Representation of work spaces using a parametric model to support time-space conflicts analysis

(A case study for time-space conflict analysis for the International Linear Collider project)

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Abstract

Time-space conflict analysis has been used to improve work schedule in the construction industry. This paper presents a case study where we test the validity of 4D-based time-space conflict analysis for improving the installation schedule of the system components in the International Linear Collider (ILC) project. Conducting time-space conflict analysis for the installation work requires representing work spaces necessary to install the components. In this paper, we explore the most suitable methods to represent the work spaces to support the time-space conflict analysis. Throughout the exploration, we apply three different methods (i.e., a method using isotropic "tolerance" concept, a method using traditional 3D solid modeling, a method using parametric modeling) to represent the work spaces. From the application of these three different methods, we compare and discuss the strengths and weaknesses each of the three methods.

Keywords

Work space, work space representation, time-space conflict, 4D model, parametric model

Introduction

4D modeling and time-space conflict analysis based on 4D model have been used to improve work schedules in the construction industry (Rad 1980; Akinci et al. 1998; Katz 1998; Akinci et al. 2002; Guo 2002; Heesom et al. 2004; Zhang et al. 2005). The virtual design and construction (VDC) technologies to support the 4D-based time-space conflict analysis have been evolved. This paper presents a case study where we apply 4D-based time-space conflict analysis to improve the installation schedule of technical system components in the new International Linear Collider (ILC) project. In this case study, we explore the virtual design and construction technologies that are suitable for the time-space conflict analysis for the ILC project. Specifically, this exploration study focuses on identifying the most efficient method (i.e., technology) to represent the work spaces required for the installation of the technical system components.

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In the ILC project, many technical system components need to be installed in a short time period with limited work space (i.e., 4.5 meter diameter tunnel). Since the space is limited for installation of the system components, increase in space per unit time can result in time-space conflicts in which one activity's space requirements interfere with those of another activity or with work-in-place. Previous works have demonstrated that 4D-based time-space conflict analysis prior to actual work can help planners identify potential risks of decreased performance due to time-space conflicts (Akinci et al. 2002; Guo 2002; Zhang et al. 2005). The identification of the potential time-space conflicts will effectively improve the actual installation schedule for the ILC project.

To conduct the 4D-based time-space conflict analysis, the spaces required for the installation of the components need to be represented in a 4D model. Akinci et al. (2002) identified that an activity requires multiple types of spaces such as labor crew space, equipment space, hazard space, protected space, and space for temporary structures. Depending on the types of spaces conflicting, they categorized time-space conflicts into different types. Representing the multiple types of spaces required for the installation of the components in the ILC project is challenging because the geometry of the components is complex and subject to change.

In the case study presented in this paper, we test three different methods to represent the work spaces required for the installation of the system components. Through the application of the different methods, we analyze how those methods are suitable and efficient to generate the multiple types of spaces. To discuss the suitability, we compare those methods in terms of the feasibility to represent the different types of space correctly, the time efficiency to generate the required spaces, and the flexibility with the potential design change of the components. We also demonstrate the power of the 4D-based time-space conflict analysis to improve the installation schedule for the ILC project.

In the next section, we describe the need for 4D-based time-space conflict analysis for the installation work in the ILC project and the challenges to represent the work spaces to support the time-space conflict analysis.

Test case

The scope of the installation activities covers a large geographical area with an overall machine length of 30 linear kilometers and includes a complex network of about 72 km of underground tunnels at the depth of approximately 100m (Figure 1). These tunnels include housing for all of the technical equipment needed to operate the ILC Sub System including the electron/positron (e-/e+) source, e-/e+ damping rings, 5 GeV low emittance transport beam lines, Main Linear Accelerator (Linac), beam delivery section and interaction region to the high powered beam dumps. In all, this requires the installation of ~2,000 superconducting cryogenic modules (Figure 2), over 13,000 magnets and approximately 650 high level RF stations.

Components that need to be installed for every superconducting radio frequency (RF) section (each 38 meters) in the Main Linac's Service Tunnel include a horizontal klystron, RF transformer, charging supply transformer, pulse transformer, Low Conductivity Water

(LCW) piping skid, a chilled water skid for and nine RF racks. In addition, an electrical skid with a conventional transformer and an emergency transformer is to be installed for every fourth RF station (Figure 2)

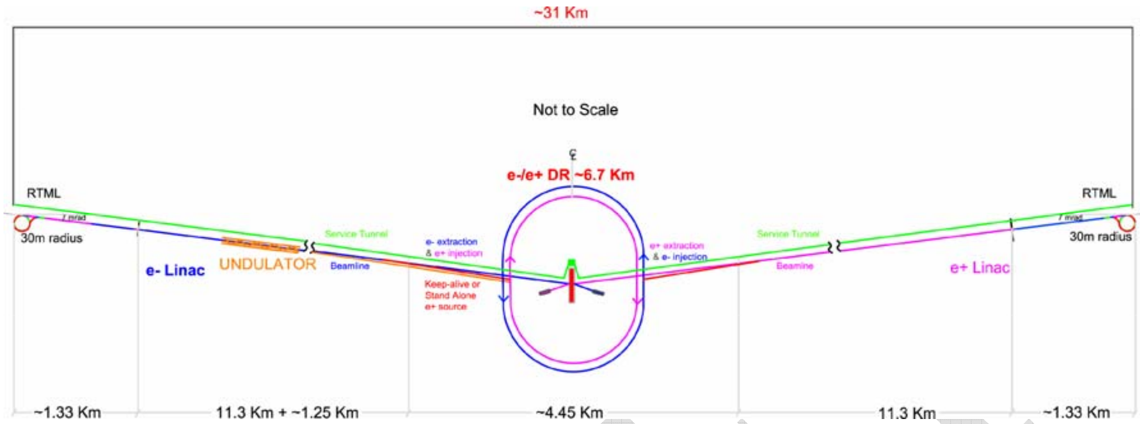

Figure 1 Plan view of the ILC layout

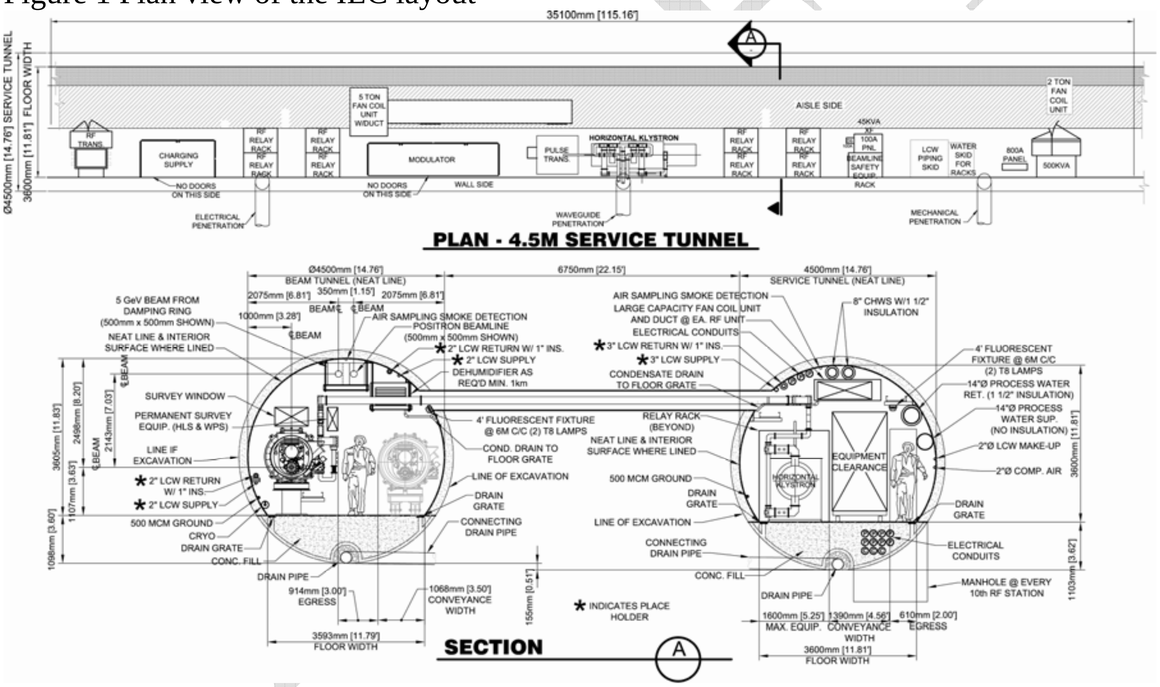

Figure 2 Layout and cross section of one RF section

Challenges in developing installation schedule

The installation process consists of moving, placing, adjusting and fixing the cryogenic modules and other system components. An assumption for sequencing the process is that the installation of continuous pipes and racks come first. Then the installation of cryogenic modules and other non-continuous components follow. The base production rate of the installation schedule is that three cryogenic modules (one RF unit, 38 meters) are going to be installed per day in 3 shifts.

A time constraint of the installation schedule is that the installation of the components is requested to be completed within the limited period, 3 years. The total length of Main Linac section alone is about 24 km. Assuming 20 days of work per month, the installation of cryogenic modules in the beam tunnel will take about 2.6 years, which conforms to the 3 years of total installation duration. The installation of the 20 pieces of system components within one RF unit of the service tunnel must be progressed at the same rate (i.e., a day). The space available for installation is very limited because only half of the tunnel cross section can be used for the installation. The other half is used to move components along the tunnel. Considering the limited time (i.e., a day), space, and the number of the components, it is probable that the component being installed may lack space and have time-space conflicts with other work-in-place. Furthermore, installation of certain components (e.g., cryogenic module) needs to be done under specific conditions (e.g., clean room condition) where the interferences between different works must be avoided. The requirement for the specific conditions increases the risks to have time-space conflicts during the installation of the components. Consequently, the installation schedule for the system components in the ILC project may have high risks to include many unpredicted time-space conflicts. Detecting and mitigating the unpredicted lack of space and time-space conflicts prior to the actual installation would increase the confidence in the installation schedule.

4D modeling and work space representation requirements

To conduct time-space conflict analysis, we developed a 4D model integrating the 3D model and installation schedule. Since this case study aims to test the power of 4D-based time-space conflict analysis to improve the installation schedule, we developed the 4D model and analyzed the time-space conflicts only for two RF sections (total 76 meters) in the Main Linac. Figure 3 illustrates the 3D model of the two RF sections. As this figure shows, the tunnels and components in the tunnels are represented as 3D solids in Autodesk AutoCAD system. The 3D model shown below does not represent the space required for the installation of the components.

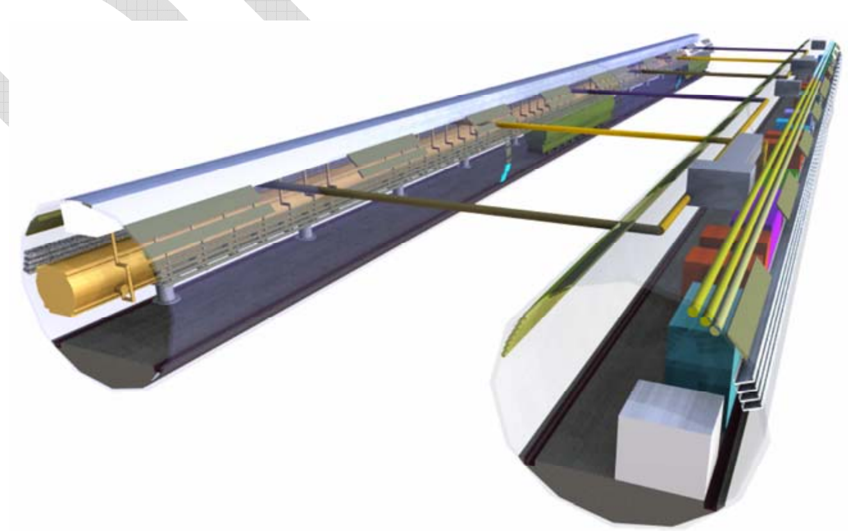

Figure 3 3D model of two RF sections

Given the 3D model of the components, time-space conflict analysis requires representing the work spaces required for the installation of the components. Representing the work spaces from the 3D model of the components is a challenging task due to the following reasons. First, the shapes of the components are complex. They are not only rectangular prisms located parallel to orthogonal planes. In addition, the work spaces required for the installation of the components are multiple types. The multiple types of work spaces for an activity have different shapes and volumes. Figure 4 shows an example of the different types of work spaces required for the installation of "fan coil unit", "pipe", and "power supply" in the Main Linac's service tunnel only.

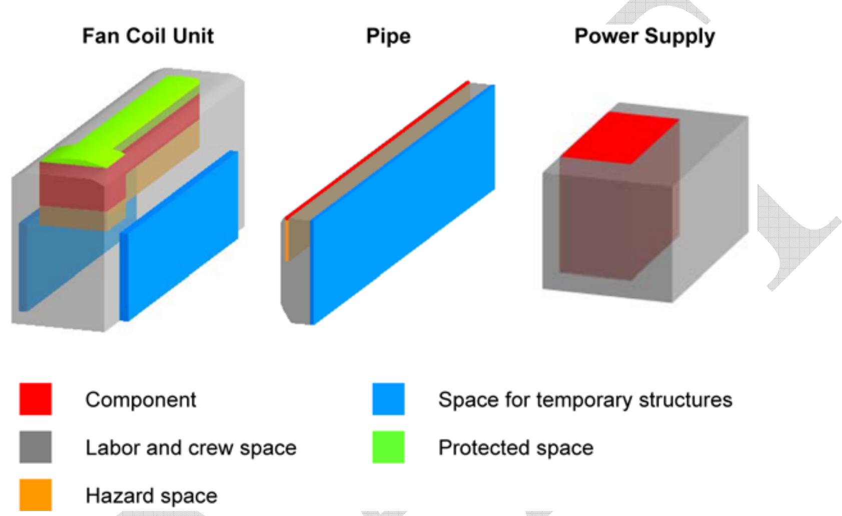

Figure 4 Representation of multiple types of work spaces

In our first case study, we used three different methods to represent the work spaces. The first method uses isotropic tolerance distance to represent the work spaces. Using this method, the 3D components for the work spaces are not physically included in the 3D model. Instead of generating actual 3D components for the work spaces, this method assumes the work spaces based on the tolerance distance. The second method uses traditional way to build 3D solids. We manually developed the 3D components for every piece of the work spaces. The third method adopts the parametric modeling concept. The parametric modeling generates 3D components for the work spaces based on the definition of the geometric relationships between the components and the work spaces. The next section describes those three methods and time-space conflict analysis process associated with the methods in detail.

Methods to represent the work spaces

This section describes three different methods we used to represent the work spaces and the framing of the time-space conflict analyses based on these methods. We adopted "narratives" to describe the framing of the time-space conflict analyses. Narratives are formal descriptions of the time-space conflict analyses including representations, reasoning, and their interdependencies (Haymaker et al. 2003). We used the narratives in this paper to describe the software packages we used, representations, and their dependencies.

Method 1 - using isotropic "tolerance" concept

This method assumes the work spaces required for the installation of components using isotropic tolerance concept. Figure 5 shows examples of work space assumption using this method. As this figure shows, this method assumes the geometries of the work spaces as indicated by the tolerance distance (i.e., 5m) from the faces of the components.

Figure 6 shows the process of time-space conflict analysis. We built a 3D model using Autodesk's AutoCAD that represents only the technical system components as 3D solids. We developed a 4D model for the installation of the components using the Navisworks Timeliner by linking 3D model to the installation schedule in Primavera. We conducted time-space conflict analysis using the Navisworks Clash Detective. The Navisworks Clash Detective allows specifying the tolerance distance. Using the tolerance a time-space conflict in which the geometry of component 1 intersects that of component 2 by a distance of more than the set tolerance.

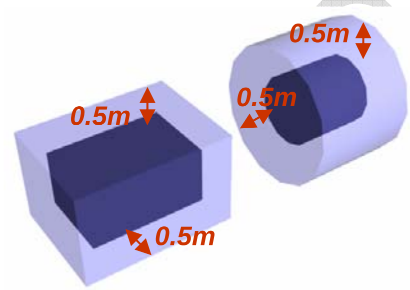

Figure 5 Work space assumption using isotropic tolerance distance

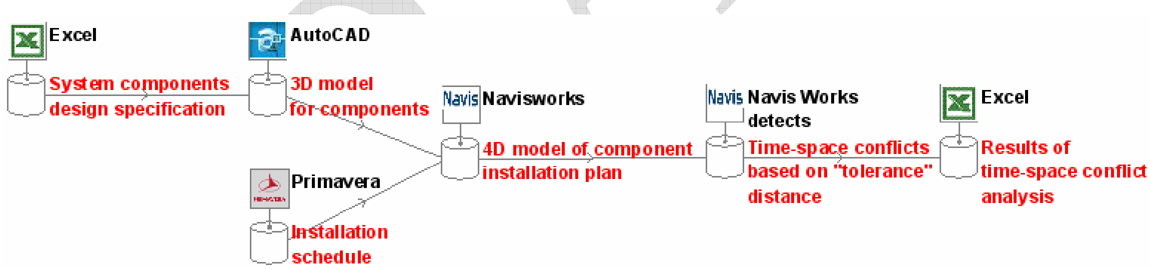

Figure 6 Time-space conflict analysis using isotropic tolerance concept

Method 2 - using solid modeling approach

This method follows a traditional 3D modeling practice where modelers need to manually develop 3D representation for every component included. Every piece of the work spaces are represented as a separate 3D component. In this case study we generated 3D solids for the work spaces. Figure 7 shows the process of time-space conflict analysis based on the representation of work spaces using this method. This process is similar to the previous one. The only difference is that this process requires an additional step to generate 3D components for the work spaces.

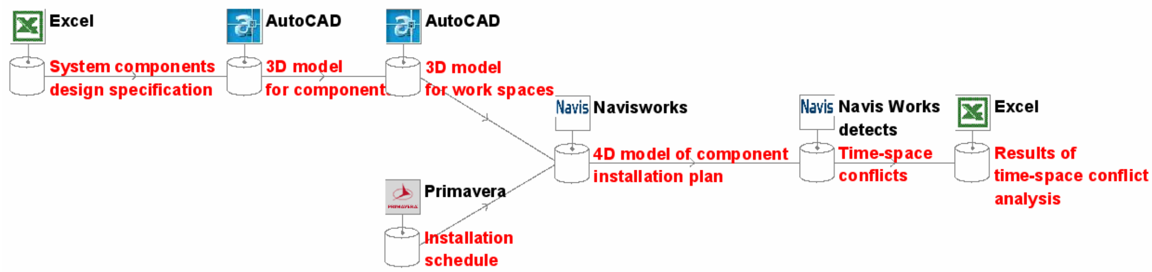

Figure 7 Time-space conflict analysis using solid modeling approach

Method 3 - using parametric modeling approach

Parametric modeling approach has been used to build 3D model and define the relationships between building components in the 3D model (Inozemtsev et al. 2000). For example, using parametric modeling approach a modeler can define the relationship between a wall and a window. The window is embedded in the wall (i.e., any part of the window cannot be outside of the wall) and the distance from the edges of the wall to the edges of the window. Given the properties of the window, the relationship between the wall and the window can be used to put the window in an appropriate position. The relationship also enables the modeler to relocate the position of the window in the wall when the design (e.g., width, height) and the location of the wall change.

We adopted the parametric modeling concept to generate the work spaces required for the installation of the system components. We used CATIA as a modeling tool. Figure 8 shows the process of time-space conflict analysis using parametric modeling approach. The first step to generate the work spaces is defining the geometric relationships between the system components and the work spaces for the components. We defined the relationships by specifying the geometric properties of the work spaces (e.g., distances, angles, curvatures) as reference values to the geometric properties of the components. As there are multiple types of spaces required for the installation of each component, we defined relationships for the spaces separately. Secondly, we implemented the relationships using CATIA. The relationships enable the CATIA model to automatically generate relevant work spaces for the components. The work spaces include multiple types of work spaces and the size and shape of the work spaces are represented correctly. The third step includes resolving any incompatibility issues between the CATIA and the Navisworks (i.e., 4D modeling too). To import the CATIA model (*.igs format) to the 4D modeling tool, we converted *.igs format file into *.sat format file using Rhinoceros and then converted the *.sat file into *.dwg format file that can be imported into Navisworks.

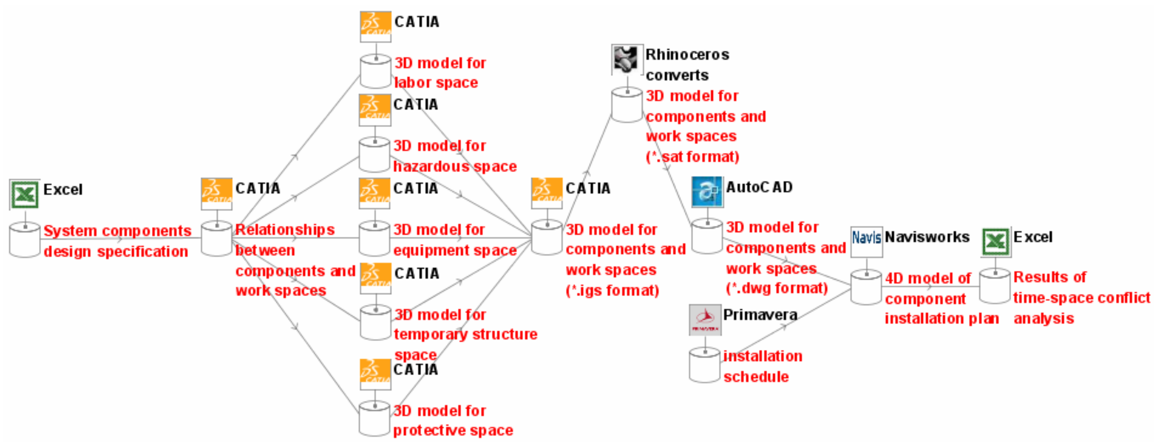

Figure 8 Time-space conflict analysis using parametric modeling approach

4D-based time-space conflict analysis

This section describes and compares the results of time-space conflict analyses using the three different methods. We compare these methods in detail to test how they are suitable to provide relevant input for time-space conflict analysis and how they are efficient in terms of the time to conduct the analysis. For testing the relevancy for input, we compare the different methods in terms of the numbers of time-space conflicts detected and analyze which method returns the correct results. We analyze the cases that are improperly included as time-space conflicts in order to know what causes the incorrect result. For testing time efficiency, we measure the time required to represent the work spaces. We also measure the time to regenerate the work space assuming when the designs of the system component change.

This section also describes examples of detailed analyses using the results from the time-space conflict analyses and how these analyses can be used to provide appropriate input for improving the installation schedule.

Comparison between different methods

Since the first method does not require generating physical 3D components for the work spaces, the process to analyze time-space conflicts using this method is simple, easy, and straightforward. The time to generate the work spaces is less than an hour. However, the test results include 600 time-space conflicts that are not correctly judged. The incorrect results come from inadequate representation of the geometries of the work spaces using this method. Figure 9 shows an example of the misjudged time-space conflict between installation of RF relay rack and the bottom of the tunnel. In this example the work space below the RF relay rack that is assumed by the tolerance distance is not necessary. In addition, this method is not relevant to represent multiple types of work spaces. Hence, it is not possible to distinguish the type of time-space conflicts.

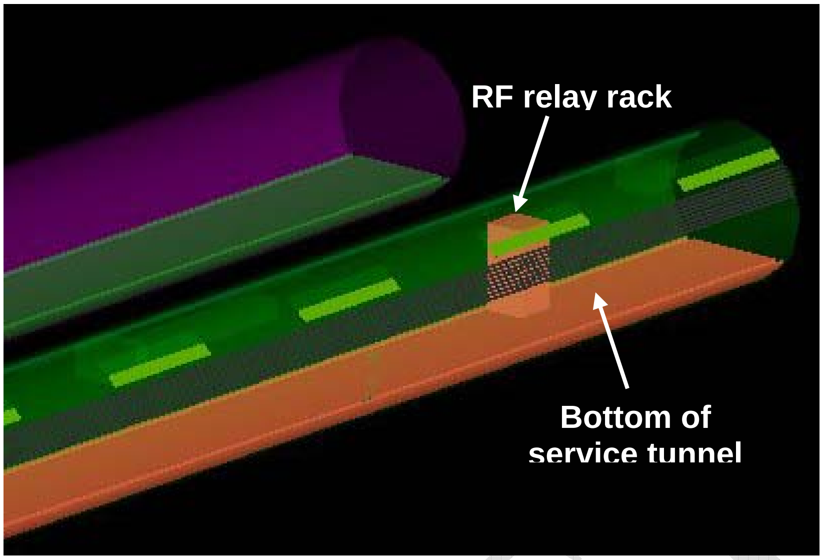

Figure 9 Misjudged time-space conflict between installation of RF relay rack and the bottom of the tunnel

Using the second method, it is possible for the modeler to build the correct geometries of the work spaces. Hence, the time-space conflict analysis using this method returns correct results. However, this method requires the modeler manually generating 3D components for every piece of the work spaces. Accordingly, the time to develop 3D models for the multiple types of spaces increases in proportion to the number of components. In this case study where we used two RF sections (total 76 meters, about 70 system components) in the Main Linac, it took about 5 hours to build the 3D components for the work spaces. Since the Main Linac only includes installation of more than 20,000 components, using the traditional method the time to develop the 3D model for the spaces required to install the technical components using the traditional method will increase accordingly. More importantly, the traditional method cannot automatically change the representation of the work spaces when designs of the technical components change. Therefore, given another set of technical components with a different design, it will take the same amount of time (i.e., 5 hours) to regenerate the work spaces for the components.

Using the third method, defining the geometric relationships between system components and the work spaces is a time-consuming process because the modeler needs to define the relationships for every piece of the work spaces separately. In this case study, it took about 5 hours to define the relationships. However, the work spaces generated in this way can correctly represent the geometry of the work spaces and hence they are relevant for time-space conflict analysis. Representing work spaces in this way also takes the advantage of defining the relationships between the components and work spaces. It is easy to change the reference values (V, H in Figure 10) that define the relationships whenever the space requirements for the components change. In addition, the relationships automatically regenerate the work spaces immediately when the designs of the system components change. Comparing to the rework time to generate the work space in the previous method, this immediate regeneration of the work spaces becomes a huge benefit for analyzing time-space conflicts when the system components have a range of design values.

Table 1 Comparison of different methods

	Method 1	*Method 2*	*Method 3*
Number of time-space conflicts	836	236	236
Correctness to represent the work spaces	Incorrect	Correct	Correct
Relevancy to represent different types of the work spaces	Irrelevant	Relevant	Relevant
Time to generate the work spaces	< 1hour	5 hours	5 hours
Time to regenerate the work spaces	< 1hour	5 hours	< 1hour

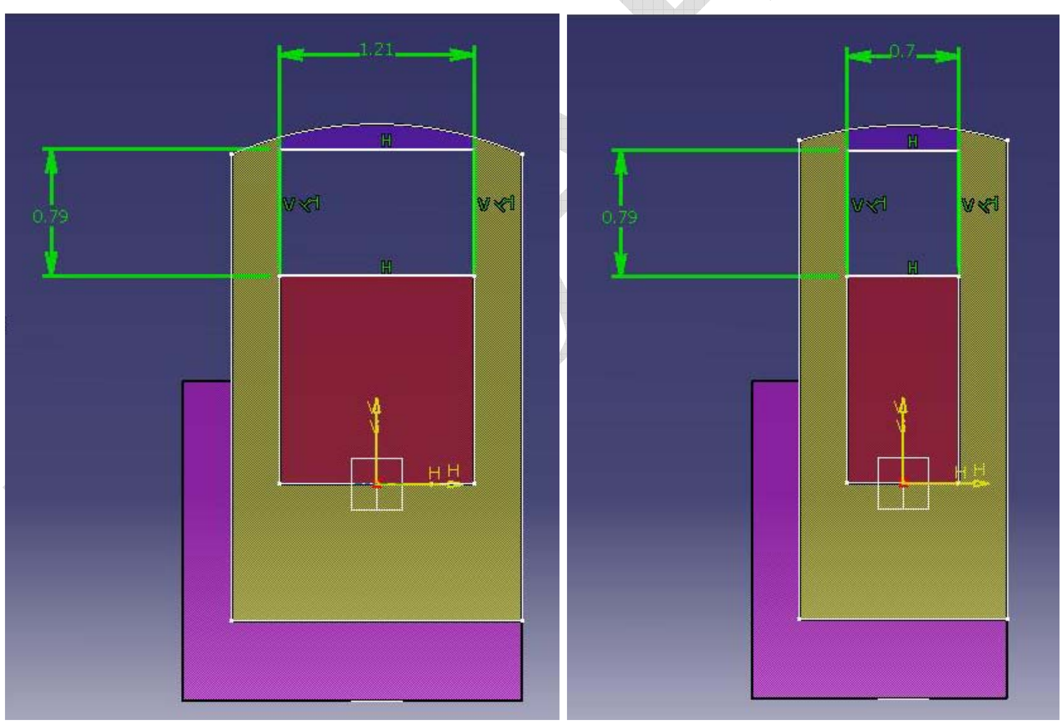

Figure 10 Representation of work space using parametric modeling approach

Analysis of the time-space conflicts in detail

With the correct representation of the work spaces and 4D-based time-space conflict analysis based on the representation, we further analyzed the detected time-space conflicts. We classified the conflicts into different types (Akinci et al. 2002) and according to their severities. Then we analyzed the location that the different types of conflicts occur.

Figure 11 shows the number and percentage of different types of conflict identified. This diagram shows that the majority of the time-space conflicts are due to the congested work space. The congestions are mostly related to the installation of the components that hang to the tunnels (e.g., piping, fan coil unit, racks, etc.). The installation of those hanging components requires whole space below the components to the floor, which increases the chance to cause interferences with other installation works in place.

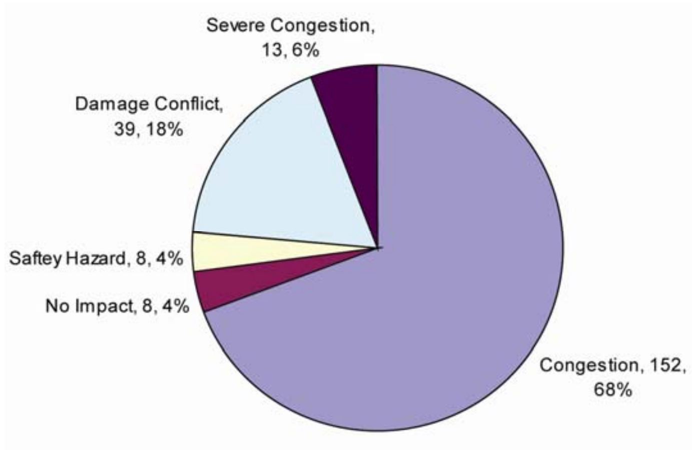

Figure 11 Type and number of time-space conflicts identified

Figure 12 graphically shows the locations of the time-space conflicts detected, the types of the conflicts, and the intersection distances of the conflicts. The intersection distance in this graph represents the distance of the two work spaces intersecting. The longer the distance is, the severe the conflict is. Integrated with the locations and intersection distances, the conflicts in Figure 12 illustrate three areas that the schedule needs to be improved. Most importantly, the area 1 and 3 in this graph include time-space conflicts that cause unsafe work condition. The conflicts in area 1 are more critical than those in area 3 because the distances of the work spaces intersecting are longer. This graph also illustrates that the severe space congestions in area 2 needs to be resolved.

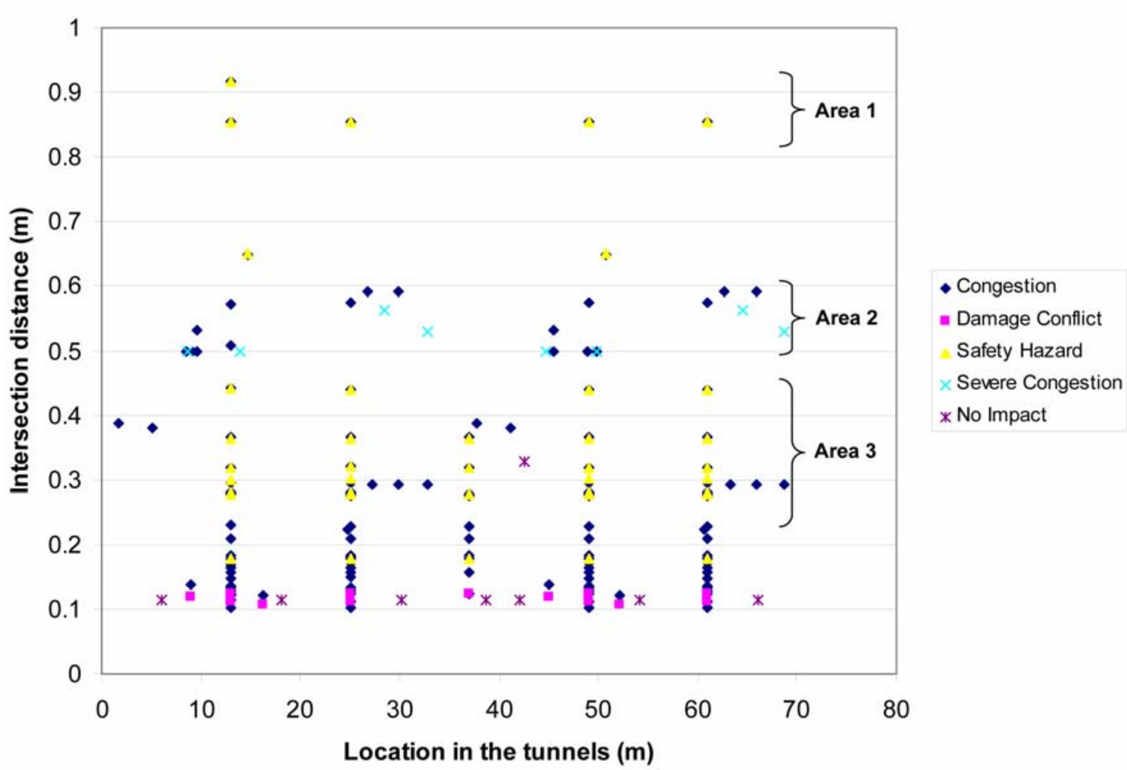

Figure 12 Location of the detected time-space conflicts and the intersection distance of the two work spaces intersecting

We mitigated the time-space conflicts by attempting to change the schedule based on these detailed analysis. Using the analysis results, we changed the sequence of the installation of the hanging components (i.e., fain coil unit, beam line, and chilled water piping) to come up with an alternative installation schedule. The alternative schedule has the same duration and activity numbers except for the sequence of the three activities. With the alternative schedule, the time-space conflicts are decreased by 12%.

Table 2 The time-space conflicts identified for the alternative schedule

	Original Schedule	Alternative Schedule
Total duration / activity numbers	~100 hours / ~100 activities	
Changes	Sequence change among “Fan coil unit installation”, “Beam line”, and “”Chilled water piping”	
Number of work space conflicts	236	208 (12% decrease)

Discussion

The results of the 4D-based time-space conflict analysis in this paper demonstrates that the analysis can help identify potential time-space conflicts (i.e., “lack of space” and "interferences between activities"). The test also shows that it is possible to classify the detected time-space conflicts into different types. In addition to the types of time-space conflicts, the results of the 4D-based time-space conflicts provides information about the location and severity of the detected time-space conflicts. Knowing the time-space conflicts prior to actual installation provides valuable input for improving the credibility of the installation schedule in the ILC project.

The application of three different methods to generate work spaces in this case study shows that assuming work spaces by the "tolerance" distance cannot represent the spaces correctly when geometries of the works spaces are not uniform to all directions. In addition, the method cannot specify different types of work spaces. Traditional solid modeling method and parametric modeling method to generate work spaces can represent the work spaces and the multiple types of work spaces correctly. However, the solid modeling method cannot automatically regenerate the work spaces when the design of the component changes. Hence, regenerating work spaces for the changed design will take the same amount of time as it took initially. Although using parametric models for generating work spaces requires time investment at the beginning to define and set the relationships between components and the spaces required to install the components, the relationships enable the method to automatically regenerate the work spaces when the design of component changes. Therefore, the method using parametric modeling to represent the work spaces is the most time efficient in terms of time especially when the planner repeats time-space conflict analysis with different parameter set.

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