Pipe spool fabrication sequencing by automated planning

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ABSTRACT

Construction of Industrial facilities involves a substantial amount of piping. Pipe spools are usually pre-fabricated from a number of raw pipes and pipe fittings (e.g. elbows, flanges, tees, etc.) in fabrication shops. Pipe spool fabrication is often affected by various disruptions from within or outside the shops. Previous research mainly focuses on shop layouts, dispatching rules, buffer location and standardized products. Another critical factor, the sequencing of pipe spool fabrication, is usually overlooked. A pipe spool can be fabricated in several alternative sequences that are often decided by shop foremen based on experience. It is rare that these alternative sequences get compared and evaluated. A simulation experiment shows that shop productivity can be improved by varying spool fabrication sequence. This paper presents an investigation of Artificial Intelligence (AI) planning approach that automatically identifies the optimal fabrication sequence for pipe spools while considering various fabrication logics. Experiments are conducted with different AI planners to evaluate their capabilities. The results indicate that one of the planners is more suitable for solving the sequencing problem than others. However, it requires special pre-processing of the input that may be prohibiting for practical use. Directions of future research to overcome these limitations are discussed.

INTRODUCTION

Industrial construction includes a wide range of projects, such as petroleum refineries and chemical and power plants. This type of construction involves intensive piping, which connects a variety of equipments and conveys process fluid and gas. Due to compressed schedule and limited space on site, industrial construction projects rely heavily on the offsite fabrication and assembly. As such, piping work is divided into three stages: pipe spool fabrication, module assembly, and site installation.

Timely supply of pipe spools to module yard and installation site is the key to the success of whole project. However, studies showed that pipe spool fabrication
shops are faced with various interruptions (e.g. out-of-sequence deliveries, change orders) and often not operating at an optimal productivity (Howell and Ballard 1996, Tommelein 1998, and Wang et al. 2009). Another major challenge faced with fabrication shops is that most of pipe spools are unique (Wyss 2009). Pipe spools can be unique in material, configuration, type of joints and many other properties. As such, pipe spools cannot be entirely or partially fabricated in advance, which means fabrication shops are unable to use on-hand inventory to buffer against variability from within or outside the shop.

Unique design and configuration means these pipe spools need to be custom built. More specifically, the fabrication process usually varies from one pipe spool to another. Since most fabrication operations (e.g. cutting, fitting and welding) involved are similar, the variation mainly lies in the sequence of these operations. The fabrication sequence determines steps that pipe spools go through from raw materials to the final product. In reality, pipe spool fabrication sequence is determined by shop foremen in heuristic manner. Given the enormous number of pipe spools involved in an industrial project and the fast-tracking nature of the project, it is quite challenging for human planners to come up with fabrication sequence with both efficiency and quality. It is not a surprise to find that fabrication sequence for the same pipe spool varies with human planners, because there is no standard way of sequencing in the industry. Moreover, a pipe spool can be fabricated in several alternative sequences. However, it is rare for these alternative sequences to get compared and evaluated.

A study by Hu and Mohamed (2011) shows that different fabrication sequences can lead to different shop performance. This motivates us to develop a solution to automate fabrication sequencing process where human skills are continuously needed and the result affects operation performance in significant ways. This paper explores the use of artificial intelligence (AI) planning technique to solve the spool fabrication sequence planning problem. The remainder of the paper starts with brief introduction of pipe spool fabrication and fabrication sequence problem, followed by a simulation experiment (Hu and Mohamed 2011) that shows the impact of fabrication sequence on the operation performance. The paper then continues with explaining reasons why choosing AI planning over other techniques. The current research progress is described by experimenting with pipe spools with increasing complexity. A tentative conclusion about capabilities and limitations of AI planning is provided at the end.

PIPE SPOOL FABRICATION

Pipe spools are fabricated from a number of raw pipes and pipe fittings (e.g. elbows, flanges, tees, etc.) in fabrication shops. Raw pipes are cut to the required sizes and moved with pipe fittings to a fitting table, where some of the components
are fitted together (i.e. temporarily connected). The resulting sub-assembly (part of the final pipe spool) continues with welding operations (i.e. permanent connected) before it comes back to the fitting table and gets fitted with other spool components. Spool fitting and welding can be grouped into two types: (1) roll fitting and welding and; (2) position fitting and welding. Roll fitting and welding means the main pipe can be turned by a rolling machine and the fitter or the welder does not have to change his or her position to perform the operation, whereas position fitting and welding occur when one or more branches of the main pipe exceed the clearance limit (see figure 1). In such case, the fitter or the welder has to move around the main pipe run to accomplish fitting or welding. As a result, position fitting and welding usually takes more time to finish than roll fitting and welding. To minimize number of position fitting and welding is one of the goals of pipe spool fabrication sequencing.

![Rolling machine](image1.png) ![Rolling machine](image2.png)

Roll fitting/welding

Position fitting/welding

**Figure 1 Roll Welding VS. Position Welding**

**PIPE SPOOL FABRICATION SEQUENCE**

The fabrication sequence defines the process of how a pipe spool will be fabricated gradually from raw materials (e.g. pipes and fittings), to intermediate spool components, and eventually to the final product. As mentioned before, a pipe spool, in many cases, can be fabricated through a number of alternative sequences. Figure 2 shows an example of a pipe spool with relatively simple configuration. It shows that the pipe spool can at least be fabricated by two different sequences from the same raw materials. Fabrication sequence1 requires three operations to produce the final product while sequence2 only needs two. Moreover, handling is needed between these operations, which further deteriorate the shop performance. In reality, sequence is determined by shop foremen in very heuristic manner and these alternative sequences seldom have a chance to be compared and evaluated. As a result, opportunities of productivity improvement slip away. The spool fabrication sequence problem was identified when several industry professionals were interviewed. The
root cause is attributed to the fact that currently there is no standard, structured way to identify sequence for pipe spools in the industry, and no academic research on this specific topic has yet been found.

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe</td>
<td>1 + 2 + 3 = 7</td>
<td>3 + 4 = 6</td>
<td>7 + 6 + 4</td>
</tr>
<tr>
<td>Elbow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flange</td>
<td>3 + 4 + 5 + 6 = 7</td>
<td>1 + 2 + 7</td>
<td></td>
</tr>
<tr>
<td>Pipe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Figure 2 Alternative pipe spool fabrication sequences (adapted from Hu and Mohamed 2011)

SIMULATION EXPERIMENT

A simulation experiment is conducted to test the hypothesis that fabrication sequence has impacts on pipe spool performance. 22 pipe spools are selected. Two alternative fabrication sequences are prepared for each pipe spool. They are inputted into the simulation model that represents the real shop operations and the make span for fabricating all 22 pipe spools is collected and compared. The result (in figure 3) shows 10.09% reduction in the make span and 16.88% decrease in the number of handlings (i.e. a type of non-value adding activity).

Figure 3 Simulation Experiment Result (Hu and Mohamed 2011)
SEQUENCING OF CONSTRUCTION PROCESSES

Previous research on sequencing construction processes mostly focuses on scheduling and prioritizing processes under limited resource availability. Relatively less attention has been paid to the area where planning is more focused on logic dependency between processes by considering the geometric and technological requirements. This paper is more related to the latter type of sequencing. A review of the previous relevant researches reveals that two major topics are: (1) identify and formalize construction sequence rationales (2) automate generation of construction sequences. Gray (1986) identify sequence rationales such as “covered by” or “weather protected by other components” that are generalized from different contractors’ schedules. Navinchandra et al. (1988) identify similar dependencies as “supported by” and “connected to”. Most of these sequence rationales are derived from the physical relationships between building components. Echeverry et al (1991) enrich the body of knowledge by adding three more types of factors that might govern the sequence of construction. Basically, they identify, in addition to “physical relationships”, “trade interaction”, “path interference”, and “code regulations”. Under each factor type, they comprehensively enumerated more specific sequencing constraints. As an extension to this, many researchers attempt to develop an Artificial Intelligent (AI) planner that not only store all the relevant sequencing rationales but also automatically apply this knowledge to identify construction sequence, e.g. OARPLAN (Darwiche et al. 1988), GHOST(Navinchandra et al. 1988), BUILDER (Cherneff et al. 1991), and MDA (Jägbeck 1994). Aalami et al. (1998) categorize these systems into two major groups: (1) process-based reasoning system, e.g. GHOST; (2) component-based reasoning system, e.g. OARPLAN. A recent study by Koo et al. (2007) pointed out that many research on domain specific AI planning systems is more focused on identifying a correct construction sequence rather than discovering a number of possible sequence alternatives. They introduce a prototype system named "CLCPM", that make use of a constraint ontology and a classification mechanism to automatically assign "role" and "status" to relevant activities in CPM. A decision will be made with regard to whether or not the sequence of the target activity could be changed.

An observation from the previous construction sequencing research is that most of them are focused on building construction projects. Many sequencing constraints are derived from the physical relationships between building components (e.g. columns, beams, walls and slabs). This makes it difficult to apply existing planning systems to industrial construction projects, i.e. the building blocks are pipe spools, equipments, and modules which most likely need to be pre-fabricated or pre-assembled before the final installation on site. The sequence constraints between these components are significantly different from those applied in building
construction. In addition, existing planning systems are mostly knowledge-based and depend on enumeration of sequencing logic and, sometimes, require an existing schedule to infer re-sequence options.

**AUTOMATED PLANNING**

Artificial Intelligence (AI) Planning is process of selecting and sequencing a set of actions that can change the system from an initial state to a desired goal state. If evaluation criteria are provided, some of AI planning techniques is able to identify optimal sequence with respect to the predefined objectives (e.g. minimum cost). Research into the AI planning has been of major interest in recent years. AI planning systems evolve from classical planning tools to more complicated planners that can address issues encountered in real-life settings such as numeric-valued variables, time constraints, or a non-deterministic environment. Planning Domain Description Language (PDDL) is the standard language for domain-independent planners. It has been refined and extended since it was first proposed by Drew McDermott (1998). AI planning has been successfully applied in several areas, such as robot navigation, manufacturability of machined parts, and emergency evacuation (Ghallab et al. 2004).

Planning problems studied in AI usually involve: (1) a dynamic system where objects of interest are interacting, (2) finite system states, (3) a set of actions that can change the system state, (4) an initial state and a goal state of the system, and, sometimes, (5) an evaluation criteria. Pipe spool fabrication sequencing problem is a good candidate for using AI planning. Pipe spool fabrication can be considered as the dynamic system, where focus is placed on objects of interest such as welds, raw pipes and piping fittings or sub-assemblies (part of the final pipe spool). Fitting and welding are actions available to change the state of raw materials or in-progress assemblies. The initial state of the pipe spool starts with a group of raw materials and the goal state is the final product. The output is a sequence of fitting and welding operations which assemble all raw materials to the final product. Evaluation criteria could be the least number of handlings or the least number of position fitting and welding.

Using PDDL to solve a planning problem entails a modeling process which results in two pieces of descriptions. First, there is a general description that represents the system and the system dynamics under study. It is stored in a Domain file. Another piece of description is specific to each planning problem (e.g. specific objects, their initial states and goal states). It is called Problem file. Usually, the same domain file can be used to solve different planning problems as long as the same system representation stays valid for these problems, whereas the problem file varies with each planning problem (i.e. different initial or goal states). Both these descriptions are fed to an AI planner which in turn uses a heuristic search method to find an optimum or near-optimum solution.
APPLICATION OF PDDL TO PIPE SPOOL FABRICATION SEQUENCE

A series of experiments were conducted to test the capability of PDDL to model and plan pipe spool fabrication sequencing problems. Three popular planners (domain-independent) were used in the experiments, namely Metric-FF (Hoffmann 2002), LPRPG (Coles et al. 2008) and LPG (Gerevini and Serina 2002). Metric-FF searches on a state space while the other two search on a plan space. The experiments begin with very simple pipe spool and then gradually move to more complex and more realistic configuration. Each experiment includes two steps: (1) using PDDL language to model a pipe spool system (e.g. Domain file) and a specific case of pipe spool (e.g. Problem file), and (2) using each of these AI planners to generate the fabrication sequence. The following are the brief description of each experiment.

Experiments

In experiment1, a simple pipe spool is designed (figure 4). No numerical values are considered. It simply tests if the AI planers can handle the logic aspect of pipe spool sequencing problem. The Domain file and Problem file are shown in figure 5 and figure 6. Experiment2 uses a pipe spool with more complex configuration (figure 4). Again, no numerical values are considered in the experiment2. For space limit, its domain file and problem file is not shown here. Although the pipe spool in experiment3 seems to have a simpler configuration than that in experiment2, it involves the major challenge that dimensions of assembly parts are considered. The motivation is that one of goals of fabrication sequencing is to minimize the number of position fitting and welding. As mentioned previously (figure 1), the way to distinguish roll welding and position welding is to see if the length of major branches exceed the clearance limit of the rolling machine. Dimensions of assembly parts have to be considered and need to be updated after each fitting or welding operation. All resulting plans are compiled in Table 1.

Figure 4 Pipe spools respectively for experiment 1, 2 and 3
The types of objects involved in pipe spool system

Predicates to describe the state of a pipe spool

Preconditions of an action

Effects of an action

Specific instances of objects

Initial states of these object instances

Goal states of these objects

Figure 5 Domain Definition file of experiment 1

Figure 6 problem definition file of experiment 1

Table 1 resulting plans from each AI planner

<table>
<thead>
<tr>
<th></th>
<th>Experiment1</th>
<th>Experiment2</th>
<th>Experiment3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPG</td>
<td>Unsolvable</td>
<td>Unsolvable</td>
<td>Step1: ROLL-X-P1-P2-1</td>
</tr>
<tr>
<td>LPRPG</td>
<td>Unsolvable</td>
<td>Unsolvable</td>
<td>(P1 P2 W1 W3 W2 C)</td>
</tr>
</tbody>
</table>
| Metric-FF      | Step1: ROLL-FITTING P1 P2 W1  
Step2: ROLL-FITTING P1 P3 W2 | Step1: ROLL-FITTING-X P1 P7 W1  
Step2: ROLL-FITTING-Y P1 P2 W2  
Step3: ROLL-FITTING-Y P1 P8 W3  
Step4: ROLL-FITTING-Z P1 P3 W4  
Step5: ROLL-FITTING-Z P1 P6 W5  
Step6: ROLL-FITTING-Z P1 P4 W6  
Step7: ROLL-FITTING-Z P1 P5 W7 | Unsolvable  | Step1: ROLL-X-P1-P2-4 |
|                |             |             | (P1 P2 W1 W1 W1 C)   |

The results obtained from all three experiments indicate that Metric-FF is more capable than the other two AI planners in terms of handling pipe spool fabrication logic. However, Metric-FF has its limitation too. In experiment 3 where numerical calculation and assignment is involved Metric-FF could not handle the
combination of conditional effects and numerical calculations. One of the ways to get around this is to break down the conditional effect by moving the condition part to the preconditions of the whole action and keep effect in the effect part of the action formulation. This requires making actions more specific and enumerating all possible situations with respect to which weld belong to which assembly parts. In PDDL or Lisp language, this is called a “grounding” process. After converting the conditional effect, LPG planner is now able to return a solution which shows in Table1. Metric-FF seems to be able to do the same but a closer check finds that it returns an illogical solution. The challenge regarding the grounding process is that the number of actions in domain file will grow exponentially with the number of welds in the pipe spool. If a pipe spool has N welds, then $2^{N-1}$ actions need to be explicitly formulated in domain file (e.g. a pipe spool with 13 welds requires 4096 actions defined). For extremely complicated pipe spools, it could be computationally prohibitive to find a solution.

CONCLUSION

This study represents an in-progress research which explores the feasibility of use of AI planning technique to solve pipe spool fabrication sequencing problems. The use of PDDL as standard AI planning language seems to capture all necessary logic of the domain. The challenge however lies in finding a suitable domain-independent planner that is capable of processing pipe spool fabrication logic and performing numeric calculations and assignments as specified in a PDDL domain file. Experiments with three most commonly used AI planners—LPG, LPRPG and Metric-FF shows that each planner has its own limits and that LPG seems to be a promising planning algorithm. To use LPG planner, a grounding process is required, which poses a challenge to sequence complex pipe spools. Future work include developing a program that can automatically perform the grounding process (i.e. generate actions without any conditional effect) and experimenting with LPG for complex pipe spools to test its planning efficiency. Future research will also investigate the applicability of domain-specific planners and dynamic programming approaches to generate optimized fabrication sequences.

REFERENCE


