QUANTIFYING EFFECTS OF SPECIFIC 4D TOOL FUNCTIONALITIES ON 4D MODELING PRODUCTIVITY

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ABSTRACT

Even though 3D models and schedules are available to contractors, 4D models are still not widely adopted in industry. Research that addresses the productivity of a 4D tool exists, but no study thus far compares the productivity of 4D tools and analyzes which functionalities within the tools enable efficiency. The productivity of three 4D CAD software was compared. The independent variable was the specific functionalities enabled by the tools. The dependent variable was the effort required to achieve each 4D modeling process step.

Specific functionalities within each tool significantly reduced the time needed to create 4D models. For example, modifying the 3D product model within the 4D tool environment, reduced the time required to import the 3D product model into the 4D tool by up to 78%. An automated zone creation function, reduced the time required to link the product to the schedule by up to 90%. This knowledge enables construction management software companies to create more efficient 4D modeling software. Furthermore, operations managers can use this research to select software that addresses specific company needs and the reasonable effort required to create 4D models encourages the use of 4D modeling.

Keywords: Four-dimensional CAD, Visualization, Construction planning, Scheduling

1   INTRODUCTION

Most construction schedules are still created and analyzed using the Critical Path Method (CPM). CPM however has several shortcomings such as not visualizing the product that is being built or not taking spatial requirements and interactions into account. These limitations are overcome with Four Dimensional (4D) CAD, a method that links a 3D model to a construction schedule (Cleveland 1989).

By definition, to create a 4D model a 3D object-oriented model (i.e. Building Information Model – BIM) and a schedule are needed and currently both are widely available to American general contractors. A study by McGraw Hill Construction found that 43% of architects and 23% of contractors in the United States use Building Information Modeling (BIM) on more than 60% of their projects (Young et al. 2008)[1]. Therefore contractors have access to BIM models. Likewise, schedules are common on construction sites. A survey of 430 Architecture, Engineering, and Construction (AEC) companies, including 133 contractors, found that 47% of owners require schedules on their projects and even when schedules are not a contractual requirement, 67% of contractors still use a CPM schedule (Galloway 2006).

Other studies have documented the benefits that 4D CAD modeling provides such as improving crew coordination, shortening the construction period, reducing change orders, reducing RFIs, and improving the effectiveness of communication (Fischer 2000). However, even though the 3D models and schedules required to create 4D models are available to contractors, and 4D CAD has proven to provide considerable benefits, it is still not a common tool for most contractors and subcontractors (Dawood 2010).

This paper presents a study of three 4D CAD tools; Vico Office, Autodesk Navisworks Simulate, and Synchro Professional and measures the time required for each of the four process steps needed to create 4D model: import/ create product elements within the 4D CAD tool environment (*access product model*), import/ create schedule within the 4D CAD tool environment (*access schedule*), link product elements to schedule activities (*link product to schedule)*, and visualize the 4D model (*visualize 4D model*). Each tool was used to create 4D models for three case studies.

The widespread adoption of 4D CAD partially depends on how well software developers will facilitate these four process steps. Therefore, this paper investigates whether the reason for the lack of widespread 4D CAD adoption within the industry, is due to inherent difficulties in creating 4D models and which specific functionalities within the tools enable 4D modeling efficiency. In this research we use the terms 3D model and product model interchangeably.

2   LITERATURE REVIEW

One of the earliest case studies on 4D CAD was performed at Stanford University's Center for Integrated Facility Engineering (CIFE) (Collier and Fischer 1995). This study utilized 3D models linked to a Primavera software suite schedule using Jacobus Technology's Construction Simulation Toolkit software and already showed significant benefits provided to the entire project team.

From a product perspective, research has shown diverse and advanced applications of 4D CAD with examples developed for safety plan development (Chantawit et al. 2005), production planning (Riley 2000), life cycle facility management (Park et al. 2011), and automated model-based recognition of progress (Chin et al. 2005). 4D CAD has also been combined with other methods such as line of balance scheduling (Jongeling and Olofsson 2007). Research has also explored the functions required of 4D tools finding that they need to enable the user to access both 3D models and schedule within the 4D environment, deduce relationships between product elements and support automated 4D CAD analysis (McKinney and Fischer 1998).

Other research has addressed the organizational requirements needed to support the implementation of 4D CAD finding that the project team should establish standards for 3D model formats as well as protocols for the communication and resolution of model conflicts (Staub-French and Khanzode 2007).

From a process perspective, Hartmann et al. (2008) found that even with these diverse applications, 4D CAD is still usually focused on one area of application per project such as photorealistic rendering or analyzing construction operations. Koo and Fischer (2000) measured the effort needed for the process steps required by one 4D CAD tool. But they did not compare several 4D tools or try to quantify the effect of specific 4D tool functionalities on the effort required for each process step, and such a study is not available in literature.

3   RESEARCH METHODS

An ethnographic method was used to collect the time required to achieve each 4D modeling process step, and three retrospective case studies were used validate the results. Each process step was affected by a specific 4D tool functionality. Therefore, the time required by the tool that did not possess a certain functionality was taken as the base case. One 4D modeler performed the Vico Office experiments, and another

4D modeler performed the Synchro Professional and Autodesk Navisworks Simulate experiments. Both modelers possessed similar 4D modeling experience.

4 CASE STUDIES

These are the 3 case studies used for this research:

4.1.1   Gerzon Accessorize Schiphol Airport

Figure 1: Artist rendering of Gerzon Accessorize Schiphol Airport project.	Figure 2: Snapshot of 4D model of Gerzon Accessorize Schiphol Airport project.

The Gerzon Accessorize Schiphol Airport project is a small mechanical, electrical, plumbing, and finishes project of a retail store located in Schiphol airport in Amsterdam. The project budget was $255,740 and the site layout area was 100 m2. An ethnographic method was used to collect data on the actual durations of the activities over the project's 2 week duration and so the 4D model was created retrospectively and with a high construction schedule level of detail (LOD). The work was performed indoors, within the airport, and the scope of the model was the entire project; the mechanical, electrical, plumbing, as well as internal and external finishes for the retail store. The 3D model was modeled in Revit Architecture 2012, and was 4.34 MB large with 125 product elements. The schedule was in XML format with columns for activity description, activity code and predecessors with 60 activities.

4.1.2   Lucille Packard Children Hospital (LPCH) – Basement Structure

Figure 3: Artist rendering of Lucille Packard Children's Hospital.	Figure 4: Snapshot of 4D model of Lucille Packard Children's Hospital basement floor structure model

The expansion to the Lucille Packard Children Hospital (LPCH) is a $510 million, 3 substructure and 6 superstructure floor quaternary care hospital project. Construction started in early 2012 and will be completed in 2016. Upon completion the hospital will house 150 beds within 547,000 ft^2.

Even though a 4D model was available from the project team for the entire structural works of the project, for our comparison, we limited the scope of the structure to the basement floor, i.e., mat slab, columns, external and internal walls (see Figure 4).

The 3D model for the basement floor was modeled in Revit Architecture 2012, and the file size for this scope was 3.96 MB. Also, a multi-level WBS Primavera P6 Project Management schedule was made available by the project team. The 3D model contained 216 product elements; 16 slab elements, 20 external walls, 48 internal walls and 132 columns and the schedule contained 448 activities.

4.1.3 LPCH Makeready Utilities Tunnel

The old and new LPCH hospitals are linked via a utilities tunnel. The tunnel is 260' long and the project budget is $17 million. The construction duration is from July 25th 2011 to Nov 6th 2012. The concrete structure was modeled in a 2.17MB Revit Architecture 2012 file and contained 116 elements and the schedule contained 89 activities.
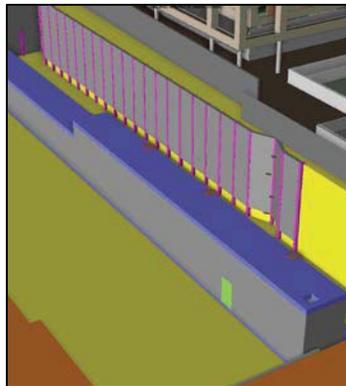

Figure 3: Snapshot 4D model of LPCH Make Ready Utilities tunnel concrete structure construction.

4.2 4D CAD Tools

We chose to analyze three 4D modeling tools; Autodesk Navisworks Simulate 2012, which is developed by the world's largest AEC industry software developer, Synchro Professional, because the company is specialized in 4D tool development and, Vico Office which is an integrated Scope-Cost-Schedule solution. This section provides an overview of the 4D CAD tools compared.

4.2.1 Synchro Professional V4.5

Synchro Professional V4.5 is a dedicated 4D CAD tool that allows the 4D modeler to combine 3D models from different modeling software such as Revit Architecture, AutoCAD, SketchUp, and Tekla Structures with project schedules from scheduling software such as MS Project, and the Primavera software suite. Subsequently, it helps in the creation of 4D CAD content which can be used for schedule validation, spatial conflict identification, and crew management. Synchro Professional facilitates a bi-directional information flow between the 4D CAD interface and the scheduling software. The 4D modelers found this to be the best tool for modeling objects within the 4D tool environment.

4.2.2 Autodesk Navisworks Simulate 2012

Autodesk Navisworks Simulate 2012 from Autodesk, provides a collaborative platform to integrate multiple trade-specific 3D models to perform constructability analyses and schedule simulation. It accepts a wide range of file formats such as IFC, DWG, DWF, SKP, FBX, 3DS, DXF, DGN, PRP, PRT, STP, IPT, and IAM and as such, the 4D modelers found this to be the best tool for interoperability between

various file formats. It supports small to large scale projects and its efficiency in reducing the file size makes it a great tool for managing complex BIM environments with multiple models. It is widely used for clash detection and spatial conflict resolution, but has limited functionality for 4D CAD schedule simulation. Autodesk Navisworks Simulate supports importing project schedules from different scheduling platforms such as MS Project, Excel, and the Primavera suite. The 4D modelers on this experiment also found this to be the best software for filtering and grouping objects based on object properties.

4.2.3 Vico Office R3.2

Vico Office R3.2 is an integrated Scope-Cost-Schedule (SCS) solution that incorporates 8 modules in one dashboard. The dashboard for Vico Office is called the Vico Office Client and the modules are: Vico Office Constructability Manager which allows multiple 3D models such as structural and architectural to be combined so that product clashes in the design can be identified by the construction management team, Vico Office Takeoff Manager which allows quantities to be directly pulled from the 3D model while allowing the user to interact with the estimate and 3D model simultaneously, Vico Office Cost Planner which allows the creation of cost items linked to both the 3D model and schedule activities, Vico Office Cost Explorer which allows the owner to recognize which decisions have the most influence on the budget and schedule, Vico Office LBS Manager which allows the user to break the project into locations by drawing zones, Vico Office Schedule Planner a line of balance scheduling tool, and finally the Vico Office 4D CAD Manager which creates 4D models (Vico Software Inc. 2011).

One of the main advantages of the Vico Office Suite is that its modules are integrated and changes in one module are reflected automatically in other modules, saving the user considerable effort. For example, if the user modifies the production rate of a task in one of the modules, the effect will automatically translate to schedule duration, and the 4D model will also be updated. As a result one key difference that the 4D modelers appreciated is that in Vico Office, a 4D model is created automatically from the user's input, i.e. it is a byproduct of the user's modeling effort.

Vico Office allows the import of Autodesk Revit Architecture, Tekla Structures and ArchiCAD models as well as CAD-Duct and IFC files, via an export button in the three supported 3D BIM software applications. Vico Office Schedule Planner supports schedule imports from MSP, Primavera P3, as well as XML format.

5 PROCESS STEPS TO CREATE 4D MODELS

The following 4 steps are required to create a 4D model:

1. **Import/ create product elements within the 4D CAD tool environment (*access product model*)**

   In this paper, this process step is referred to as *"access product model"* and it contains two sub processes; a) importing the 3D model into the 4D CAD tool and b) converting model to construction intent. We refer to 3D models created for design purposes as design intent models and these often need be converted into 3D models intended for construction scheduling purposes, which we refer to as construction intent models. For example, in the LPCH Basement Structure project, one of the walls was modeled as one internal wall but in reality was actually two walls; one internal and one external wall. The processes to build them are different and they need to be built at different times and therefore this wall needed to be split into two parts. This increases the Level Of Detail (LOD) of the product model. Some tools allow this to occur within the 4D CAD tool environment whilst others require the user to do the changes in the 3D tool environment and re-import the model.

2. **Import/ create schedule within the 4D CAD tool environment (*access schedule*)**

   The schedule can be imported into the 4D CAD tool from various scheduling software or created within the 4D CAD tool. Some 4D CAD tools can import schedules with multi-tiered WBS structures whilst others import all activities including summary activities under one level. The construction schedule LOD often needs to be changed and sometimes this can occur within the 4D CAD tool by adding or removing activities, and other times needs to occur within the scheduling software, requir-

ing a re-import of the schedule into the 4D CAD tool. This process step is referred to as *"access schedule"* in this paper.

3. **Link product elements to schedule activities** *(link product to schedule)*

    The user needs to link the 3D model to the schedule within the 4D CAD tool environment. However, often the schedule and product model are incompatible. For example the construction schedule LOD is not aligned with the Product LOD, or an activity or product element is missing and needs to be added. In this paper increasing the construction schedule LOD was included in this step. This process step is referred to as *"link product to schedule"* in this paper.

4. **Visualize 4D model**

    For proper visualization of the 4D model, the user needs to set colors for the different phases of each activity; start, construction, and end. For analyses to be performed on the 4D model, the speed of the simulation also needs to be calibrated.

Once the 4D model is created it can be used to perform analytical functions in an additional process step:

5. **Analyze the construction schedule using the 4D model**

    In this step the user extracts value from the 4D model. The 4D modeler could realize that the schedule sequence is incorrect, such as a ceiling built before its supporting columns. Or the 4D model could highlight possible methods for decreasing schedule duration by changing the order of work. We did not address this step in this research since the duration of this step is dependent on what analyses need to be performed.

6   RESULTS

This section presents the duration of each process step required to create a 4D model within each of the three 4D CAD tools studied for each of the three case studies. Some results have comments included as notes at the end of this section.

Table 1: Gerzon Accessorize Schiphol Airport project

	VICO OFFICE	SYNCHRO PROFESSIONAL	AUTODESK NAVISWORKS SIMULATE
Import/ create product elements within the 4D CAD tool environment (*access product model*)	5 min (model was created with construction intent so no product LOD transformation necessary)	2 min (model was created with construction intent so no product LOD transformation necessary)	2 min(model was created with construction intent so no product LOD transformation necessary)
Import/ create schedule within the 4D CAD tool environment (*access schedule*)	5 min[2]	30 min (Synchro Professional does not support XML format so the schedule was imported to MS Project and then imported to Synchro Professional)	2 min (Autodesk Navisworks Simulate supports XML format)
Link product elements to schedule activities	1hr 30min	2 hrs 20 min	2 hrs 40 min
Visualize 4D model	Instant (<1min)	34 min	1 hour 14 min
Total	1 hrs 40 min	3 hrs 26 min	3 hrs 58 min

[2]The schedule was created inside Vico Office and this took 6 hrs. The 4D modeler did not know that he could import an XML file. Hence we included 5 min as the import value.

Table 2 - LPCH Basement Structure

	VICO OFFICE	SYNCHRO PROFESSIONAL	AUTODESK NAVISWORKS SIMULATE
Import/ create product elements within the 4D CAD tool environment (*access product model*)	a. 3 min (Importing design intent model) b.1 hrs 35 min (Converting from design intent to construction intent)	a. 4 min (Importing design intent model) b. 7 hrs 12 min (Converting to construction intent)	a. 4 min (Importing design intent model) b. 9 hrs 52 min (Converting to construction intent)
Import/ create schedule within the 4D CAD tool environment (*access schedule*)	5 min[3]	10 min	10 min
Link product elements to schedule activities	54 min	3 hrs 23 min	8 hrs 12 min
Visualize 4D model	14 min	16 min	2 hours 06 min
Total	2 hrs 51min	11 hrs 05 min[4]	20 hrs 24 min[4]

[3]The 4D modeler did not know that he could import an XML file. Hence we included 5 min as the import value.
[4]To model the entire structure for the hospital i.e. 3 substructure and 6 superstructure floors took 41hrs 30min in Synchro Professional and 65hrs 30min in Autodesk Navisworks Simulate.

Table 3 - LPCH Make Ready Utilities Tunnel Structure

	VICO OFFICE	SYNCHRO PROFESSIONAL	AUTODESK NAVISWORKS SIMULATE
Import/ create product elements within the 4D CAD tool environment (*access product model*)	a. 1min (Importing design intent model) b. 2 hrs 10 min (Converting to construction intent)	a. 10min (Importing design intent model) b. 3hrs 40min (Converting to construction intent)	a. 10 min (Importing design intent model) b. 7hrs 35min (Converting to construction intent)
Import/ create schedule within the 4D CAD tool environment (*access schedule*)	5 min[5]	10 min	10min
Link product elements to schedule activities	1 hrs 23 min	1 hrs 50 min	2 hrs 35 min
Visualize 4D model	25 min	24 min	1hr 16min
Total	5 hrs 26 min	6 hrs 14 min	11 hrs 46 min

[5]Creating the schedule in Vico Office took 3 hrs 43 minutes since the tool does not support Primavera P6 Project Management software import but the other tools were importing Primavera P6 Project Management software schedules which is why we included a 5min value for this comparison.

7   ANALYSIS OF DATA AND COMPARISON OF TOOLS

When creating a 4D model, it is often necessary to change the product or construction schedule LODs. For example in the LPCH Basement Project the product model originally had 6 slab elements for the entire floor. This was split by the 4D modeler into 16 parts to reflect the daily pours, increasing the product LOD. The 4D modeler also increased the LOD of the original construction schedule from "Build mat slab" to "Formwork for mat slab", "Rebar for mat slab", "Inspect formwork", "inspect rebar", "Pour concrete for mat slab", "Cure mat slab", and "Strip formwork for mat slab". These examples illustrate that both product and construction schedule LODs need to be changed for 4D modeling.

The durations for "converting the model to construction intent" are lower in Synchro Professional than in Autodesk Navisworks Simulate; 7hrs 12min (Synchro) vs. 9hrs 52min (Navisworks) for the LPCH Basement Structure and 3hrs 40min (Synchro) vs. 7hrs 35min (Navisworks) for the LPCH Make Ready Utilities Tunnel. (The product model for the Gerzon Accessorize Schiphol airport was already created with construction intent). This is because Synchro Professional allows the user to increase the product LOD within the tool by adding simple product elements to the 3D model as well as splitting existing product elements into subcomponents. Whereas, in Autodesk Navisworks Simulate the user is forced to go back and forth between the 3D modeling tool and the 4D CAD tool as the product model is changed to construction intent.

The Vico Office LBS manager allows the 4D modeler to increase the product LOD by creating zones (see Figure 7). This saves time since Vico Office automatically calculates the corresponding quantities in each zone and uses the production rates to calculate durations for the resulting sub-activities in each zone. For example in the LPCH Basement Structure project it is sufficient to draw the zone lines to split the slab into 16 parts. This automatically calculates durations for the sub-activities "Formwork", "Rebar" …"Strip Formwork". The user still needs to insert the logic for the individual sub-activities but this is also done within the Vico Office environment. This automated product and construction schedule LOD increase, is why the time needed to "convert model to construction intent" in Vico is much shorter than Synchro Professional and Autodesk Navisworks Simulate. For the LPCH Basement Structure project the durations for this process step were 1hr 35min (Vico) vs. 7hrs 12min (Synchro) vs. 9hrs 52min (Navisworks). For the LPCH Make Ready Utilities Tunnel the time requires by this process step was 2hrs 10min (Vico) vs. 3hrs 40min (Synchro) and 7hrs 35min (Navisworks). The LPCH Make Ready Utilities Tunnel had only 3 zones vs. the 16 in the LPCH Basement Structure project which is why the difference was less pronounced in the LPCH Make Ready Utilities Tunnel project. Note that converting the design intent model to construction intent was responsible for most of the duration of the "*access product model*" step, with "importing the model" responsible for only a small percentage (1%).
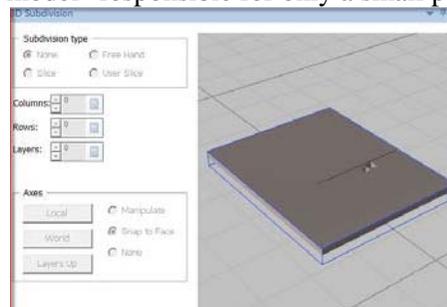

Figure 6: Splitting a slab into smaller parts within Synchro Professional.

Even though Vico Office allows the user to effectively split product elements by creating zones, but it does not allow for creating elements within the Vico environment. This was not important in these case studies as no product elements needed to be added.

Increasing the construction schedule LOD also requires less effort in Synchro Professional and Vico Office as compared to Autodesk Navisworks Simulate, because Autodesk Navisworks Simulate imports schedules under one WBS LOD and places all summary activities and their corresponding sub-activities in one level. This makes it difficult to navigate the schedule and the find required activities for linking to product elements or checking if an activity needs to be added. For example in the LPCH project, the 4D modeler had to navigate over 4000 activities to find or add relevant activities. This is why the duration for "*linking product to sche*dule" in Autodesk Navisworks Simulate was longer than in Synchro Professional (the Vico Office 4D modeler created his own schedules and did not import which is why the comparison was not made with Vico Office in this analysis). The time required by this process step was 2hrs 20min (Synchro) vs. 2hrs 40min (Navisworks) in the Gerzon Accessorize Schiphol Airport project, 3hrs 23min (Synchro) vs. 8hrs 12min (Navisworks) in the LPCH Basement Structure project, and 1hrs 50min (Synchro) vs. 2hrs 35min (Navisworks) in the LPCH Makeready Utilities tunnel project.
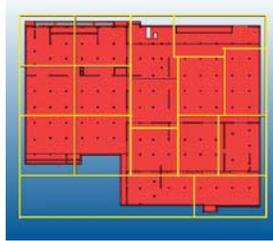
Figure 4: Vico Office's LBS Manager module showing the LPCH basement slab being split into 16 zones.

As afore mentioned, the 4D modeler using Vico Office did not import a schedule from Primavera P6 Project Management software and instead created his own within the Vico Office environment. In the LPCH basement project the 4D modeler only had to create 4 activities (slabs, internal walls, external walls and columns) and 7 sub-activities (Formwork, Rebar, etc…) for each activity. The 4D modeler only had to link the 4 main activities (slab, internal wall, external wall, and columns) to the 3D model and the sub-activities were automatically linked to the relevant product elements. This is why the time required by this step for the LPCH Basement Structure project was 54 min (Vico) vs. 3hrs 23min (Synchro) vs. 8hrs 12min (Navisworks).

Creating the 4D visualization took much longer in Autodesk Navisworks Simulate than in Synchro Professional and Vico Office, mainly due to increased rendering time. The time required for this step in the Gerzon Accessorize Schiphol Airport project was 1min (Vico) vs. 34min (Synchro) vs. 1hr 14min (Navisworks). The time required for this step in the LPCH Basement Structure project was 14min (Vico) vs. 16min (Synchro) vs. 2hrs 6min (Navisworks) and for the LPCH Make Ready Utilities Tunnel Structure project 25min (Vico) vs. 24min (Synchro) vs. 1hr 16min (Navisworks).

The total time for all steps was shorter within the Vico office environment than the other software. This is mostly explained by Vico Offices' automated product and construction schedule LOD increase capability and its integrated functionality. For the Gerzon Accessorize Schiphol Airport project all steps took 1hrs 40min (Vico) vs. 3hrs 26min (Synchro) vs. 3hrs 54min (Navisworks), for the LPCH Basement Structure project 2hrs 51min (Vico) vs. 11hrs 05min (Synchro) vs. 20hrs 24min (Navisworks) and for the LPCH Make Ready Utilities Tunnel Structure project 5hrs 26min (Vico Office) vs. 6hrs 14min (Synchro Professional) vs. 11hrs 46min (Autodesk Navisworks Simulate).

8   CONCLUSIONS

Specific functionalities within 4D CAD tools have a significant impact on the time required to create 4D models. Allowing the 4D modeler to increase the product LOD within the 4D CAD tool reduced the time required for the "*access product model*" step by 78% and 38%, respectively for Vico Office and Synchro Professional as compared to the time required in Autodesk Navisworks Simulate.

Specific functionality within 4D CAD tools, such as allowing the user to change the product and process levels of detail within the tool and importing multi-level WBS structure schedules can have a dramatic impact on the time needed to create a 4D model. The low effort required to create 4D models is important not only for creating 4D models, but also for updating them as project schedules are modified.

Linking product elements to schedule activities in Synchro Professional took 56% of the time required in Autodesk Navisworks Simulate. In projects like the LPCH Basement Structure project where the product and construction schedule LODs needed to be significantly increased, the automated process within Vico Office's LBS manager decreased the time required to *link product to schedule* by 73% and 90%, respectively as compared to Synchro Professional and Autodesk Navisworks Simulate. On average the total time required in Vico Office and Synchro Professional was 23% and 56%, respectively, of the total time required in Autodesk Navisworks Simulate.   This experiment also shows that smaller 4D models can be created in about 10hrs and larger projects, such as the entire structure for the $510 million LPCH project, need around 54hrs to model. Furthermore, no significant technical challenges were encountered in creating 4D models using any of the tools.

These results are of importance to 4D tool software developers since they show what functionalities they can develop to further facilitate the 4D modeling process. They are also of interest to construction managers, as they demonstrate that creating 4D models requires a relatively small amount of effort, pointing to 4D models being within the reach of any project team. Consultants or operations managers charged with updating standard operations procedures can also use these results to help identify what Virtual Design and Construction (VDC) technologies are ideally suited for enhancing specific company operations.

However, there are limits to the value that 4D CAD tools can add. For example, because they do not create schedules, they are well suited to detect problems within current schedules but not for giving solutions to detected problems. Also, workspaces are still not commonly modeled in 4D models, and so users need to infer workspace and other spatial clashes mentally (Akinci et al. 2002). Furthermore, 4D CAD tools could offer automated tools to detect problems or highlight potential opportunities for schedule improvements.

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