Mitigating Workspace Congestion: A Genetic Algorithm Approach

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Abstract

Workspace Planning and Management is a critical component in the design and planning process to achieve efficiency and effectiveness in construction. Early identification of problems relating to workspace clashes has been shown to be a vital component of constructability analysis. However, there is a lack of quantification methodologies to identify and subsequently resolve such workspace congestion issues. This paper extends the quantification methodology previously proposed by the authors, by further introducing a heuristic genetic algorithm for resolving such workspace congestion issues via schedule repair, which may be modelled as an optimization problem. The novelty of the chromosome design allows the genetic algorithm to direct its search within the feasible search space. An oil refinery refurbishment case study is used to show the applicability of the proposed framework for minimizing congestion. In the case study, schedule repair of the original construction programme is carried out to minimize workspace clashes. The genetic algorithm proposed is demonstrated to temporally arrange the activities in the schedule, hence reducing the schedule clashes between overlapping activities. This achieves a more constructible programme with respect to workspace congestion.

Keywords: genetic algorithm, schedule repair, workspace congestion, workspace planning and management

Introduction And Background Literature

Construction Space is often modelled as a construction resource which affects almost every construction activity (Thabet and Beliveau, 1994). Workspace Planning and Management plays a vital role in construction management by identifying and analysing construction space requirements for workspace clashes. Examples of such Workspace Planning practices include early consideration of various space utilizations in planning site layout, programming high-level construction sequences, and selecting suitable construction methods (Song and Chua, 2005). However, this has often been overlooked in the project management process leading to schedule conflicts and a decrease in productivity due to congestion in the construction space (Zouein and Tommelein, 2001).

The consideration of Workspace Planning and Management in project management is often a critical component in the design and planning process to achieve efficiency and effectiveness in construction. Early identification of problems relating to workspace clashes has been shown to give added benefits such as improved safety, decreased conflicts among workers, reduced crew waiting and work stoppage, better quality as well as reduced project delays (Mahoney and Tatum, 1994, Heesom and Mahdjoubi, 2004). Hence, Workspace Planning and Management is a vital component of Constructability Analysis.

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Various methodologies for space planning and management have been introduced in prior research to address the issue of analysing spatial conflicts (Thabet and Beliveau, 1994, Riley and Sanvido, 1997, Akinci, *et al.*, 2002, Guo, 2002). A key idea in the aforementioned methodologies is to detect the potential interferences between workspaces. Through this detection, the visualization of space utilization among trades can be achieved, which will help engineers to identify possible congestion arising from the detected workspace collisions. Despite the availability of the above methodologies, quantification methodologies for workspace conflict detection are limited, and this lack results in a lack of resolution frameworks for workspace congestion issues.

Chua, *et al.* (2010) provided such a quantification method for capturing workspace congestions from a 4D CAD model of worksite operations. The value of the quantification method lies in allowing Planners to decide on an optimal schedule to reduce dynamic workspace conflicts, hence reducing the risk of schedule overrun arising from workspace clashes. This paper presents a resolution framework based on the quantification method introduced by Chua, *et al.* (2010). A suitable chromosome representation is proposed within the framework to enhance the efficiency of the algorithm. The proposed framework is then validated using a schedule repair problem involving an oil refinery refurbishment project.

Overview of Workspace Modelling Methodology

Representing Spatial Temporal Utilization In Workspaces

Present methods rely on visualisation of changes to construction sequences using 4D CAD, which relies on the experience of Planners to elicit conflicts. The indicators developed by Chua, *et al.* (2010) complements this visualisation aspect of 4D CAD, by allowing the construction sequencing and its corresponding activities to be identified and subsequently analysed quantitatively.

A new abstract metric attribute, Utilization Factor, ρ is introduced which quantitatively measures the level of usage for a given workspace from two perspectives: spatial and temporal. Spatial Utilization, U_s is the ratio index of the space required by the operator/equipment to the total available space allocated to an activity; the Operator Space being the amount of space necessary for the operator to perform the activity. Multiple crews may be considered by summing up the total operator spaces needed. The Total Boundary Space refers to the amount of space depicting the activity space. U_s is the intensity of a space imposed by an activity determined as follows:

$$U_S = \frac{\sum \text{Operator Space}}{\text{Total Boundary Space}} \tag{1}$$

Temporal Utilization, U_t recognizes that workspaces may not always be utilized throughout the activity's operation time and may be used to describe the intermittent nature of continuous activities. The temporal utilization may then be expressed as a ratio depicted in Equation 2. If time is considered as a resource, temporal utilization may be viewed from an economic perspective of time required (or temporal demand) by the operator and the time available (or temporal supply).

$$U_S = \frac{\text{Actual Time Utilized}}{\text{Total time of activity operation}} \tag{2}$$

The resultant Utilization Factor (ρ) is then defined as the geometric mean of both U_s and U_t which provides a representation of the consequences of spatial and temporal demands as it depicts the “average” product of the two utilization factors, and given by

$$\rho = \sqrt[a+b]{U_s^a \times U_t^b} \tag{3}$$

where *a* and *b* are user-defined weights, which allow unequal emphasis to be placed on either the spatial or temporal utilization of a workspace. This unequal emphasis could arise from the Planner's judgment/priorities.

Quantifying utilization is necessary for the study of worksite conflict and congestion as Utilization provides a low-level abstraction of space demand and supply from the operative level perspective. It provides a value to aggregate and quantify workflow patterns so that it may be incorporated into high-level space planning. More uniquely, ρ implicitly considers both spatial and temporal perspectives in a single ratio.

Quantifying Spatial-Temporal Interference Between Workspaces

Worksite conflict and congestion occur due to the interferences between competing workspaces. The concept of utilization is extended to activity workspace interference, and quantifies the effects of the interferences from the utilization viewpoint. This results in an index useful for decision making, allowing project managers to identify congested workspaces.

“Dynamic Space Interference” (*DSI*) quantifies the utilization when interference with other workspaces is experienced. The measure characterizes the obstruction to the ability to work around time and space constraints imposed by other workspaces when interference occurs. Equation 4 formulates the *DSI* for the primary workspace *A*, where ρ_i is the Utilization Factor of *i* which is an element of a set of interfering workspaces, S_{iA} the overlapping volume between *A* and *i*, S_A the spatial volume of *A*, t_{iA} the time interval over which *A* and *i* overlap and t_A the activity duration of *A*.

$$DSI_A = \rho_A + \sum_i \left(\rho_i \cdot \frac{S_{iA}}{S_A} \cdot \frac{t_{iA}}{t_A} \right) \qquad \forall i \in \text{Interfering Space Entities} \tag{4}$$

DSI_A can be abstracted as a space-time-volume of workspace *A* with an inherent spatiotemporal demand-supply ratio (ρ_A). When an infringement occurs, there is an added demand on the same spatiotemporal supply imposed by the interfering workspaces given by the second term in the equation.

DSI has no upper bound; *DSI* values greater than 1 indicate that the space-time demand has exceeded its supply, and that worksite conflict has occurred. An important implication is that while the utilization of the primary workspace (ρ_A) is low, the additional demands placed on the space by other interfering workspaces may cause the activity to experience worksite congestion. At the operative level, the operators of interfering workspaces can be expected to accommodate each other's spatial and temporal demands on the same space, reaching a compromise through `local scheduling' to prevent incursions. From the perspective of space-time economics, a higher DSI_A indicates that *A*'s ability to perform such local scheduling becomes increasingly difficult.

In summary, *DSI* implicitly accounts for overlaps of multiple spaces. Moreover, it captures the idea that the amount of work done can be redistributed `locally' when interferences occur. By basing its foundation on the concept of utilization, graphical methods developed (Riley and Sanvido, 1995, Riley and Sanvido, 1997) through the considerations of workflow can now be aggregated and represented as a quantifiable variable. In essence, *DSI* offers a measure of utilization which serves to bridge the operator's space requirements with the activity's workspaces.

A High-level Indicator For Decision Making

The evaluation using *DSI* would lead to two outcomes for a schedule: “Feasible” or “Infeasible”. An Infeasible schedule indicates that some workspaces have *DSI* values more than 1, indicating that the activity's space demands exceed the supply available. This can consequently be identified as worksite conflict, and resolution through re-sequencing of activities may be necessary. A Feasible schedule is one where all the workspaces are not congested, with respective *DSI* values of less than 1.

Congestion Penalty Indicator, *CPI* is devised as a high-level indicator to allow different feasible project schedules or critical time windows to be evaluated, analysed and compared. The indicator maps the *DSI* activity values generated earlier to a piecewise “disutility” scale. Equation 5 represents the *CPI* for workspace *A* where the congestion tolerance factor, α denotes the Planner's tolerance to worksite congestion.

$$CPI_A = \begin{cases} \dfrac{1 - \exp^{\frac{\mathrm{DSI_A} \cdot \alpha}{C}}}{1 - \exp^{\alpha}} & \text{if } \mathrm{DSI_A} < C \\ \infty & \text{otherwise} \end{cases} \tag{5}$$

The composite congestion indicator CPI_{Total}, is then formulated as the sum total of all the *CPI* values of the activity space entities in the critical time window, as shown

$$CPI_{Total} = \sum_{i \in N}^{N} CPI_i \qquad \text{where N is the set of interacting space entities} \tag{6}$$

Hence, the schedule with lower congestion potential will be denoted by a lower composite CPI_{Total} value, representing a sense of the impact of activity congestion.

Genetic Algorithm Resolution Framework

Mathematical Model For Mitigating Workspace Congestion Via Schedule Repair

Problem Overview

The resolution framework is cast as a schedule repair problem: This means that the activities on the critical path maintain zero float, and are not allowed to extend beyond the early start project makespan; only non-critical activities may be rearranged within the bounds of their available float with the objective of minimizing the overall worksite congestion.

Each workspace is defined by spatial attributes with the temporal characteristics (start and duration) of the activity it references. The decision variables of the problem are the start times of the activities which in turn affect the associated workspaces. The domains of these start times are assumed to be integer and positive.

Precedence constraints refer to the time constraints between some activities, and define a partial order between activities. This is represented within the model as:

$$Start_j + Dur_j \leq Start_k \qquad \forall j, k \in activities \tag{7}$$

Objective Function

The objective function is to minimize the congestion penalty index as shown:

$$fitness = CPI_{Total} + \left(\text{Penalty} \times \sum_i \{Start_i + Dur_i\} \right) \tag{8}$$

A penalty function is added to the objective function in Equation 78 This penalty function is a product comprising the sum of the start of the activities and an arbitrarily small penalty value to create schedule pressure to the early start. This schedule pressure means that the algorithm ranks the solutions with earlier activity start times higher. This ensures a one-to-one mapping of the chromosome space to the solution space, so that two solutions exhibiting the same CPI_{Total} value (fitness value) can be differentiated, with the solution having earlier start times preferred. A small value is arbitrarily chosen as the penalty value. In practice, this is reasonable as it is also reflective of the Planner's preference.

Genetic Algorithm Design

Chromosome Design

The chromosome design is an extension of the current float decoding method (Chan, *et al.*, 1996, Chua, *et al.*, 1997), and consists of two sets of genes: Priority genes and offset genes. The priority genes are randomly generated real-valued keys which encode the priority of the activity based on its topological ordering. Higher valued priorities are chosen for scheduling first. Offset genes are also randomly generated real-valued genes encoding the offset from the earliest possible start within the feasible time window available for each activity.

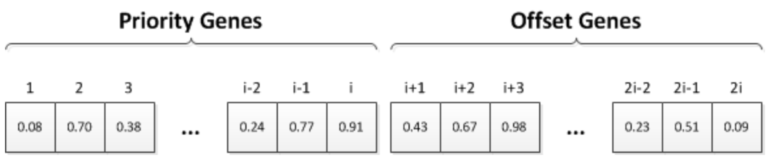


Figure 1. Chromosome Design

The start time of each activity is calculated using Equations 9 and 10, where *j* is the activity, *l* is the set of activities with a lower priority value than *j*, and FT_j is the maximum of the finish time of predecessors of activity *j*.

$$Start_j = FT_j + Offset \times CurrentFloat_j \quad (9)$$

$$CurrentFloat_j = LateFinish_j - \min_l(Finish_l) - dur_j \quad (10)$$

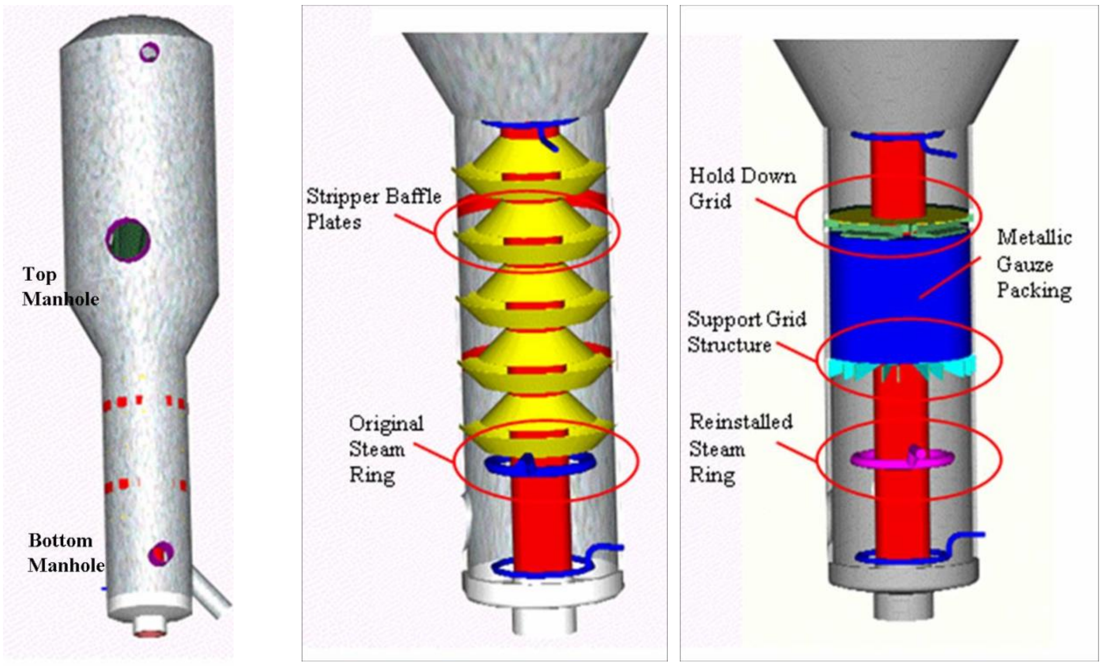
The novelty of the chromosome design and its associated decoding method is that it ensures the precedence constraints are never violated. This allows the genetic algorithm to focus its search within the known feasible regions, enhancing the efficiency of the algorithm.

Other Genetic Algorithm Operators

The two-point crossover operator, mutation operator and binary tournament selection mechanism are used within the genetic algorithm framework. These operators and mechanisms are chosen as they are known to work well for general classes of similar scheduling problems (Back, 1994).

Oil Refinery Refurbishment Case Study

An oil refinery refurbishment example involving the overhaul of an existing oil refinery by a major refinery company is used to demonstrate the validity of the method. The works included the internal modification of a stripper column with an internal diameter of 3.6m. The column has a central core riser 1.2m in diameter. The process involved the removal of a series of 10 baffle plates inside the stripper column by plasma cutting, after which the internal walls of the column were revamped to allow for the installation of two internal grid structures. New metallic gauze packing comprising eight gauze layers would be loaded onto a grid structure at the bottom, and subsequently "held down" by a grid structure at the top. Simultaneously, a new steam ring below the removed baffle stripper plates was to be replaced.



(a) (b) (c)

Figure 2. Scope of Work

To expedite the work, the Planner has suggested a new construction method to allow for concurrent work to be carried out. However, additional preventive/safety measures have been put in place to ensure that the concurrent work can be carried out safely.

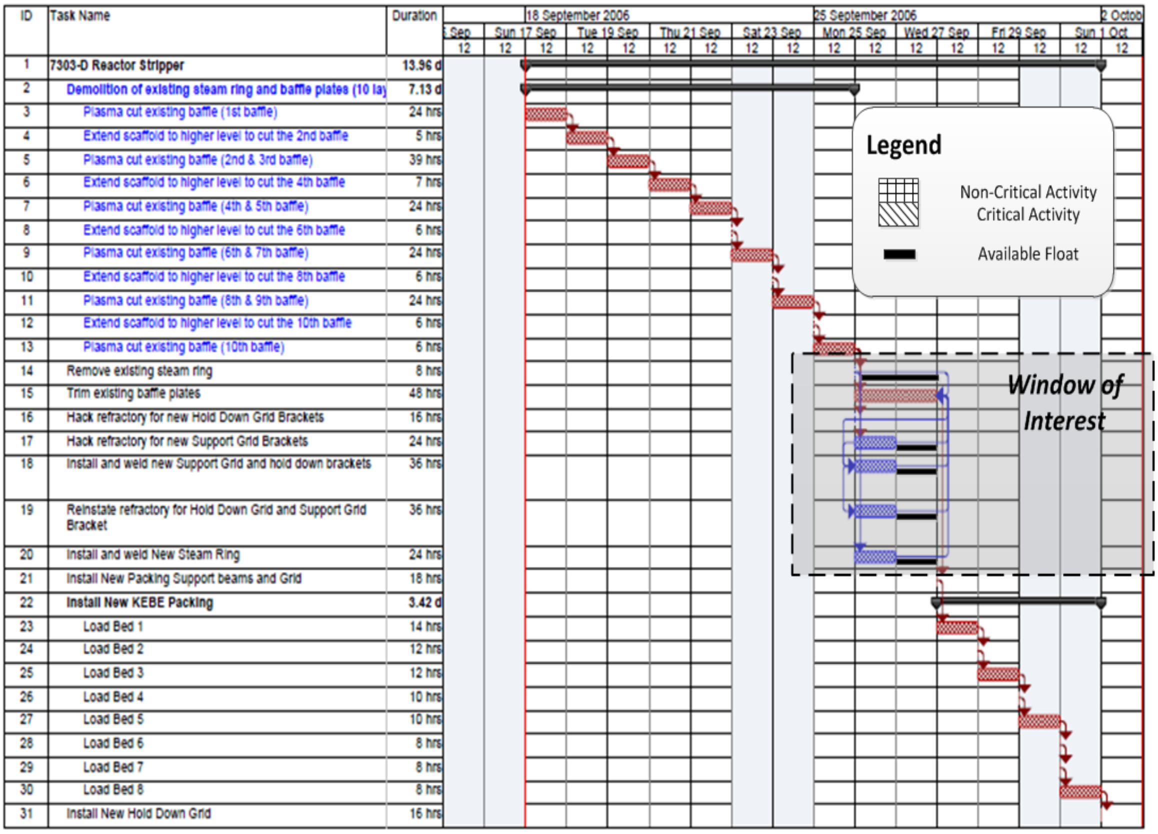


Figure 3. Gantt Chart of Proposed Alternative with Time Window of Interest

Figure 3 shows the Planner's proposed schedule. A window of interest is identified as shown in the figure, where the activities in consideration are not critical, and are thus available for temporal rescheduling. This window consists of 7 activities with variable start times. Only one of the activities is critical (Trim existing baffle plates) while the others have available float. Between these activities, there are 18 workspaces and pathspaces with their properties shown in Table 1. For schedule repair, the activities are to respect the precedence constraints between them, but cannot extend beyond the "Trim existing baffle plates" activity, as this would cause them to be on the critical path and unnecessarily delay the overall project schedule.

In general, the sequence of work involved segregating the workspace into two, an upper workspace containing the Hold Down Grid and its supporting brackets, and a lower workspace containing the Support Grid with its brackets, via a protective system put in place during the "Trim existing Baffle Plates" activity. An opening through the protective system allowed the workers to access the upper workspace as shown in the schematic (Figure 4). The protective system was later removed during the installation activity of the support grid.

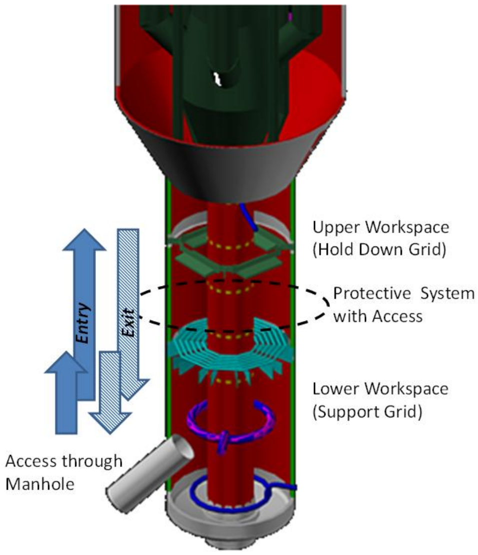


Figure 4. Workspace Access Schematic

Table 1. Properties of Workspace Entities

Workspace Entities	Volume(m^3)	U_t	U_s	ρ
Trim_Baffle_WS	59.3155	1	0.0323	0.1799
Refactory_Remove_WS_Upper Workspace	9.7193	1	0.1975	0.4445
Refactory_Remove_WS_Lower Workspace	9.7193	1	0.1975	0.4445
SupportBracket_WS	10.2213	1	0.1878	0.4334
SteamRing_Removal_WS	7.3704	1	0.2604	0.5104
HoldDown Bracket_WS	10.2213	1	0.1878	0.4334
Trim Baffle_PS	14.6257	0.3	0.1312	0.1985
SupportBracket_PS	18.7906	0.3	0.1021	0.1751
Steamring_Removal_PS	4.8596	0.3	0.3951	0.3443
Refactory_Removal_PS_ Upper Workspace	11.0029	0.3	0.1744	0.2288
Refactory_Removal_PS_ Lower Workspace	18.7906	0.3	0.1021	0.1751
HoldDown Bracket_PS	11.2804	0.3	0.1702	0.2260
Refactory_Install_PS_ Upper Workspace	11.0029	0.3	0.1745	0.2288
Refactory_Install_PS_ Lower Workspace	18.7906	0.3	0.1022	0.1751
Refactory_Install_WS_ Upper Workspace	9.7193	1	0.2011	0.4484
Refactory_Install_WS_ Lower Workspace	9.7193	1	0.1975	0.4445
Steamring_Install_WS	7.3704	1	0.1628	0.4035
Steamring_Install_PS	4.8596	0.3	0.2469	0.2722

The genetic algorithm ran with population size of 500 over 200 generations with the results generated as per Figure 5. The GA was able to improve the solutions found, finally arriving at a schedule with a congestion penalty index of value 2.623. The resultant schedule for the activities in the window of interest is illustrated in the Gantt Chart ofFigure 6. Here, it can be seen that the activities are staggered to reduce the overlapping of the interfering workspaces.

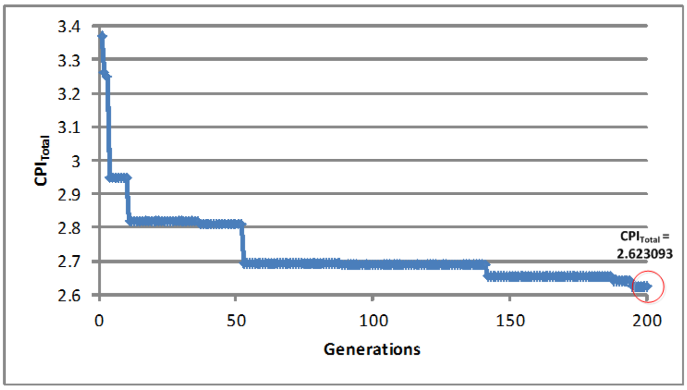


Figure 5. Convergence of CPI_{Total} over 200 Generations in Schedule Repair Case

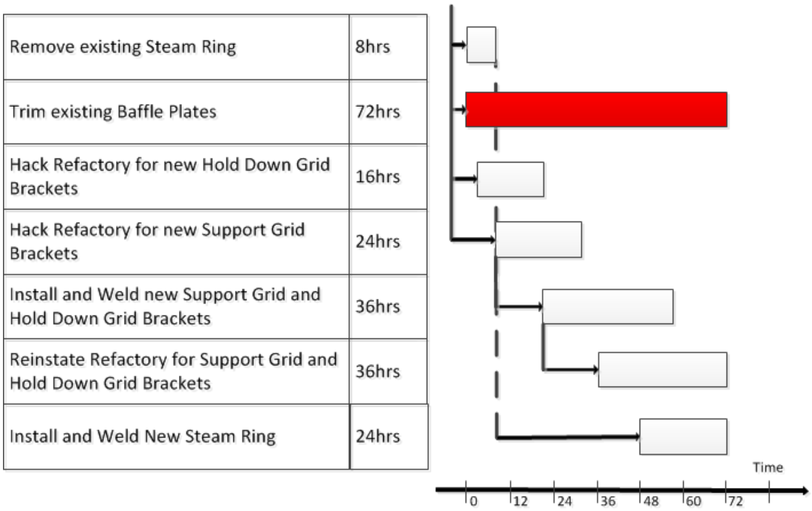


Figure 6. Gantt Chart showing Improved Schedule after 200 Generations

Effect Of Consuming Float On Congestion

The effect of temporally delaying activities in the construction schedule on lowering the amount of congestion onsite will be analysed in this section. Delaying the activities consumes the float times available, but is able to reduce the amount of temporal overlap between the activities, resulting in lower CPI_{Total} computation.

For comparison, the initial early start schedule and the improved schedule are compared to demonstrate how the improvement between the schedules was achieved. Since CPI_{Total} computation is dependent upon the individual Dynamic Space Interference (DSI) indicators (Equation 4), these are used to analyse the effects of temporally delaying the activities. The results are shown in Table 2.

Table 2. Comparison of DSI for Early Start Schedule and Improved Schedule

Workspace Entities	DSI (Early Start Schedule)	DSI (Improved Schedule)	Difference in DSI
Trim_Baffle_WS	0.4523	0.3599	0.0923
Refactory_Remove_WS_Upper Workspace	1.1799	0.7142	0.4656
Refactory_Remove_WS_Lower Workspace	1.2282	0.8909	0.3373
SupportBracket_WS	1.1564	0.9430	0.2134
SteamRing_Removal_WS	1.3238	0.9292	0.3945
HoldDown Bracket_WS	1.0939	0.8288	0.2651
Trim Baffle_PS	0.7507	0.5732	0.1776
SupportBracket_PS	0.6271	0.4710	0.1562
Steamring_Removal_PS	1.2859	0.8966	0.3893
Refactory_Removal_PS_ Upper Workspace	0.7646	0.4617	0.3029
Refactory_Removal_PS_ Lower Workspace	0.8891	0.4614	0.4277
HoldDown Bracket_PS	0.7203	0.5455	0.1748
Refactory_Install_PS_ Upper Workspace	0.7298	0.5256	0.2042
Refactory_Install_PS_ Lower Workspace	0.7145	0.4528	0.2617
Refactory_Install_WS_ Upper Workspace	1.1299	0.8163	0.3136
Refactory_Install_WS_ Lower Workspace	1.1915	0.808	0.3834
Steamring_Install_WS	1.0880	0.6401	0.4480
Steamring_Install_PS	1.0661	0.6189	0.4472

Intuitively, DSI can be thought of as an abstraction of the ratio of space demand to availability placed on a space-time-volume. Recall that the space-time-volume can be thought of as a multi-dimensional volume containing the product of the spatial and temporal dimensions. This means that DSI values exceeding 1 have a greater demand than the availability of the space-time-volume.

From the results of Table 2, the early start schedule is infeasible, and subject to high amounts of congestion. 10 of the 18 work package entities exceed 1. Through shifting the activity start times within their available float, the improved schedule is able to reduce the DSI values. Now, none of the space entities are infeasible with respect to congestion, and reductions of up to 46% are achieved in terms of DSI values. However, some of the work package entities are still indicative of potentially high values of congestion (DSI values more than 0.85), and these require greater attention from the Planner.

The work package entities with potentially high values of congestion are identified as: *Refactory_Remove_WS_Lower_Workspace*, *SupportBracket_WS*, and *SteamRing_Removal_WS*. For the *SteamRing_Removal_WS*, the high DSI value is due to its inherently high utilization (From Table 1, 0.5104). However, for *Refactory_Remove_WS_Lower_Workspace*, and *SupportBracket_WS*, an additional consideration is the amount of spatial-temporal overlap with other interfering entities. As a counter-example, *Refactory_Install_WS_Upper_Workspace* has a higher utilization, but due to its lower amount of interference, has a lower DSI value compared to *Refactory_Remove_WS_Lower_Workspace*, and *SupportBracket_WS*.

In summary, the proposed congestion penalty indicator CPI allows a quantitative measure of worksite congestion to be used within an optimization problem. The resolution of the optimization problem via a genetic algorithm search provides a reasonable schedule which is able to avail a mitigated strategy through the temporal arrangement of the activities to reduce the congestion problem.

Conclusions

The paper extends the work done by the authors, and presents a genetic algorithm resolution methodology for schedule repair to minimize the conflict arising from workspace congestion. The case study illustrates the application of this framework for minimizing workspace congestion, by demonstrating its use on the schedule repair of a congested oil refinery tower. This case study serves as a validation that the indicators proposed previously by the authors for measuring and quantifying workspace utilization is usable as an objective within an optimization framework. Additionally, the case study discusses why the indicator is valid, by comparing the solution found with the initial schedule proposed by the Planner.

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