ISSP: Integrated Schedule and Space Planner

Ass. Prof. P. P. Zouein, ASCE AM and D. Shedid

Lebanese American University, Department of Industrial Engineering and Department of Computer Engineering

pzouein@lau.edu.lb

Abstract: *This paper presents the ISSP system for activity scheduling and site layout planning under spatial constraints. The importance of tying schedule and layout data has been established and dealt with extensively in the literature. Many decision-support tools were developed to assist planners in space scheduling but these were limited to providing the user with a platform that ties spatial and temporal data in the project and left it up to the user to decide on positions of resources and schedule adjustments to solve spatial conflicts that may arise in the process of constructing site layouts over time. The ISSP system, presented here, provides a graphical user-interactive interface with underlying layout and scheduling algorithms that construct feasible layout and schedule solutions under 2-dimensional spatial constraints between resources. The underlying algorithms optimize positions of resources by minimizing handling and rehandling costs of these on site. ISSP can also be integrated with existing scheduling and layout planning decision-support tools to enable users to override the system's decisions to reach "user-satisfycing" solutions.*

Key Words: *site layout planning, dynamic layout, space scheduling, graphical user interface, smart models*

INTRODUCTION AND BACKGROUND

The importance of tying schedule and layout data has been established and dealt with extensively in the literature. Tommelein and Zouein (1993) termed the problem of allocating space to resources governed by a construction schedule, and conversely, changing the schedule (i.e., changing activity precedence, resource selection and allocation, or activity durations) when space availability is inadequate, as the space scheduling problem. Indeed, space often becomes scarce when multiple activities occur at the same time in close proximity. Numerous material handling paths and storage spaces contribute to the challenge of finding adequate space to execute tasks. Space scheduling is needed to avoid spatial conflicts and interferences between stored material, equipment, and crew work areas.

Space scheduling has received more attention in recent years because schedule compression, now a common project requirement, leads to increased spatial interference among resources on site. Inadequate work space and interference during travel can result in access blockage, congestion, safety hazards, and risk of damaging the end product thereby creating waste in the workflow and diminishing productivity (Fischer and Tatum 1997, Akinci et al. 1998). Many decision-support tools (Morad et. al. 1992, Tommelein and Zouein 1993, Riley and Sanvido 1997, Thabet and Beliveau 1997) were developed to assist planners in space scheduling but these were limited to providing the user with a platform that ties spatial and temporal data in the project and left it up to the user to decide on positions of resources and schedule adjustments to solve spatial conflicts that may arise in the process of constructing the site layouts. Some of these tools provide learning lessons from understanding reasons for failure (Choo and Tommelein 1999). Other (Akinci et al. 1998) tools for space management developed a framework to formally assess schedule impacts of time-space conflict analysis based on a 4D production model and adopted an analysis approach to space management. Existing systems also differ based on the way they model and represent spaces. Riley and Sanvido (1997) represented activities space requirements as any combination of twelve unique types of spaces: work elements, layout area, unloading area, material path, personnel path, storage area, prefabrication area, work area, tool and equipment area, debris path, protected area, and hazard area. Akinci et al. (1998) built on previous research studies done in representing activity space requirements over time and automated the generation of work space requirements over time.

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This paper presents the ISSP system, an integrated Schedule and Space Planner. ISSP models activity space requirements as any combination of three different types of spaces that could be used to represent the space area requirements for material storage, equipment and tools area, work and crew production areas. These spaces differ in the way their areas vary over time as the corresponding activity progresses. ISSP combines the advantages of a user-friendly environment for data entry, display and ease of manipulation to the power of an intelligent decision-support tool that is capable of suggesting schedule and layout solutions to space scheduling problems. ISSP underlying algorithms optimize positions of resources by minimizing transportation and relocation costs of resources on site.

THE ISSP MODEL

ISSP provides a graphical and interactive interface with underlying layout and scheduling algorithms that construct feasible layout and schedule solutions under 2-dimensional geometric constraints on acceptable positions of resources. ISSP allows its user to define project data in the form of activities and resources needed for their performance. ISSP provides up to four different categories of resources based on differences in their space needs. It also allows defining activities that can be performed with different durations and thus different sets of resources. The models used in ISSP for representing resources, activities, time, and space are described in details in Zouein and Tommelein 1999, 2001. The following sections describe their implementation in ISSP.

Assumptions

In ISSP, the term resource describes any of a wide variety of physical or regional objects that occupy space on a construction site. Physical objects have a volume, regional objects delineate only a two-dimensional area. A resource might refer to a building or a facility to be constructed, an obstacle such as a tree or a trench, a road, a laydown or a staging area, a piece of equipment, a warehouse, a work area, construction material, etc. All resources are modeled as 2-dimensional objects with rectangular shapes. They have fixed dimensions for the duration of a layout but dimensions may vary from one layout to another. A resource position is uniquely defined for a given layout by its orientation (0° if the long side of the resource is parallel to x-axis and 90° otherwise) and the x- and y-coordinates of the centroid of its corresponding rectangle.

Resources

ISSP differentiates between resources based on how their space requirements vary with construction progress. Four different classes of resources are used to describe the space requirements of resources:

- Profile-A can be used to model the area requirements of resources whose space needs depend on the progress rate of a construction activity. The total quantity of the resource needed by the activity is assumed to be available on site when the activity starts and the area on site occupied by the resource decreases at a rate proportional to the activity progress rate. For this profile, ISSP requires as input the area needed to accommodate the resource when the activity starts and a length to width ratio used by ISSP during runtime to compute the length and width of the space occupied by the resource at any point in time during the progress of the activity.

- Profile-B can be used to model the area requirements of resources that depend on a construction activity but whose space needs remain constant over the activity duration. The space area occupied by the resource is assumed constant for a given activity duration or progress rate of the activity. This area is assumed to be smaller if the activity progresses at a faster rate. For this profile, ISSP asks the user to input a length-to-width ratio needed to compute the dimensions of the area occupied by the resource for different activity durations. Since a Profile-B resource has different area requirements for different activity durations, the area occupied by the resource for a given duration of the activity is specified in the activity interface for different resource levels (see next section).

- Profile-C can be used to model the area requirements of resources that are associated to one or more construction activities and have fixed dimensions that do not vary with activity progress. ISSP asks the user to input the dimensions, i.e., length and width of the area needed to accommodate this resource.

- Profile-D can be used to model the area requirements of resources that are independent of activities such as demarcated areas, obstacles, and trailers. ISSP asks the user to enter the length and width of this resource and the time period for which it exists on site.

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Figure 1 shows ISSP interface for inputting resource data for Profile A and D resources. The user can assign a fixed position on site for any type resource defined by the user by specifying the x- and y-coordinates of the upper left corner of the rectangle representing it. The user can also assign to resources a relocation weight (see Fig. 1) which represents the cost or penalty for moving the resource from one layout to the next. The user can assign any value from 0, indicating no cost for relocation, to a very large number indicating that the cost of moving this resource is prohibitive.
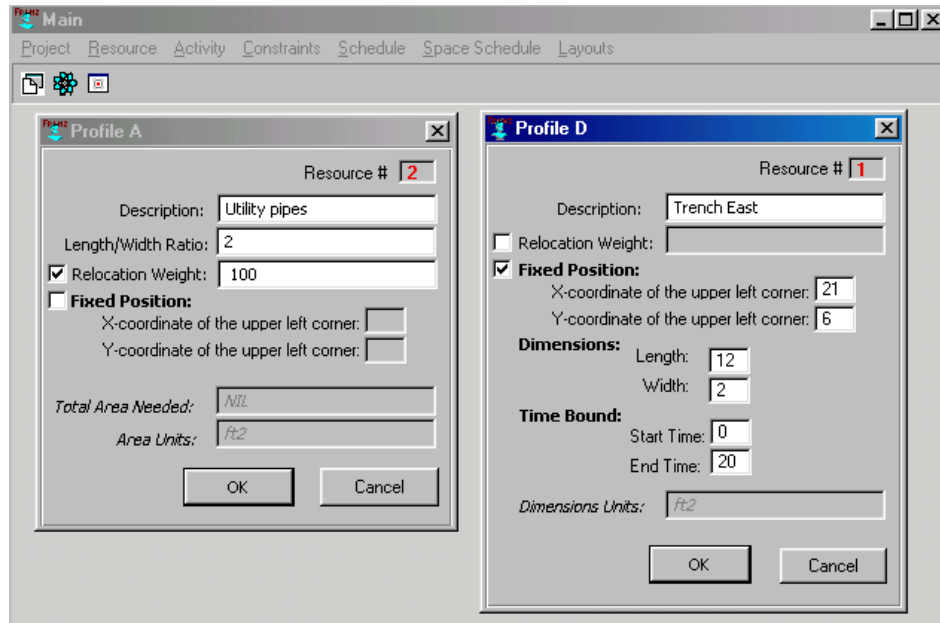

Figure 1: ISSP Interface for Inputting Profile-A and Profile-D Resource Data

Activities and Resource Levels

Figure 2 shows ISSP interface for defining new activities. The user can define precedence between activities by selecting from a list of previously defined activities in the system. The user can also define up to three alternative durations for the activity through defining alternative sets of resources for its performance described in three resource levels: minimum, maximum and normal resource level. Note that the minimum and maximum levels correspond to the longest and shortest durations of the activity respectively. The user can define the resources used by the activity for a resource level by selecting it. For a particular resource level the user can select from the lists of Profile-A, -B and -C resources the ones used by the activity for its performance. Resources are listed by notation that ISSP assigns to them when first entered by the user. The user can click on any resource to get details on its description or other attribute (see in Fig. 2 the *Edit* window of resource B-4 which appears as a result of clicking on B-4). In addition to resources, the user is asked to input a duration for the activity if performed at this resource level. The user assigns a resource level at which the activity will be initially performed. ISSP may change the resource level of an activity if changes in the schedule are needed to resolve spatial conflicts.

Constraints

The constraint menu item can be used to define closeness preference relationships between resources and 2-dimensional location constraints on their relative positions on site. When the user selects any of the sub-menu items listed under the menu item constraints, the user is prompted with a set of time frames to select from and for which constraints should be defined. This is so because ISSP allows the user to define different constraints between a pair of resources for different time frames. The time frames shown represent the smallest time intervals demarcated by the arrival or departure of resources to and from site. A time frame for the period starting at time k and ending at time l is denoted PTF-k-l.

The "proximity weights" sub-menu item provides the user with a window entitled proximity weights (shown in Fig. 3) and a table listing vertically and horizontally all resources that co-exist on site for the time period selected by the user. The user can use this table to enter any value greater or equal to zero to indicate proximity relationships or closeness desirability between pairs of resources. A large value means

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that the two resources should be placed in close proximity and therefore the distance separating them in the layout should be minimized. A value of zero means no interaction between the two resources and thus the distance separating them is irrelevant. To indicate that two resources should not be close to one another location constraints should be defined between them to restrict the distance separating them to be no less than some user-specified value.
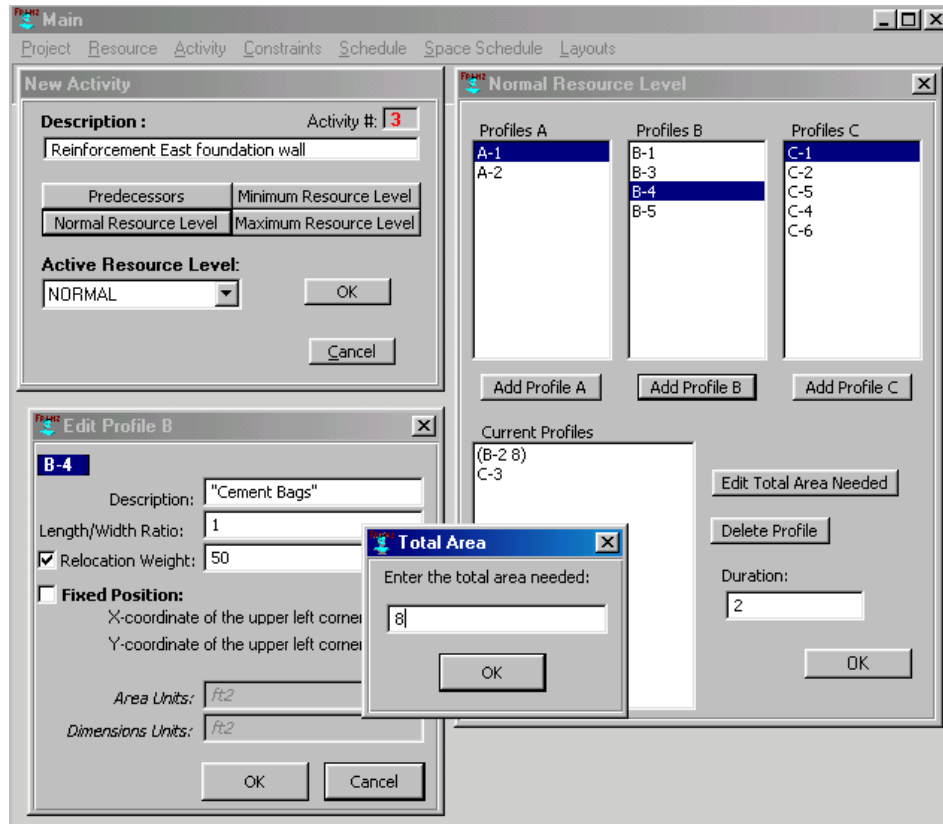

Figure 2: ISSP Interface for Inputting Activity and Resource Levels Data

The "Location Constraints" sub-menu item provides the user with a listing of all types of 2-dimensional constraints that can be defined between pairs of resources (see Fig. 3). Following is a brief description of each:

- *In-Zone* constraint can restrict the possible positions of a resource to be within the boundaries of another resource that represents a zone (e.g., a fenced-in or laydown area)
- *Minimum (maximum)* distance constraints limit the distance between the facing sides of 2 resources (e.g., C-1 and D-3 as shown in Fig. 3) in the x- or y-direction to be greater (or less) than a specified distance (say 0 unit distance in the x-direction as in Fig. 3 to indicate that they should be adjacent in the layout).
- Orientation constraints specify that a resource be to the *North* (*South, East, West*) of some reference resource.
- *Parallel* (*Perpendicular*) constraints limit 2 resources to have their long sides parallel (perpendicular) to one another.

Location constraints must be satisfied for resources' positions to be considered feasible.

Note that resources are listed by their notation, the user however can double click on any resource to access any information regarding it. Fig. 3 shows the edit window of resource C-4 open as a result of double clicking on it.
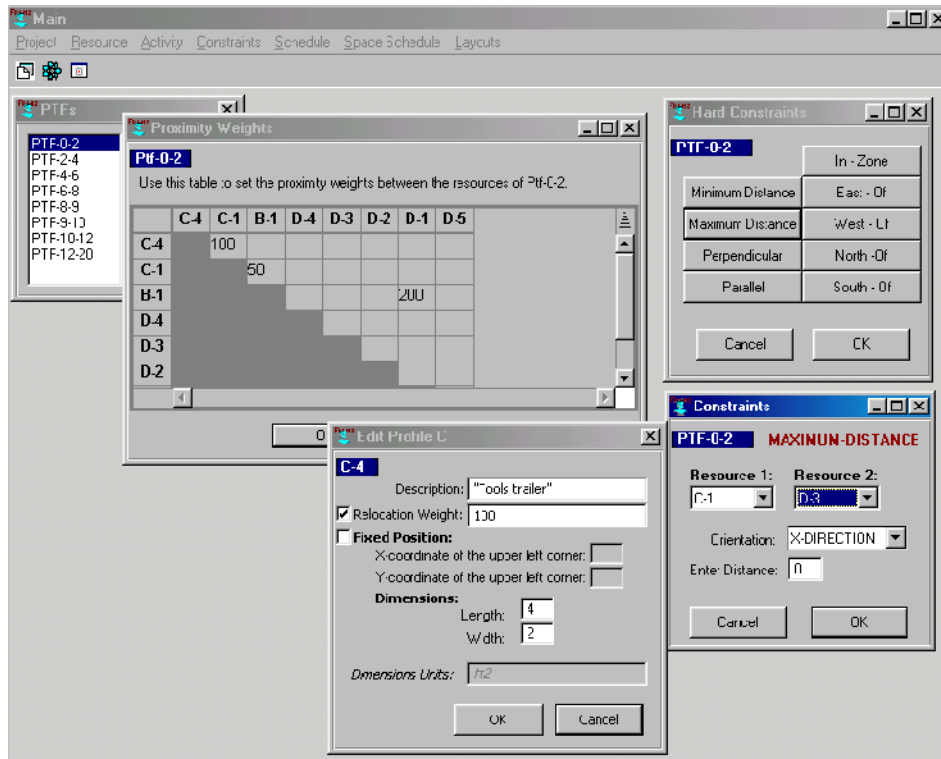
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Figure 3: ISSP Windows for Inputting Proximity Weights and Location Constraints

ISSP UNDERLYING ALGORITHMS

There are a number of algorithms embedded in ISSP that automate the construction of the site layouts and adjust the activity schedule to resolve spatial conflicts that arise during layout construction because of limited space. The static layout algorithm attempts to construct feasible layouts that minimize resource transportation costs for a user selected time frame. That is, it solves for resource positions that satisfy location constraints between resources and that minimize the sum of the weighted distances separating them in the layout. The dynamic layout construction algorithm constructs a sequence of time-varying layouts. The algorithm attempts to reallocate space on site to resources by minimizing the sum of both transportation and relocation costs of resources. The space scheduling algorithm checks and adjusts a given schedule to ensure that it is "space feasible". That is it constructs the dynamic layout for the entire project duration and applies time-space tradeoffs strategies to resolve spatial conflicts identified during dynamic layout construction. The algorithms used for layout and space schedule construction are described in details in Zouein and Tommelein 1999, 2001. Next is a description of their implementation in ISSP.

Scheduler

The user selects the menu item *Schedule> Initialize* to invoke the scheduler in ISSP. The scheduler performs standard CPM computations to determine early and late start and finish dates of activities based on assigned activity duration in the active resource level and precedence relationships between activities. The scheduler computes also activity floats both total and free float. Activity floats are used to prioritize activity selection for resolving spatial conflicts when encountered by ISSP during dynamic layout construction.

Static Layout

The user selects the menu item *Layout> Static Layout Construction* to construct the static site layout for a given time frame. At this selection, a window showing a listing of all PTFs is displayed for the user to select from the time frame for which he/she wants ISSP to construct the static layout. The static layout construction algorithm used by ISSP to construct the layout for a user selected time frame is described in detail in Zouein 1995, and Zouein and Tommelein 1999. The algorithm starts by calling a constraint satisfaction and propagation algorithm to determine sets of possible positions (SPPs) for all resources that coexist on site in the selected time frame. Sets of possible positions of a resource are all feasible positions

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of the centroid of the rectangle representing it that satisfy the location constraints between the resource and other resources on site. The algorithm then starts from the set of feasible positions and singles out a position for each resource one at a time. The single position (say of resource *i*) should minimize distance-based proximity and relocation cost (Z_t) in the layout *t* that spans the time frame of the user-selected PTF-k-l.

$$Z_t = \bullet \bullet w_{ij} \times d_{ij} + \bullet \ w'_i [d_{t(t-1)} + d_{t(t+1)}] \tag{eq. 1}$$

W_{ij} represents the proximity weight between resources *i* and *j* that coexist on site in layout *t*. The first term represents the sum of all proximity costs between pairs of resources *i* and *j* weighted over the distance separating *i* and *j* in *t*. The second term represents the sum of the relocation of costs of all resources existing in *t*. Relocating a resource say *i* means assigning to *i* a position in *t* that is different from the one assigned to it in previously constructed layouts that directly precede (layout *t-1*) or succeed (layout *t+1*) layout *t* in time. Relocation cost of *i* is computed by multiplying the relocation cost of resource *i* by the distance separating its positions in the preceding and succeeding layouts.

The algorithm selects resources according to two heuristics: (1) resources with larger relocation weights and (2) resources with greater interaction with other resources as represented by the sum of their proximity weights. Rules for breaking ties between resources are:

1. Select first resource in the list of resources
2. Select a resource at random
3. Select a resource that has been positioned in a previously constructed layout.

Alternative layouts for a given PTF can be obtained by applying the algorithm with different resource selection rules or with different randomly selected positions when more than one position minimizes Z_t.

If ISSP fails to find a SPP for one or more resources at the end of the constraint and satisfaction phase or if ISSP fails to instantiate a feasible set of positions for all resources in the selected PTF, then ISSP returns a message to the user indicating that layout construction has failed to find a layout solution for the selected PTF. If the user wants ISSP to solve the conflict that lead to no solution then he/she has to select the *Space Schedule Construction* menu explained next.

To view the layout of any PTF or to view the SPP of resources at the end of the constraint satisfaction and propagation phase, the user can select the menu item *Layouts>View* and then a particular PTF from the list of PTFs for which a layout was constructed. This feature is explained next.

Dynamic Layout

Selection of the menu item *Layouts>Dynamic Layout Construction* pops the user with a window listing all PTFs generated by ISSP from the current project schedule. At the user selection of one or several PTFs, ISSP starts the construction of the dynamic layout which consists of creating a sequence of layouts each spanning the duration of a PTF. Each layout in the sequence is constructed so that eq.1 is minimized and so that the overall sum (Z) is also minimized. In this mode, eq.1 is slightly modified as shown in eq. 3:

$$Z = \bullet \ Z_t \tag{eq. 2}$$

$$Z_t = \bullet \bullet w_{ij} \times d_{ij} \times \bullet_t + \bullet \ w'_i [d_{t(t-1)} + d_{t(t+1)}] \tag{eq. 3}$$

Where $\bullet_t$ is the length of time over which layout t extends. Eq. 1 was modified to reflect the nature of flow in a dynamic environment considering the possibility of relocating resources and where proximity costs are weighted over not only distance but also time.   Dynamic layout construction may fail to find a layout solution for any of the PTFs for the reasons highlighted above. To resolve the spatial conflict, the user can choose to run ISSP in *Space Schedule Construction* mode which is explained next.

Space Schedule Construction

Space Schedule construction is initiated by selecting the menu item *Space Schedule>Construction*. The objective of ISSP, when run in this mode, is to develop a schedule of activities with the shortest project duration that complies with site space limitations. ISSP starts with the current unconstrained schedule and then lengthens the project duration, as needed, during dynamic layout construction to decrease the total space required in problematic time frames where spatial conflicts were reported. The steps undertaken by the space scheduling algorithm implemented in ISSP are summarized below:

1. ISSP constructs the layout of PTFs, one at a time, and in sequential order, based on the current schedule and corresponding PTFs.

2. If ISSP fails to construct a feasible layout for one of the PTFs (say PTF-k-l), then ISSP declares a spatial conflict in this time frame, else ISSP stops when a feasible dynamic layout for the entire project duration is constructed.

3. If a spatial conflict is declared, ISSP fires one of the time-space trade-off strategies, explained next, to reduce the total area required in it at minimal increase in project duration.

4. ISSP calls the scheduler to update start and finish dates of activities and other related data based on the strategy applied.

5. ISSP reconstruct the layout of PTF-k-l and iterates steps 2 to 5 until layouts for all PTFs have been successfully constructed.

Space Schedule Strategies

This menu item allows the user to set ISSP to run in *Fully Automated* mode or *User Driven* mode when selecting time-space tradeoffs strategies for lowering total area required in time frames where a spatial conflict was reported.

In the Fully Automated mode, ISSP selects the strategy-activity combination that will lower the area requirement in the problematic time frame and results in no or minimal increase in project duration. The strategies that ISSP selects from are:

1. Delay an activity that starts in this time frame
2. Change the resource level of an activity to one with lower area requirement.

In the User Driven mode, the user labels a resource that exists on site during the problematic time frame. Depending on the profile of the resource selected, ISSP will select from the following strategies the one that will remove the selected resource from the current problematic time frame and will minimize any increase in project duration.

1. Delay an activity that starts in this time frame
2. Change the resource level of an activity to one with lower area requirement
3. Store the resource off-site.

ISSP VIEW LAYOUT INTERFACE

After or any time during static, dynamic, or space schedule construction, the user can view the partially or fully constructed layouts of the selected time frame(s). Figure 4 shows ISSP View Layout interface. In particular, it shows the final layout as constructed by ISSP for the time frame PTF-0-2 for the project data shown in Figures 1 to 3.

INTEGRATION CAPABILITIES WITH OTHER SOFTWARE

ISSP is implemented in Allegro Common Lisp, v. 6.1 and runs on a PC. Currently, the authors are working on augmenting the capabilities if ISSP by providing the user with added flexibility in the management of resources and editing of the constructed layouts. This is sought through integrating ISSP with commercialized project management software such as Primavera Project Planner or MS project, and/or layout decision support tools such as MovePlan (Tommelein and Zouein 93 and Zouein 95.). For example, after constructing the dynamic layout using ISSP, the user can call the menu function *Edit Layouts using MovePlan*. As a result, activities, resources, schedule, and layout data, get automatically saved as an ASCII file and loaded onto the MovePlan application. ISSP users can then use MovePlan layout interface to edit positions of resources as they see it fit. The user can click and drag any of the rectangles representing a resource and reposition it to comply with considerations other than minimizing proximity and relocation cost.

CONCLUSIONS

This paper presented the ISSP system for integrating activity scheduling and space planning for a project. ISSP is unique amongst other space planning and scheduling tools in that it provides its users with more than a template for tying spatial and temporal data and the interface needed for users to plan, modify and integrate schedules and site layouts. It is equipped with scheduling and layout algorithms capable of constructing schedule and layout solutions for solving space scheduling problems.
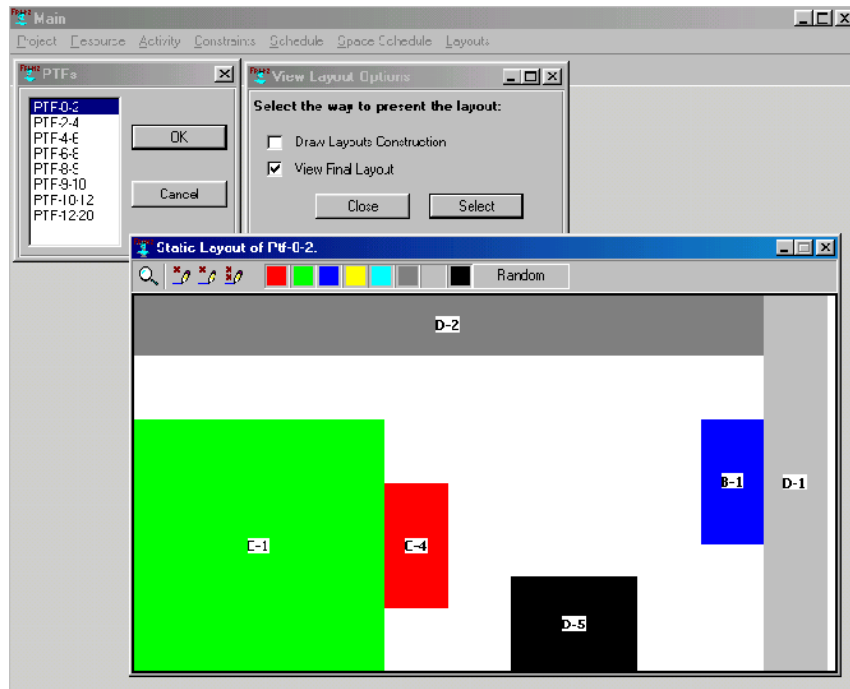
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Figure 4: ISSP View Layout Interface for the Project Data shown in Figure 3

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