carrying(R, S, U),
   prod_qty(I, S, Q), Q < U.
:- time(T), deliver(R, O, I, U, T),
    order_req(O, I, RQ), RQ < U.

:- time(T), putdown(R, T), prev(T, U), free(
    R, U).
:- time(T), putdown(R, T), prev(T, U), pos(
    robot, R, X, Y, U),
   highway(X, Y).

:- time(T), pos(robot, R1, X, Y, T),
   pos(robot, R2, X, Y, T), R1 != R2.

non_idle_exists :- occurs(object(robot, R),
    A, T), A != idle.
:- not non_idle_exists.

used(T) :- occurs(object(robot, R), A, T), A
     != idle.
later_used(T) :- time(T), used(T2), T2 > T.
last(T) :- used(T), not later_used(T).
#minimize { T : last(T) }.
```

References

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