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A dynamic programming solution to automate fabrication sequencing of industrial construction components

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ABSTRACT

Increasing complexity of petro-chemical projects, fast-tracked engineering, and tighter schedules pose a challenge for pipe spool fabrication shops. To maintain competitiveness, it is necessary to improve the shop performance, i.e. fabrication cycle time. Pipe spool fabrication sequence is found to have significant impact on cycle time and presents an area with potential for improvement. Traditionally, fabrication sequences are determined by shop foremen in a heuristic manner and optimality is not guaranteed. This paper presents a dynamic programming (DP) algorithm to automatically identify the optimal fabrication sequences for pipe spools. Simulation experiments are conducted to test the effectiveness of the algorithm by comparing the cycle times resulting from the algorithm-generated sequences and human-planner-designed sequences, respectively. The results show that the DP algorithm reduces unnecessary position-welding (9 out of 20 position-welds) and results in a reduction in the total fabrication cycle time by a range of 4.8% to 12%.

1. Introduction

A surging global demand and soaring prices of natural oil and gas put unprecedented pressure on existing oil production infrastructure in Alberta. This leads to a significant wave of capital investment into oil and gas projects. Many of these projects are referred to as *mega* industrial projects meaning that the capital investment required per project will exceed $1 billion [1]. Cost, however, is only one of the characteristics that describe the *mega* status of a petro-chemical project. It is usually implied that mega-projects are also technologically complex and have a very long project execution period. For example, a typical project involves many trades and disciplines (e.g. civil, steel structure, piping, electrical, mechanical, HVAC), and has an extremely high level of engineering and construction activities (e.g. 3.5 million engineering man-hours and 15 million construction man-hours are required for a $2.5 billion project in Alberta) [2]. In addition, these activities are interwoven and tightly coupled with one another; a change or deviation in one activity can produce a cascade of effects on others that depend on it.

Piping is always the largest job within a project [3] and is a critical and costly process for industrial construction projects [4]. Piping is usually broken up into three stages—shop fabrication, module assembly, and site installation. This is mainly due to the fact that, considering the remote location, severe weather conditions, and congestion issues, it is more efficient and effective to pre-fabricate and pre-assemble parts of a project in a controlled environment (e.g. fabrication shops and module assembly yards) than on site. It has been reported that the use of shop fabrication has significantly increased over the past 20 years [5]. Fig. 1 depicts different stages of the piping supply chain.

Pipe spools are building blocks to the piping system of industrial construction projects. They are fabricated in fabrication shops and are shipped to either a module assembly yard (i.e. on-module piping) or a construction site (i.e. off-module piping). Timely delivery of pipe spools has great impact on the successful execution of industrial projects, overall. However, the performance of pipe spool fabrication shops has been found not quite satisfactory [6–8]. This is because pipe spool fabrication shops are susceptible to various disruptions from within or outside the shop (Fig. 1). For example, the supply of ISO drawings or raw materials could be late or out of sequence. Change orders from the owner or general contractor could generate a huge amount of rework. Rush orders from the assembly yard or the site can also cause deviations from the original shop schedules. In addition, most pipe spools have unique designs and need to be custom built [9]. Pipe spools can be unique in material, shape, configuration, type of joints, and many other properties. As such, pipe spools cannot be entirely or partially fabricated in advance, which means fabricators are unable to use on-hand inventory to buffer against the variability from within or outside the shop.

To improve pipe spool fabrication shop performance, a number of innovative attempts [7,10,11,8] have been made and many factors have been investigated. These include shop layout, dispatching rules, buffer location, and standardized products. However, there is one factor

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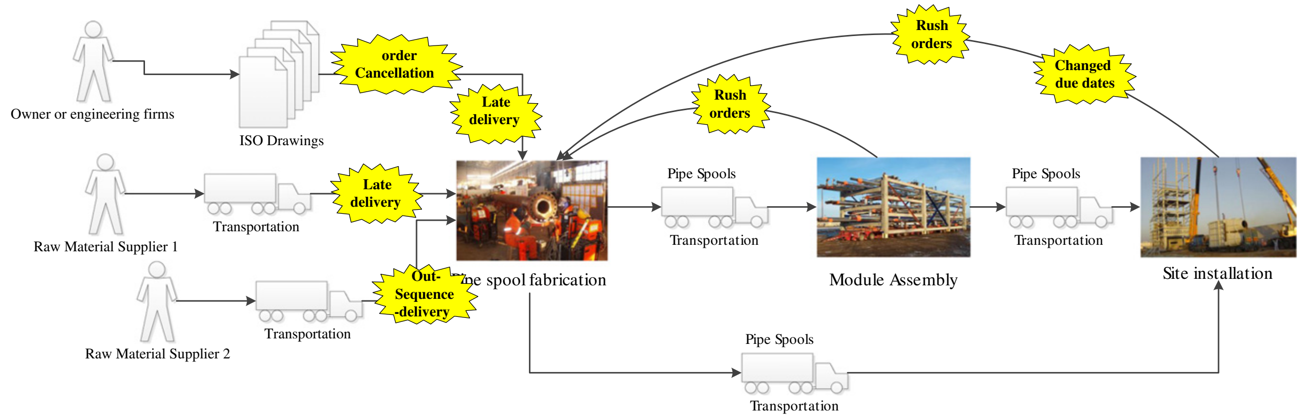

Fig. 1. Disturbances from piping supply chain of an industrial construction project.

that is overlooked, which is the sequence of pipe spool fabrication. The fabrication sequence determines the process that pipe spools go through from raw materials (i.e. raw pipes and pipe fittings) to the final product. Unique configurations cause the fabrication sequence to vary from one pipe spool to another. This is different from manufacturing, where the majority of products have similar configurations and follow a few typical fabrication steps. Pipe spool fabrication sequence is usually determined by shop foremen based on personal experience and intuition. Interviews with shop foremen and superintendents show that the fabrication sequence for the same pipe spool could vary with human planners, because there is no standard way of sequencing in the industry. In fact, many pipe spools can be fabricated in several alternative sequences. However, it is rare for these alternative sequences to be compared and evaluated.

The magnitude of the impact that fabrication sequence could have on fabrication performance has been investigated by Hu and Mohamed [12]. A simulation model is developed to represent the shop operations and pipe spools with two alternative fabrication sequences (a good scenario and a bad scenario, but not necessarily the best and the worst). The total cycle times for all pipe spools are collected and compared (Fig. 2). The results show that change in fabrication sequence can lead to 10.09% reduction in the total cycle time for all pipe spools and 16.88% decrease in the number of handlings during the fabrication.

Sequencing of pipe spool fabrication, and especially, identification of the optimal fabrication sequence, need to be addressed. A review of literature on construction sequencing finds that most past research only focuses on sequencing rationales of building projects. However, the building blocks for industrial construction projects (e.g. steel structures, equipment, pipe works, and cable trays) are very different than those for building projects (e.g. columns, beams, walls, slabs). This makes it hard to apply the existing sequencing rationales or planning systems to industrial construction projects.

A search for problem solving techniques in computing science has found that artificial intelligence (AI) planning and dynamic programming (DP) are good candidates for solving the pipe spool fabrication sequencing problem. The use of AI planning has been investigated in a previous paper [13]. Conclusions include (1) AI planning suffices in handling all the logic of pipe spool fabrication; but (2) existing AI planners have limited parsing capability (to parse the system description with both numerical calculations and conditional effects which are required by the pipe spool fabrication problem) which makes it difficult to solve real-life pipe spool problems. This paper mainly focuses on exploring the applicability of DP.

In this paper, a DP-based algorithm to identify the optimal fabrication sequences of pipe spools is presented. The paper starts with a description of the pipe spool fabrication sequencing problem. Review of previous research on construction sequencing is provided in the next section and the gap in the body of knowledge is pointed out. A brief discussion of AI planning technique and its application on a pipe spool fabrication problem is given. The main focus of the paper is placed on the use of DP. First the pipe spool fabrication problem is formulated in DP manner. A DP-based algorithm is then proposed and simulation experiments are conducted to test its effectiveness. Finally, limitations and future research directions are discussed.

2. Pipe spool fabrication

Pipe spools are fabricated from a number of raw pipes and pipe fittings (e.g. elbows, flanges, tees) in fabrication shops. To reach the final product, raw pipe spool parts need to go through three major types of operations: cutting, fitting, and welding. Cutting always occurs at the beginning of the fabrication process and is only applied to raw pipes (not pipe fittings). Generally, fitting precedes welding, since

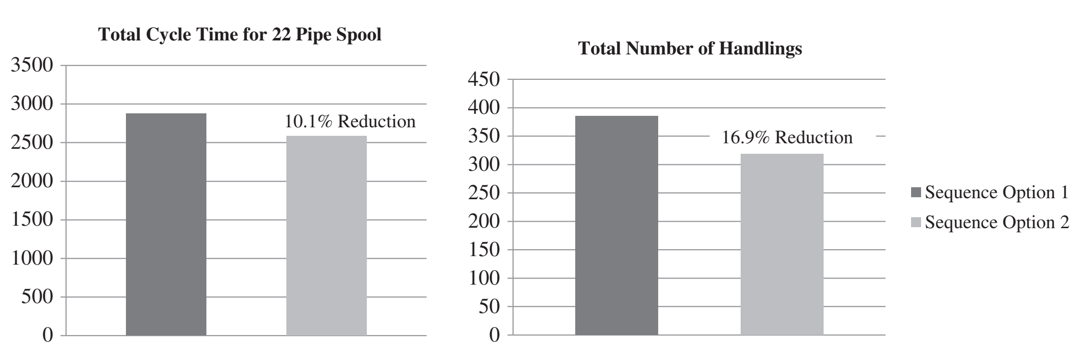

Fig. 2. Simulation experiment result [12].