# Quantification of Spatial Temporal Congestion in Four-Dimensional Computer-Aided Design

David K. H. Chua[1]; K. W. Yeoh[2]; and Yuanbin Song[3]

**Abstract:** This paper further develops the models proposed by prior research in the field of workspace conflict using four-dimensional computer-aided design. The approach developed here analyzes spatial demand and supply from the perspective of construction operators, and a modeling methodology based on spatiotemporal utilization is proposed. The utilization factor model is developed to show that the criticality of the operator's spatiotemporal demand leads to worksite congestion and that congestion is a form of worksite conflict. The interference of other space entities increases the space demand, and this increment is quantified with a "dynamic space interference" index This indicator is developed to identify activity spaces which suffer congestion. A decision making tool, the "congestion penalty indicator," is developed which obtains a schedule-level value for analysis, evaluation, and comparison. Finally, a case study on the refurbishment of an oil refinery column is used to demonstrate the application of the above concepts in successfully identifying a better schedule with respect to on-site congestion.

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## Introduction

The unique nature of construction projects is characterized by the distinctive site constraints imposed. Among these constraints, space planning and management plays a vital role in the construction project management process by identifying and analyzing construction-space requirements within the Architectural, Engineering and Construction community. However, this is often overlooked. The consideration of space management in project management is critical to the design and planning process to achieve efficiency and effectiveness in construction. Incorporating these spatial requirements 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 (Dawood and Mallasi 2006). Examples of space planning include early consideration of various space utilizations in planning site layout, programming high-level construction sequences, and selecting suitable construction methods which can be a vital component of constructability analysis (Song and Chua 2005).

McKinney and Fischer (1998) highlighted the difficulties of using mental models and present scheduling methods to keep track of project information changes. Project information is often recorded on separate documents and tools, making it difficult for planners to mentally visualize changes to the construction sequence (Koo and Fischer 2000). Four-dimensional (4D) computer-aided design (CAD) overcomes this difficulty by incorporating the temporal element in three-dimensional (3D) models. This has the advantage of visually conceptualizing construction plans and facilitating communication between project participants, thus promoting the constructability of a project.

Despite the advantages 4D CAD offers to space planning and management, the main challenge lies in the difficulty of detecting and explaining workspace conflicts during the analysis of a project's construction-space requirements. This is because several competing space requirements do not necessarily lead to conflict.

This paper overcomes the above challenge through the use of the intuitive concept of space utilization. The proposed modeling methodology based on utilization, semantically distinguishes workspace conflict and congestion while showing a relation between the two. A mathematical model is also proposed to quantify spatial and temporal utilization which bridges the low-level operation and higher-level activity spaces. In addition to answering the above challenges, a high-level indicator called *"congestion penalty indicator"* is also introduced to facilitate management-level decision making in evaluating and comparing alternative project schedules.

## Relevant Literature

A large library on workspace conflict detection using $n$D CAD exists. Various methodologies for modeling space utilization requirements have been proposed for the analysis of spatial conflicts, while the idea of interference between workspaces is fundamental to some of the present literature (Akinci et al. 2002a,c; Guo 2002; Riley and Sanvido 1995; Thabet and Beliv-

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eau 1994b). The proposed models provide various means of modeling and analyzing spatial requirements. Previous research has recognized the importance of space as a construction resource and has subsequently incorporated it as an integral part of planning constraints (Thabet and Beliveau 1994b; Winch and North 2006; Zouein and Tommelein 2001).

Thabet and Beliveau (1994a) noted that construction sequences were often constrained by the sequential occupation of workspaces. The utilization of space associated with these sequences is then analyzed from a comparison of space supply and demand. Winch and North (2006) further refined this idea by defining and analyzing the criticality of space in a manner analogous to critical-path method.

Akinci et al. (2002a) introduced a taxonomy of space conflicts which correctly defines conflict as a high-level knowledge construct, encompassing various forms including congestion, unavailability of access, safety hazards, damage of finished products, and design conflict. From this taxonomy, a distinction is made between conflict and congestion, indicating the difference between the two phenomena. This distinction is important from a semantic perspective, as congestion is just one of the many forms of conflict that is evident from spatial construction requirements.

Mallasi (2006) realized that prior research was defined according to two different paradigms: identifying conflict at an activity level and identifying conflict at a high-level project scale. A quantification method was consequently proposed, which bridged the two paradigms by assigning user-defined weightages and pegging the value to the space criticality concept proposed by Winch and North (2006).

Guo (2002) analyzed spatial conflict and temporal conflict separately, introducing two independent interference indicators called the interference space percentage and the interference duration percentage. Additionally, the spatial requirements of movement paths (pathspaces) for workers, equipment, and materials on-site have not been adequately modeled. The inclusion of pathspaces which are abstracted as pathspace requirements (minimum path height and minimum path width) could facilitate the verification of the availability of access to work faces.

Additionally, other research used graphical methods to explain potential congestions in collided areas and detection of interferences among trades. Riley and Sanvido (1997) argued that abstracting workspaces in "solid" CAD models was not truly representative of on-site construction. Instead, they focused on patterns of workflow to characterize their research.

In summary, the different approaches adopted in previous studies were defined on three levels: project, activity, and operative. The project-level analysis looked at conflict on the construction schedule (Thabet and Beliveau 1994b; Winch and North 2006), while the activity-level analysis evaluated conflict through pair-wise comparisons of activity processes in a 3D CAD model (Akinci et al. 2002a,b; Guo 2002). Finally, the operative-level approach studied the movement and workflows of individual workspace users who are commonly the construction operators (Riley and Sanvido 1995; Riley and Sanvido 1997). The current research seeks to abstract space utilization from the operative-level perspective for space planning at activity and project levels.

## Modeling Methodology and Conflict Detection

The modeling methodology used is this paper is based on an ontological description of the actual utilization of universal site space. The universal site space comprises the entire space in a construction site that is relevant for the modeling whether empty or used by construction products, processes, or resources. The ontological representation serves to define the nature of worksite conflicts and forms the basis for quantifying spatiotemporal congestion or conflict of a schedule. The ontological constructs are the space elements within the universal site space which can be mapped onto CAD elements referred to in this paper as "space entities."

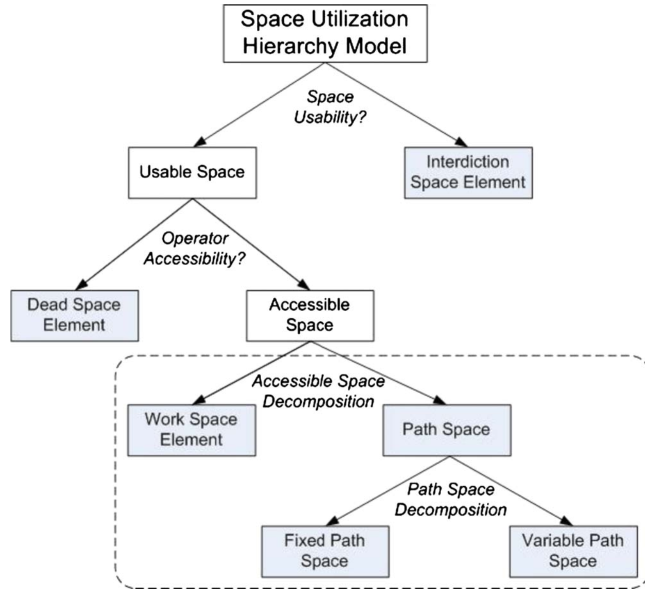


**Fig. 1.** Space utilization hierarchy model

The ontological model or space utilization hierarchy model shown in Fig. 1 is presented as a binary tree with the space element types as leaf nodes. The space element types are characterized in terms of spatial utilization from two perspectives: usability and operator accessibility. From the perspective of usability, interdiction spaces are spaces where no product, process, or resource is allowed to occupy, and are typically specified for reasons of hazards or protection. On the other hand, usable spaces can be further characterized from the perspective of operator accessibility. Dead spaces are generally occupied by a "permanent" physical product component such as slabs and walls, whereas accessible spaces are transiently occupied, often depicting human or operator occupation. A further distinction of accessible spaces between activity workspaces and pathspaces is made. Workspaces are defined as space entities where processes are carried out and are typically adjacent to workfaces, while pathspaces are defined as entities where movement of workers, equipments, and/or physical materials from an initial designated origin to the final destination takes place.

The current paper explicitly models pathspaces as space entities rather than abstract requirements. This paper further distinguishes the pathspace entity into two types: fixed pathspaces and variable pathspaces. Fixed pathspaces may be prescribed for resources of certain characteristics which will require confined routes. Variable pathspaces represent pathspace entities that define various permissible routes for movement. The spatial modeling of variable pathspaces is then the union over the boundaries of all possible pathspace entities. The availability of multiple paths lessens the impact of interference on the encroached path entities.

A taxonomy based on pairwise comparison between different space elements of the space utilization hierarchy model is pre-



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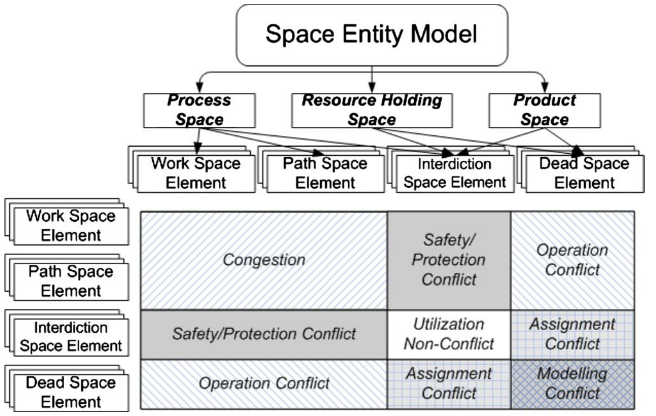


**Fig. 2.** Detection of conflict and congestion

sented in Fig. 2 to distinguish conflict and congestion scenarios. The spatial demand derived from multiple project perspectives of product, process, and resource gives rise to the above space entities depicted in Fig. 2. Products and resource holding areas are generally characterized by a dead space representing its existence in the universal site space and an interdiction space for protection. On the other hand, processes are generally characterized by workspaces, pathspaces, and interdiction spaces for safety.

The interactions between different space entities yield potential conflicts on the worksite. Five forms of conflict are identified in this taxonomy. Modeling conflict exists in dead space-to-dead space interactions, depicting the scenario where physical construction products and/or resources occupy the same time and space. safety/protection conflict exists in interactions between interdiction to workspace and interdiction to pathspace. Such interactions describe situations where operators enter hazardous or protected zones. Operation conflict is the scenario where work operators are obstructed due to the presence of interfering construction products or resources. Assignment conflict occurs when assigned interdiction spaces interact with each other or with dead spaces. Such interactions may not give rise to actual real-world conflict, for example, two protection spaces may overlap without causing any potential hazard or damage but two safety spaces could overlap to present a potential hazard. Last, congestion, as a form of conflict, is observed only between various work performers through the interactions of pathspaces and workspaces.

From the above discussion, the first four forms of conflicts identified can be evaluated immediately through inspection of the spatial entities. An overlap of spaces indicates a conflict. However, with congestion there is a degree of crowding which may not necessarily constitute a conflict and is often the most difficult to detect; the methodology is developed in the remaining sections of the paper.

## Quantitative Model of Congestion

The above discussion illustrates that models to analyze conflict and congestion can be formulated with the inception of the idea of utilization. In fact, this paper defines utilization from a perspective of space and time or space-time-volume and proposes a framework for quantifying worksite congestion from this concept of utilization.

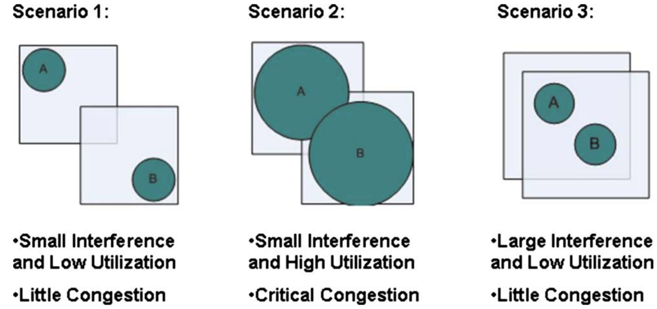


**Fig. 3.** Relationship between utilization and spatial interference

### *Quantification of Utilization by a Space Entity*

The concept of utilization can simply be described as a measure of how much a resource is put in use through the concept of space demand and supply so that worksite conflict is evaluated as a function of such space economics. The operative-level utilization underlies one main thrust of this research and provides a vital link bridging operation space with activity space.

Understanding the concept of operative-level utilization provides a richer and hence, more accurate depiction of congestion and conflict. For example, consider two operators, A and B occupying two separate workspaces which overlap each other. Fig. 3 shows a simplified pictorial summary of three separate scenarios involving A and B. Scenario 1 shows the case of little overlap (interference) of workspace with little space utilization by the operators. The operators could easily work around to ensure that they do not simultaneously occupy the "interference regions." However, for the same interference, a higher utilization of the workspaces would result in severe congestion, as illustrated in Scenario 2. Conversely, where there is a high degree of overlap in workspace, a low utilization can still create a situation of low congestion, as depicted in Scenario 3. The above example emphasizes the importance of considering both aspects of workspace interference and space utilization (at operative level) in analyzing congestion.

A new attribute, utilization factor ρ is introduced which quantitatively measures the level of usage for a given space entity 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:

$$U_S = \frac{\sum \text{operator space}}{\text{total boundary space}} \tag{1}$$

Spatial utilization can be conceived from two perspectives. First, $U_s$ can be considered as the probability of finding the construction operator entity in the entire workspace or path space. Hence, the greater the utilization factor, the greater is the probability of encountering the operator. Second, $U_s$ can be described from the perspective of space economics. Here, the operator space is the demand on the space entity while the total boundary space is the supply available. Hence $U_s$ is the ratio of the space demand to the space supply. These two perspectives make spatial utilization an intuitive measure of the spatial requirements of an activity, allow-



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ing the effect of increasing crew sizes within a single activity to be modeled.

In effect, the concept of spatial utilization can also be extended to the other space entities introduced in the space utilization hierarchy model. Since a physical product or resource can be expected to fully occupy its allocated space, we can assign a value of 1 to the $U_s$ of dead spaces. Similarly, by definition, a hazard or protection space is not expected to have any occupation, so that $U_S=0$ is used for interdiction spaces. By definition, variable path-space entities are aggregations of all possible paths so that $U_s$ is based on the union of the total boundary spaces of all possible paths.

Temporal utilization $U_t$ recognizes that space entities may not always be used throughout the activity's operation time and may be used to describe the intermittent nature of continuous activities. This is especially evident in pathspace entities where the actual usage (utilization) of the space is a fraction of the activity's duration. The temporal utilization may then be expressed as a ratio depicted in Eq. (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)

$$U_t = \frac{\text{actual time utilized}}{\text{total time of activity operation}} \tag{2}$$

The resultant utilization factor ($\rho$) is then defined as the geometric mean of both $U_s$ and $U_t$ which is a reasonable representation of the consequences of spatial and temporal demands and given by

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

where $a$ and $b$ are user-defined weights which allow for unequal emphasis to be allotted to either the spatial or temporal utilization of a single entity. This unequal emphasis could arise from the planner's judgment/priorities.

The mathematical definition of $U_s$ and $U_t$ causes $\rho$ to be bounded between 0 and 1. It follows that space entities with $\rho=1$ are fully used in terms of both time and space. Economically, the spatiotemporal supply is fully taken up by the spatiotemporal demand. Space entities with $\rho=0$ are unutilized as no demand exists.

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, $\rho$ implicitly considers both spatial and temporal perspectives in a single ratio.

### *Quantifying Spatiotemporal Interference*

Worksite conflict and congestion occur due to the interferences between space entities. This section extends the concept of utilization to that of activity workspace interference and quantifies the effects of the interferences from the utilization viewpoint. This will result in an index useful for decision making, allowing project managers to identify congested workspaces.

An index measure called "dynamic space interference" (DSI) is introduced here which quantifies the utilization when interference with other activities is experienced. The measure characterizes the obstruction to the ability to work around time and space constraints imposed by other activities when interference occurs. Another way of conceptualizing DSI is the measure of the extent that a work operator can accommodate the interferences due to other activity workspaces. Eq. (4) formulates the DSI for the Primary Space Entity A, where $\rho_i$ is the utilization factor of $i$ which is an element of a set of interfering space entities, $S_{i\mathrm{A}}$ the overlapping volume between A and $i$, $S_{i\mathrm{A}}$ the spatial volume of A, $t_{i\mathrm{A}}$ the time interval over which A and $i$ overlap, and $t_{i\mathrm{A}}$ the activity duration of A

$$\mathrm{DSI}_\mathrm{A} = \rho_\mathrm{A} + \sum_i \left( \rho_i \times \frac{S_{i\mathrm{A}}}{S_\mathrm{A}} \frac{t_{i\mathrm{A}}}{t_\mathrm{A}} \right) \quad \forall\, i \in \text{interfering space entities} \tag{4}$$

$\mathrm{DSI}_\mathrm{A}$ comprises the utilization of the primary space entity ($\rho_\mathrm{A}$) and an increment component which is a function of the utilization of interfering activity space entities $i$, $\rho_i$, as well as the spatial and temporal infringement into the primary space entity given by $S_i/S_\mathrm{A}$ and $t_i/t_\mathrm{A}$, respectively. $\mathrm{DSI}_\mathrm{A}$ can be abstracted as a space-time-volume of space entity A with an inherent spatiotemporal demand-supply ratio ($\rho_\mathrm{A}$). When an infringement occurs there is an added demand on the same spatiotemporal supply imposed by the interfering entities given by the second term in the equation. Detailed derivation is provided in the Appendix together with an example of its use for multiple space interference.

DSI has no upper bound. However, from the semantic understanding of utilization, 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 activity ($\rho_\mathrm{A}$) is low, the additional demands placed on the space by other interfering activities may cause the activity to experience worksite congestion. At the operative level, the operators of interfering space entities 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 $\mathrm{DSI}_\mathrm{A}$ 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, 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.

## Spatiotemporal Decision Making

### *Need for a High-level Indicator*

The evaluation using DSI would lead to two outcomes for a schedule: "feasible" or "infeasible." An infeasible schedule indicates that some activities 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 resequencing of activities may be necessary. A feasible schedule is one where all the activities are not congested with respective DSI values of less than 1. Here, the value of 1 is chosen as a convenience to represent an upper boundary or critical value. Other DSI values may also be chosen at the planner's discretion to specify meaningful critical values, which indicate the level of utilization that constitutes worksite conflict.



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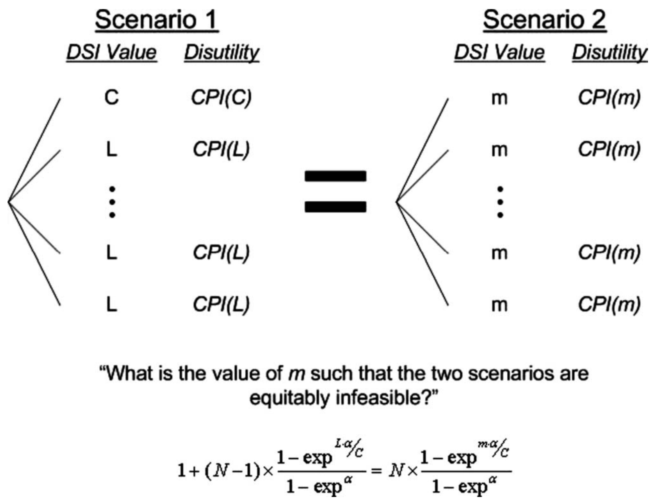


**Fig. 4.** Preference tradeoff for eliciting CPI

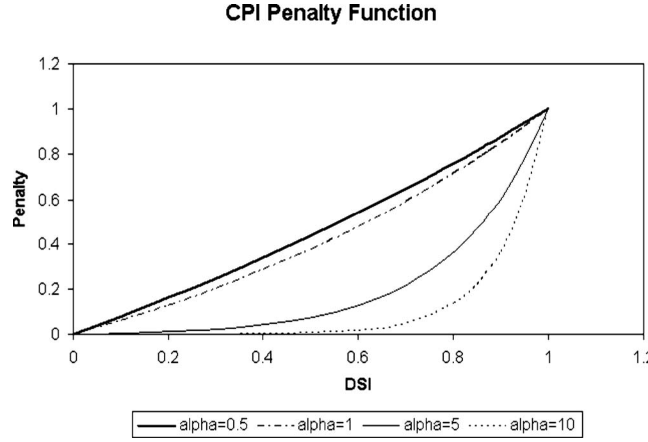


**Fig. 5.** Effect of α on CPI

A high-level indicator [congestion penalty indicator (CPI)] is devised to allow different feasible project schedules or critical time windows to be evaluated, analyzed, and compared. The indicator maps the DSI activity values generated earlier to a piecewise "disutility" scale. Eq. (5) represents the CPI for Space Entity A where the congestion tolerance factor $\alpha$ denotes the planner's tolerance to worksite congestion. The function establishes two reference points at DSI=$C$, where $C$ indicates the user-determined critical value and DSI=0. The first reference point refers to the point of critical utilization of the space entity while the second refers to the point of no utilization. Since the point of critical utilization can be deemed "infeasible," the value of CPI at DSI=$C$ and larger are evaluated as $\infty$.

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

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

$$\mathrm{CPI_{Total}}=\sum_{i\in N}^{N}\mathrm{CPI}_i\tag{6}$$

where $N$=set of interacting space entities. Hence, the schedule with lower congestion potential will be given by lower composite $\mathrm{CPI_{Total}}$ value, representing a sense of the impact of activity congestion.

### *Eliciting the Planner's Congestion Tolerance*

The value of congestion tolerance factor $\alpha$ in Eq. (5) may be elicited from the planner in a similar manner employed in utility theory, by determining the tradeoff between the planner's preferences for two given scenarios. One scenario has a single activity with the critical DSI value $C$ while its interacting activities have low DSI values $L$. The other scenario has all interacting activities with a moderate DSI value of $m$ which is involved in the tradeoff. Since $C$ is the planner's critical utilization level, Scenario 1 is the lower bound of "infeasibility." The trade-off question would then be: "What is the value of $m$ such that the two scenarios are equitably infeasible?" as depicted pictorially in Fig. 4. $m$ is thus the acceptable limit for which the Scenario 2 becomes infeasible like the first.

Equating the $\mathrm{CPI_{Total}}$ of both scenarios as shown in Fig. 4, and rearranging the terms yield Eq. (7) from which the planner's congestion tolerance factor $\alpha$, and thus the planner's inherent attitude toward congestion, can be determined

$$\frac{1}{\exp^{\alpha}-1}[\exp^{\alpha}+(N-1)\exp^{L\alpha/C}-N\exp^{m\alpha/C}]=0\tag{7}$$

The greater the value of $\alpha$, the greater is the curvature, depicting a more "tolerant" attitude as shown in Fig. 5. For the same value of DSI, the corresponding CPI value of a more tolerant curve (larger $\alpha$) is lower than that of a less tolerant curve. The value of $\alpha$ is affected primarily by the planner's choice of $m$. Higher values of $m$ lead to higher values of $\alpha$. This is to be expected, as the higher the planner's tolerance to congestion, the corresponding acceptable limit of DSI values for Scenario 2 is expected to be higher. CPI values less than 1 indicate that the tolerable congestion cutoff identified by the planner has not been reached. From the derivation, it is evident that a schedule with $\mathrm{CPI_{Total}}$ more than 1 is infeasible as determined by the planner's preference. By introducing the utility approach, the $\mathrm{CPI_{Total}}$ provides a consistent scale to evaluate congestion potential subjected to a congestion tolerance.

## Case Study: Internal Refurbishment of Oil Refinery Reactor Column

The following case study is used to show the applicability of the proposed quantification methodology for analyzing congestion. Using the CPI and DSI indicators, the schedules could be improved to lower spatial congestion. The improvement of the schedule with respect to the quantified congestion provides a basis for optimization to be carried out but is beyond the scope of the present study.

The case study involved an overhaul of an existing oil refinery by a major refinery company. The works included the internal modification of a stripper column with an internal diameter of 3.6 m. The column has a central core riser 1.2 m 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 compris-



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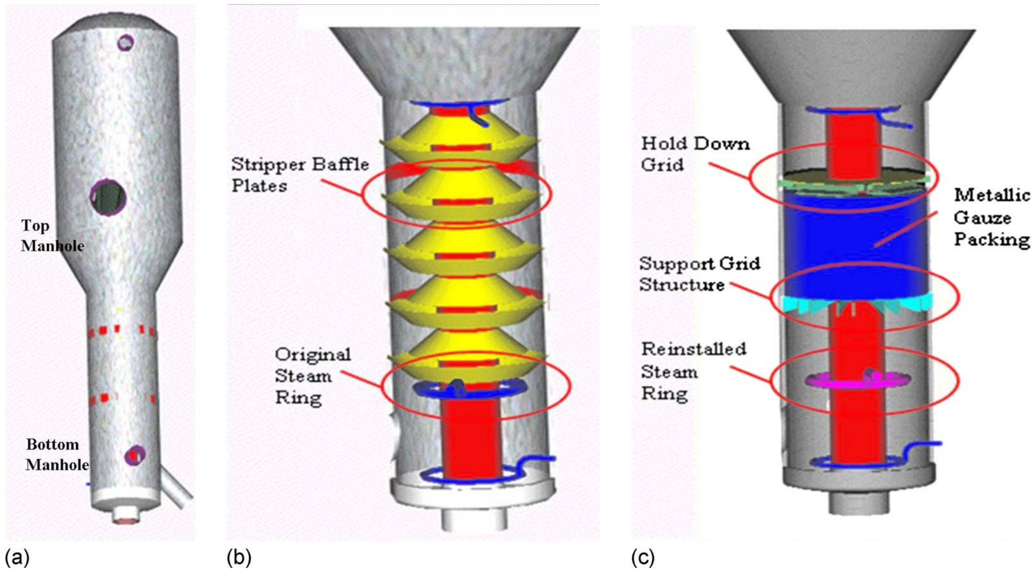


**Fig. 6.** Graphical representation of works: (a) external column; (b) previous internal structure; and (c) refurbished internal structure

ing 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. The works were supervised by a site engineer.

The waste from the plasma cutting was removed through a manhole at the bottom of the column, while the loading of the metallic gauze packing was done through a manhole located at the top of the stripper column. The potential interferences between the access paths through the manholes and the workspaces for installation and removal coupled with the narrow space between the column wall and the internal riser made site conditions extremely cramped with a potential for severe site congestion. The pictorial representation of the works involved is shown in Fig. 6, where Fig. 6(a) depicts the external tower, Fig. 6(b) the existing internal structures, and Fig. 6(c) the refurbished internal structures.

Fig. 7 shows the critical time window of the original schedule for the refurbishment phase. Due to the tight time constraint, work proceeded on a 24-h schedule throughout a 7-day work week. In total, the project was completed in 18 days.

Fig. 8 depicts the space entities of the activities in the critical time window of Fig. 7. The pathspace entities are also included in the analysis although they are not explicitly shown in for clarity. The pathspaces are defined such that they originate from the top and bottom manholes shown in Fig. 6(a) toward their respective workfaces. Various works were simultaneously being carried out: the trimming of the sharp edges of the steel baffle plates and the installation of both the hold down brackets and support brackets. The result of the simultaneous workflows is the existence of multiple interactions between workspace and pathspace components. These interactions lead to the phenomenon of congestion of workspace within the internal column.

The crew size for each activity was four men with each man assumed to occupy an operator space of 0.6 $m^3$. Equal weightage between temporal and spatial utilizations was also assumed. From the estimation of the site engineer, the pathspaces had 30% temporal utilization while the workspaces had 100% temporal utilization. Table 1 shows the calculated DSI for the activities in Fig. 7. The results indicated that the Workspace for the Removal of the Steam Ring (*SteamRing_Removal_WS*) was the activity with the highest DSI value (0.95 for workspace and 0.75 for pathspace) which was indeed perceived on-site to be most congested by the site engineer. The analysis further indicated that this was due to the multiple paths from concurrent activities which infringed the

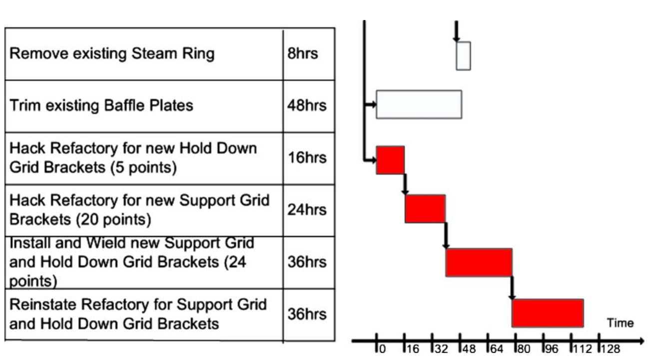


**Fig. 7.** Schedule of refurbishment works

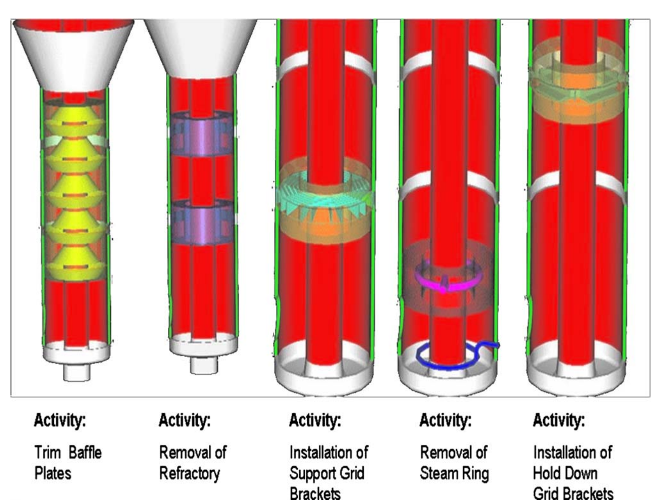


**Fig. 8.** Layout of relevant workspaces



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**Table 1.** Results of Space Interference Factors

| Activity space entity | Description | DSI |
|---|---|---|
| Trim_Baffle_WS | Workspace for trimming of baffle plates | 0.33 |
| Refactory_Removal_WS_1 | Workspace for removal of top refactory for hold down grid | 0.69 |
| Refactory_Removal_WS_2 | Workspace for removal of bottom refactory for support grid | 0.69 |
| SupportBracket_WS | Workspace for installation of support grid brackets | 0.53 |
| SteamRing_Removal_WS | Workspace for removal of steam ring | 0.95 |
| HoldDown_Bracket_WS | Workspace for installation of hold down grid brackets | 0.53 |
| Trim_Baffle_PS | Pathspace for trimming of baffle plates | 0.38 |
| SupportBracket_PS | Pathspace for installation of support grid brackets | 0.32 |
| SteamRing_Removal_PS | Pathspace for removal of steam ring | 0.75 |
| Refactory_Removal_PS_1 | Pathspace for removal of top refactory for hold down grid | 0.38 |
| Refactory_Removal_PS_2 | Pathspace for removal of bottom refactory for support grid | 0.43 |
| HoldDown_Bracket_PS | Pathspace for installation of hold down grid brackets | 0.28 |
| Refactory_Install_PS_1 | Pathspace for installation of top refactory for hold down grid | 0.26 |
| Refactory_Install_PS_2 | Pathspace for installation of bottom refactory for support grid | 0.20 |
| Refactory_Install_WS_1 | Workspace for installation of top refactory for hold down grid | 0.50 |
| Refactory_Install_WS_2 | Workspace for installation of bottom refactory for support grid | 0.50 |
| Trim_Baffle_WS | Workspace for trimming of baffle plates | 0.33 |
| Refactory_Removal_WS_1 | Workspace for removal of top refactory for hold down grid | 0.69 |
| Refactory_Removal_WS_2 | Workspace for removal of bottom refactory for support grid | 0.69 |
| SupportBracket_WS | Workspace for installation of support grid brackets | 0.53 |
| SteamRing_Removal_WS | Workspace for removal of steam ring | 0.95 |
| HoldDown_Bracket_WS | Workspace for installation of hold down grid brackets | 0.53 |

activity space required by *SteamRing_Removal_WS*.

The activity with the longest free float, namely, "trim baffle existing plates," was selected for rescheduling to demonstrate how a better schedule with respect to congestion could be generated. The graphs in Fig. 9 show the effect of varying the start time of the *Trim_Baffle* activity between its early start and late start on the DSI values of the interfering activity workspaces and pathspaces. The activity comprises two different space entities: the *Trim_Baffle* workspace and the *Trim_Baffle* pathspace. The delay of this activity changes the interaction pattern of these space entities with the space entities of the other activities; the other interaction patterns remain unchanged.

For that critical time window with 16 interacting space entities, a critical value of 1 and tolerance limit of 0.7 yields a congestion tolerance value of $\alpha=9.24$ that would represent the site engineer's preference. Varying the start time of the *Trim_Baffle* activity from its early start to late start, results in varying CPI values for the 16 interfering activity space entities. Fig. 9 shows the composite $\text{CPI}_{\text{Total}}$ for the critical time window. It is evident from Fig. 9 that a minimum $\text{CPI}_{\text{Total}}=0.28$ can be obtained if the *Trim_Baffle* activity is delayed 51 h after its early start ("Hour 51") as compared to the maximum $\text{CPI}_{\text{Total}}=0.94$ which occurs 39 h after the early start ("Hour 39"). This can be justified by analyzing the interactions of the activities at Hour 51 and Hour 39. At Hour 39, eight other activity space entities interfere with the *Trim_Baffle* activity, while at Hour 51 only the "installation of support grid and hold down brackets" and the reinstate refactory activities are affected.

The CPI value quantifies the level of congestion as a composite index, and demonstrates the idea that rearranging the activity floats can minimize activity interactions and consequently reduce congestion. CPI can be used as a decision making tool to evaluate projects from a congestion perspective. Moreover, it offers the opportunity for simple optimization techniques to be employed to generate improved schedules in critical time windows.

## Conclusions and Future Work

An ontological description of space utilization is introduced from which a taxonomy was developed which specifically distinguishes various classes of conflict, of which congestion may be the most difficult class to analyze. Simply considering spatial overlaps of workspaces is inadequate for classifying congestion as a form of conflict. Arising from this, a few key ideas are proposed. First, the concept of utilization describes the spatiotemporal supply and demand, and may be abstracted by a space-time-volume. In this way, the usual space economics has been extended to comprise a fourth dimension of time explicitly in the analysis of congestion conflicts. Second, the operative-level utilization perspective is important to distinguish spatiotemporal congestion of overlapped workspaces. The operation space determines the minimum space necessary for an activity to be executed. This operative-level utilization perspective is an abstraction of the workflow in the activity and provides the basis for the characterization of both spatial and temporal utilizations. The above ideas lead to the development of two indicators in the proposed approach: DSI and CPI.

While DSI measures the local workaround, CPI allows the schedule in a critical time window to be evaluated, analyzed, and compared. It is derived analogous to the utility theory. Similarly, it incorporates a preference trade-off to elicit a tolerance value, which determines the "disutility" of congestion to the planner. The CPI indicator is then the sum of the disutility values of each



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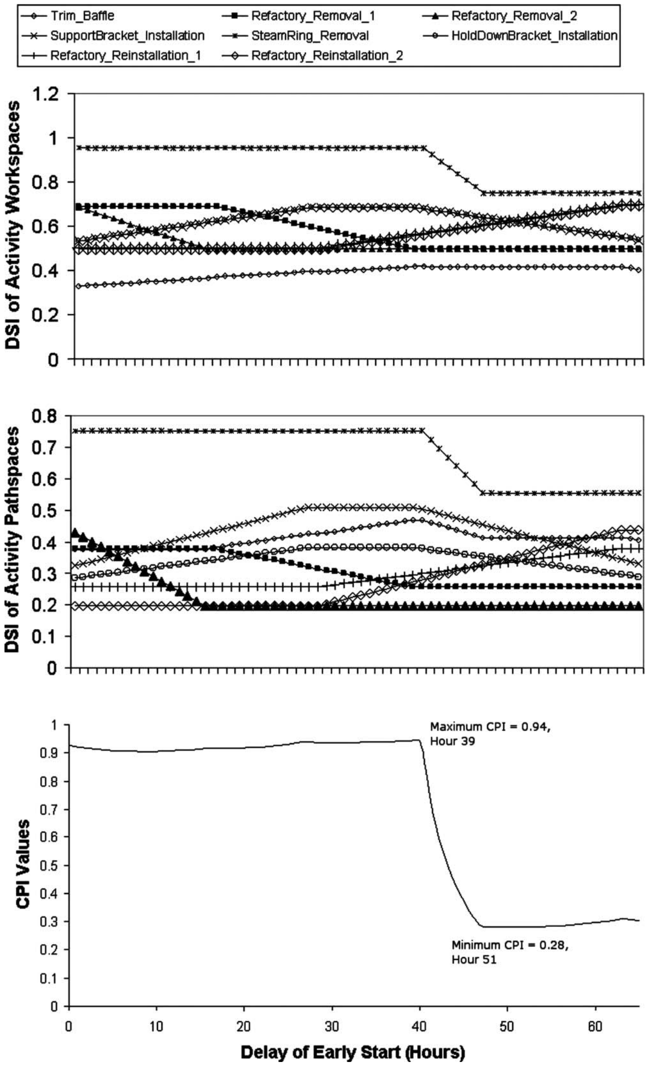


**Fig. 9.** Effects of delaying the ES of *Trim_Baffle* workspace

space entity in the critical time window. The case study demonstrates the application of the above indicators, and illustrates the impact of utilization in identifying congestion as a form of conflict.

The proposed indicators can be used to complement current constructability analysis involving 4D CAD. 4D CAD offers an effective medium to visually conceptualize construction plans, as well as visualizing changes to the construction sequence. The indicators then allow the effects of congestion to be captured in current 4D CAD models as part of the constructability analysis as well.

One basic assumption of the indicators is that the operators are able to accommodate one another, achieving a "compromise" which allows them to achieve local work around. This compromise is reflected in the $U_s$ and $U_t$ values which "averages" the utilization in the space entity. This method captures the utilization of activities without having to deal with the details of the location of the operators, while enabling the abstraction of information at the higher activity level. This assumption may be challenged and addressing this forms the basis for future work which could involve stochastically analyzing the location of the operator and determining its effects on the degree of interference between activities.

Another extension to the current work could include the development of schedule optimization techniques under spatiotemporal constraints using the proposed quantification methods. Other extensions could involve experimental validation of the relative importance of temporal and spatial effects on congestion characterized by weights $a$ and $b$ in Eq. (3) and combining productivity studies with congestion modeling through an integrated analysis of the effects of "crew overmanning" and "trade stacking."

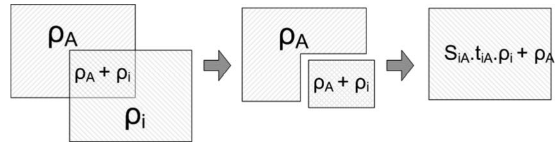


**Fig. 10.** $\mathrm{DSI_A}$ for overlapping entities


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## Appendix. Derivation of DSI

The derivation of DSI is based upon the abstraction of a space-time-volume of a space entity (in this case, A), with an inherent spatiotemporal utilization $\rho_A$. A space-time-volume is defined as the product of space and time such that time is treated as a spatial dimension. Imagine another space-time-volume from a set of interfering space entities, $i$ with $\rho_i$ infringing upon the space-time-volume of Space Entity A, as shown in Fig. 10. This figure simplifies the explanation by considering only two-dimensional (2D) abstractions but 3D abstractions can be extended. The overlapping portion with space $S_{iA}$ and time $t_{iA}$ experiences two values of utilization $\rho_A$ and $\rho_i$. The demand from the additional utilization is then evenly distributed as shown in Fig. 10.

The additional demand from an interfering entity is given by

$$S_{iA}t_{iA}\rho_i$$

Hence, the total demand from all the interfering activities on the Space Entity A is given by

$$\rho_A S_A t_A + \sum_i \rho_i S_{iA} t_{iA}$$

Therefore, for a given spatiotemporal supply $S_{iA}t_{iA}\rho_i$, the final form of the equation for $\mathrm{DSI_A}$ as in Eq. (4) may be derived as follows:

$$\mathrm{DSI} = \frac{\text{total spatiotemporal demand}}{\text{spatiotemporal supply}} = \frac{\rho_A S_A t_A + \sum_i (\rho_i S_{iA} t_{iA})}{S_A t_A}$$

$$= \rho_A + \sum_i \left( \rho_i \frac{S_{iA}}{S_A} \frac{t_{iA}}{t_A} \right) \tag{8}$$

Fig. 11(a) demonstrates the above concept through a simplified 2D abstraction of multiple workspace overlapping one another. Here, Activity Workspaces A, B, and C overlap one another, and the overlapping areas $S_{AB}$, $S_{AC}$, and $S_{BC}$ shown indicate the interferences between A-B, A-C, and finally B-C, respectively. Fig.




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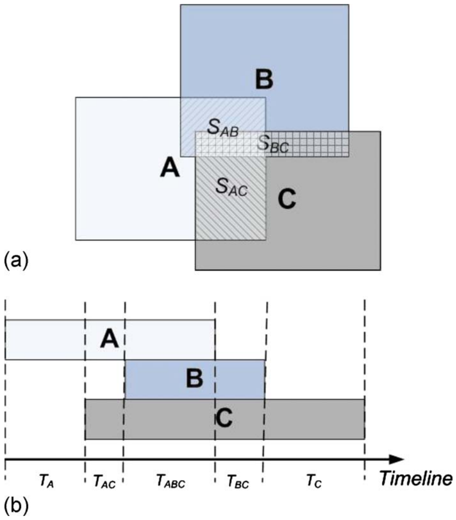


**Fig. 11.** Illustration of $\mathrm{DSI}_{\mathrm{A}}$ for multiple overlapping entities: (a) spatial overlapping of entities; (b) Gantt chart showing temporal overlapping of entities

11(b) shows the same activities on a Gantt Chart illustrating the temporal overlaps of the activities. Five temporally overlapped intervals are identified as shown in Fig. 11, each representing a discrete time interval with a homogeneous activity configuration. Using Activity A with volume, $S_{\mathrm{A}}$ and duration $\mathrm{Dur}_{\mathrm{A}}$ in Fig. 11, as an example, $\mathrm{DSI}_{\mathrm{A}}$ can be evaluated using Eqs. (8) or (4) as follows

$$\mathrm{DSI}_{\mathrm{A}} = \rho_{\mathrm{A}} + \rho_{\mathrm{B}}\left(\frac{S_{\mathrm{AB}}}{S_{\mathrm{A}}} \times \frac{T_{\mathrm{ABC}}}{\mathrm{Dur}_{\mathrm{A}}}\right) + \rho_{\mathrm{C}}\left(\frac{S_{\mathrm{AC}}}{S_{\mathrm{A}}} \times \frac{T_{\mathrm{AC}} + T_{\mathrm{ABC}}}{\mathrm{Dur}_{\mathrm{A}}}\right) \quad (9)$$

## Notation

*The following symbols are used in this paper:*

$C$ = user-determined critical value of congestion;
$\mathrm{CPI}_{\mathrm{A}}$ = CPI of Entity A;
$\mathrm{CPI}_{\mathrm{Total}}$ = total CPI for schedule comparison;
$\mathrm{DSI}_{\mathrm{A}}$ = DSI of Entity A;
$\mathrm{Dur}_{\mathrm{A}}$ = duration of Entity A;
$L$ = arbitrary low value of DSI;
$M$ = arbitrary moderate value of DSI
$N$ = number of space entities;
$S_{\mathrm{A}}$ = spatial volume of Entity A;
$S_{\mathrm{AB}}$ = overlapping area of Entities A and B;
$S_{\mathrm{AC}}$ = overlapping area of Entities A and C;
$S_{i,\mathrm{A}}$ = overlapping volume between Entities A and $i$;
$T_{\mathrm{ABC}}$ = temporal overlap of Entities A, B, and C;
$T_{\mathrm{AC}}$ = temporal overlap of Entities A and C;
$t_{\mathrm{A}}$ = temporal duration of Entity A;
$t_{i,\mathrm{A}}$ = temporal overlap between Entities A and $i$;
$U_s$ = spatial utilization;
$U_t$ = temporal utilization;
$\alpha$ = congestion tolerance factor; and
$\rho_i$ = utilization factor of space Entity $i$.

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