Experiences with 3D and 4D CAD on Building Construction Projects: Benefits for Project Success and Controllable Implementation Factors

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ABSTRACT: From our experience of a wide range of questions that A/E/C professionals are asking, the AEC industry is facing the challenge to determine the benefits of 3D and 4D CAD and what it takes to implement this advanced technology. This paper focuses past experiences of using 3D and 4D CAD on building construction projects.

By reviewing a collection of A/E/C projects from the United States, Norway, and elsewhere, the authors demonstrate: 1) 3D CAD allows improved design, team collaboration, and smooth project execution; 2) 4D CAD enables the exploration and improvement of the project execution strategy, facilitates improvements in constructability with corresponding gains in on-site productivity, and makes possible the rapid identification and resolution of time-space conflicts. These experiences acknowledge 3D and 4D CAD as a key driver and a primary enabler for better design of Product, more cohesive Organization, and more efficient Process (POP) that lead to project success.

This paper also illustrates the real implications of working with 3D and 4D CAD. A detailed case study on the Pilestredet Park Project in Oslo, Norway demonstrates: 3D and 4D CAD is not simply a question of investment but depends more on appropriate planning and managing the implementation, i.e., understanding what you can and want to do, identifying right timing, people, data, tools, and putting 3D and 4D models in the right process to reap the benefits. This outcome will enable facility managers and A/E/C service providers to make informed judgments about the appropriate controllable factors in implementing 3D and 4D CAD.

1 INTRODUCTION

One of the challenges of adopting 3D and 4D CAD ("time" is the fourth dimension added on the 3D CAD) in the construction industry is the uncertain payoff. Until AEC firms are convinced that the benefits are real, relatively few of them will embrace 3D and 4D CAD. For example, the industry guest speakers for the Stanford Construction Engineering and Management Program frequently discuss why some firms take the initiative to invest in 3D and 4D CAD and others do not. Two main explanations for the decision made have emerged: a visionary leader and the threat of intense competition. Therefore, companies adopt state-of-the-art 3D and 4D CAD based on their strategic analysis of its benefits. To fill the gap between strategic vision and operational reality, we need multiple case studies of actual uses of 3D and 4D CAD on a variety of projects as well as the reported benefits from the uses of models. Multiple case studies can be one of the most cost-effective methods for learning from all the experiences of pilot projects, and for passing these experiences on to implement 3D and 4D CAD more efficiently on future projects. If these cases demonstrate the wider applicability of 3D and 4D CAD to AEC companies, then the case studies may well become an important strategic tool for evaluating the effectiveness of IT and justifying investments in IT (Schwegler et. al. 2001).

One of the challenges in implementing 3D and 4D CAD is that its use is often limited to taking advantage of the tools' visualization power to help win bids. Using 3D and 4D CAD as a marketing tool to gain a competitive edge will not be sustainable in the long run. In the long term, companies will need to figure out how to deploy such visual models effectively and efficiently across the duration of their projects (Fischer and Kunz 2004). This requires the identification of the key controllable factors in an implementation plan.

Bazjanac (2002) pointed out that "it will probably first take a new generation of consultants to show industry the benefits of changing the work paradigm, and a new generation of educators to teach future professionals how to do it before 3D and 4D modeling of buildings becomes widespread." This paper, by reporting on empirical results, aims to take a step in that direction. The first part of the paper reviews 3D and 4D applications on twenty-one A/E/C projects from the United States, Scandinavia, and East Asia. The authors synthesized the various modeling purposes on these real projects and the reported benefits from the uses of 3D and 4D CAD for different modeling purposes. The second part of the paper details a case study on the Pilestredet Park Project in Oslo and identifies the appropriate controllable factors in implementing 3D and 4D CAD.

2 VARIOUS USES OF 3D AND 4D CAD AND REPORTED BENEFITS ON CASE PROJECTS

The multiple case studies involve twenty-one construction projects, on most of which researchers and students at the Center for Integrated Facility Engineering (CIFE) at Stanford University participated in the process of 3D and 4D modeling and documentation. All case studies are fairly recent, discussing the benefits and implementation of 3D and 4D CAD in the late 1990s and early 2000s (see Table 1). The observation on these case projects showed that the implementation of 3D and 4D CAD and the benefits derived therefrom are heterogeneous with respect to modeling purposes and project phases. Appendix A summarizes the various uses/purposes of 3D and 4D CAD as well as the reported benefits (as manifested by case examples) in different project phases.

All design and construction projects follow a general process that proceeds through certain phases from inception to completion, with minor variations depending on the requirements of the project. The phases in the design and construction process that are most common to engineering design and construction projects are: Conceptual/Schematic Design; Design Development, Detailed Design, Construction Documents, Preconstruction (proposal/bidding/procurement) and Construction. To improve the existing process using 3D and 4D CAD, we need to look at each phase and determine specifically how this new technology can benefit AEC projects.

2.1 *3D and 4D CAD used in the Conceptual/Schematic Design Phase*

In the conceptual/schematic design phase, 3D CAD is used for client briefing. Modeling the facility in 3D "walk-through" helps the owner to visualize the scope of the facility. In Case 5 for example, the architects cut sections and other views from the ArchiCAD product model and generated more than ten virtual walkthroughs at different phases of the design in support for spatial visualization and communication with the clients and end-users.

At this stage, 3D CAD is also used in a virtual reality environment to support conceptual design reviews for the required sightlines, acoustics, or lighting/interior finishes so that the best functional space can be provided for end users' needs. 3D

Table 1: An Overview of Case Projects

Case #	Case Projects
1	McWhinney Office Building, Colorado (1997-1998)
2	Sequus Pharmaceuticals Pilot Plant, Menlo Park (1997- 1999)
3	Experience Music Project, Seattle (1998 - 2000)
4	Paradise Pier, Disney California Adventure, Los Angeles (1998 - 1999)
5	Helsinki University of Technology Auditorium-600 (HUT-600), Helsinki (2000 - 2002)
6	Baystreet Retail Complex, Emeryville (2000 - 2002)
7	Genentech FRCII, South San Francisco (2001 - 2003)
8	Walt Disney Concert Hall, Los Angeles (1999 - 2003)
9	Hong Kong Disneyland, Hong Kong (2001 - 2005)
10	Pioneer Courthouse Seismic Upgrade and Rehabilitation Project, Portland (2003 - 2005)
11	MIT Ray and Maria Stata Center, Boston (2000 - 2004)
12	Banner Health Good Samaritan Hospital, Phoenix (2002 - 2004)
13	California Academy of Science Project, San Francisco (2003 - 2006)
14	Terminal 5 of London's Heathrow Airport, London (2003 - 2007)
15	Residential Building in Sweden, Stockholm (2002 - 2003)
16	Pilestredet Park Urban Ecology Project, Oslo (1997-2005)
17	GSA Regional Office Building, Washington DC (2004-2007)
18	GSA Jackson Courthouse, Jackson, Mississippi (2004-2007)
19	Samsung LSI Fab Facility, Kiheung, Korea (2004-2005)
20	Camino Medical Campus, Mountain View, CA (2004-2007)
21	Fulton Street Transit Center, New York City (2002-2007)

models help to resolve functional issues before construction starts.

In the schematic design phase, the owner often initiates 4D CAD for strategic project planning. Especially for a large-size project executed by multiple prime contracts, 4D models help the owner strategically plan the project milestones and determine the optimum contractual work packages. In Case 4 for example, the owner successfully used the 4D visualization to determine the contracting packages by visualizing the break-up of project scope into various contractual "chunks" in the context of the 3D model and by seeing the progression of these contractual 'chunks' over time in the context of the 4D model. The 4D model was also used for phased handover, i.e., how to manage the scope and sequence of bid packages so as to close the gaps as work was handed off from one party to another. On another project (Case 9) from the same owner of Case 4, the 4D model coordinated the smooth process of handing over the preliminary site from the local Department of Public Works to the owner's construction team before the deadline.

2.2 3D CAD used in the Design Development Phase

In the design development phase, 3D models shift some of the project team's efforts from producing traditional outputs (e.g., design documents) to more value-adding work (e.g., exploring more alternatives). For instance, on Case 5 the architects reported about 50% time savings in the design documentation phase as a result of object-oriented libraries and catalogues, parametric properties, knowledge reuse, and various automation tools. Furthermore, the 3D models modeled three design and two life-cycle alternatives. The savings potential through life cycle cost comparisons was in the 5 to 25 % range of the project's life cycle costs.

During the development of a building project, changes that stem from design discrepancy checking are constantly made to fine tune the design. Traditional methods typically do not facilitate change effectively. The creation of design documents can be laborious and require a vast amount of low-value drafting tasks including manual checking of work. On the project (Case 5), the model checking system in 3D CAD supplemented the designers' personal skills by automatically highlighting design errors (e.g., collision of building components). Moreover, Case 20 demonstrates that general contractors can be involved early in the design development phase to validate the design, to make sure that the construction methods and techniques are considered during the design process, and to give feedback to the architect.

2.3 3D and 4D CAD used in the Detailed Design Phase

In the design development documents, many of the systems that must be included - mechanical, electrical and structural - are shown schematically, but not in detailed depictions of the manufactured items that go in the building and the systems that tie into them. The GC distributes these documents to the different subcontractors that are involved in the project. The subcontractors submit back to the GC the information associated with their proposed product, which entails specific work plans and shop drawings. The GC often initiates 3D and 4D CAD to coordinate the detailed design process. The subs are responsible to provide 3D models that are constructible (for example, if a slab will be poured in five sections then the model should represent the slab as five distinct objects.) The GC then puts together a 3D coordination model and uses the collaborative weekly work planning meetings to assign 3D objects to the activities to create a 4D simulation. The 3D coordination model establishes an interface between the different systems involved in the project and can be used to check the accuracy of the design. The 4D simulation can ensure that the works carried out by different subcontractors do not interfere. In Case 14, using 3D models for design coordination made it easier to spot and to dramatically reduce the number of design errors. Onsite RFI's were reduced by 80%. On another project (Case 2), none of the change orders in this project resulted from unexpected design conflicts among the MEP work. There were 60% fewer requests for information because many of the issues were resolved through the detailed design coordination process rather than the RFI process. In addition, the use of 3D models enables the creation of a collaborative project management context among subcontractors whose interests are often conflicting with each other. It is primarily because in a 3D environment, subcontractors are able to see potential consequences of actions prior to taking them. This lowers risk and cost for the subcontractors because the 'unknowns' are less looming.

2.4 3D CAD used in the Construction Documents Phase

3D CAD expedites the production of construction documents. 3D models allow the generation of elevations and plans in a single step as well as modifications to one model. During the construction documents phase of Case 11, 2D plans extracted from the CATIA model were detailed in AutoCAD to create contract drawings and specifications. As new data was created in this phase, it was imported back to the CATIA model, where attribute information was added to design elements.

In addition, 3D modeling in Case 14 was used to synchronize drawing production with material procurement. The concrete contractor faced an extremely congested site that accommodated only three day's worth of materials in support of construction. The batch size of drawings from 3D models was aligned with the batch size of the work packages on site. A small batch size of shop drawings and frequent orders reduced the lead-time on materials from 10 days to 3 days.

2.5 3D and 4D CAD used in the Preconstruction and Early Construction Phase

Bills of materials can be exported from 3D models to support the cost estimating and procurement process. This quantity takeoff information is extremely valuable in estimating the cost of the building as well as in estimating exactly how much material and labor will be needed in construction. In Case 2, the GC reduced the estimating effort by 25% through using “3D plus cost” integration. In Case 5, automated cost estimating led to an 80% reduction in time to generate cost estimates (including model analysis and creation of alternatives), as well as to a cost estimation accuracy of +/-3%.

Dimensions of prefab components can be exported from 3D models to automate the fabrication process. In Case 3, the 21,000 eccentrically shaped metal shingles that form the outer shell were cut by lasers guided by data generated directly from the modeling software. This ensured that fabricated panels would line up precisely on site and no or little field-fitting would be required.

3D CAD can also be used for site dimension control during the construction process. Taking Cases 3, 8, 11 for examples, laser surveying equipment linked to CATIA 3D models enabled each piece to be precisely placed in its position as defined by the 3D model.

At the proposal stage, 4D models can be used in presentation to help the owner visualize the future and demonstrate that the GC has the best approach for executing the project. Following the experience on Case 12, 4D models helped the GC in winning two major hospital expansion projects and a project for the construction of a new hospital with the same client.

4D CAD can be used as part of the bidding process to demystify the design and make construction bids closer in range. In Case 4, the owner's estimate and GCs’ bids were very close. The bid results were within +/- 2.5 percent of the budget.

4D CAD can improve schedule reliability and executability in the preconstruction phase, which enables a smooth progression of construction activities on field. As demonstrated by all the 4D cases, the 4D modeling process makes it very clear where complete scope and schedule information exists and where additional thinking about the missing information apart from 3D models and original schedule is needed. Meanwhile, by requesting clarifications during the 4D modeling process, the project team can often clear up some logic bugs in the schedule while there is still time for such adjustments without detrimental impacts on the project. Early discovery of conflicts also increases the accuracy of the schedule.

4D CAD can also be used for constructability review in the preconstruction phase to detect potential site logistical challenges and accessibility problems. On Case 20, the 4D model helped work through different scenarios of logistics and sequence planning so that decisions about logistics could be made quickly. One example of the decision that had to be made is how the underground parking structure would be integrated with the office building. The scenario shown in the 4D model was much clearer than that shown in the 2D drawings. The use of 4D models increased the number of RFIs during the preconstruction phase. However, by having 4D model, the GC expects to reduce the number of RFIs in the construction phase.

4D CAD can assist in trade coordination weeks before work starts on field. For the purpose of construction coordination in 4D, no activity should be longer than 10 days. Therefore, a 4D coordination model should reach the level of detail at which the day-to-day operations of the various subcontractors (i.e., when each of the subcontractors would be working in each zone) are represented. For instance, in the detailed model in Case 11, the geometry was broken down by individual metal panels, corresponding to each day of construction. During the construction phase, viewing a 4D model with trade management personnel elucidated work flow and provided visual justification of the general contractor's work logic. Bringing various subcontractors together to view the 4D model helped participants to predict which areas would be congested and enabled the general contractor to coordinate activity in the staging areas for the trades and resolve certain conflicts in the virtual model before they became real problems. In addition, 4D coordination models help focus the subcontractors’ attention on the project and foster collaboration between them. In Case 8, the project's general superintendent estimated that for every hour he spent working on the schedule, he needed about six hours to communicate the schedule. The 4D model enabled him to reduce that time while increasing the amount of subcontractor feedback and commitment.

To reap the full benefits of 3D and 4D CAD as delineated in the above review of the multiple case studies, we need to identify controllable factors in an implementation plan. The following example details key controllable factors of 3D and 4D CAD implementation, i.e., the why (modeling purposes), when (timing), who (stakeholders' involvement), what (modeled scope and level of detail in data model), how (software tools and work/information flows), and how much (estimated time and efforts).

3 AN EXAMPLE: THE PILESTREDET PARK URBAN ECOLOGY PROJECT IN OSLO, NORWAY

The objective of the Pilestredet Park Project [1] was to (re)develop and construct urban ecological housing and office buildings, which fulfil a broad set of quantified environmental goals. Approximately half of the original floor space were demolished (55,000 square metres), and there have been built around 85,000 square metres of new construction, plus around 55,000 square metres of renovation to existing buildings (Butters et al. 2002).

3.1 Modeling Purpose

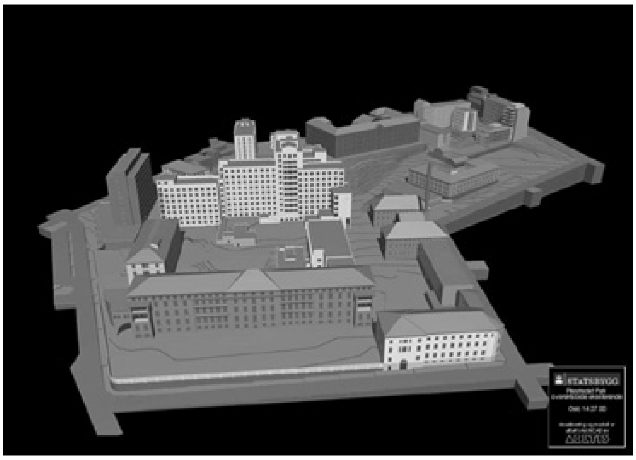
Given the strict environmental demands, no-one really knew how this was going to be done or how it would work out when the project started. The initial step for the owner (Statsbygg)[2] was to set up interdisciplinary expert teams, with resource people and consultants from different fields, to discuss and define the main ecology criteria. On the basis of these preliminary studies, the Urban Ecology Program was formulated. Having thus far outlined the background, the existing situation, the intentions and goals of the project and a total construction schedule given within 5 years, the owner realized that they might better visualize and "communicate" this large urban project within own staff, among involved architects, planners, consultants, public, neighbours, constructors and the municipality by using 3D and 4D models.

3.2 Timing

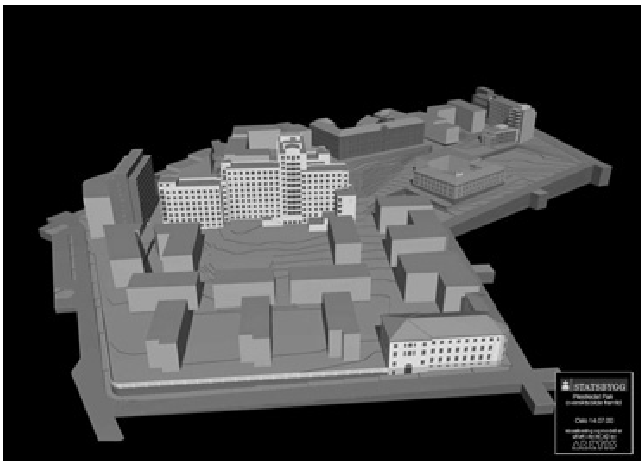
A 3D model that modeled the site and buildings was built in half a year in the schematic design phase. Simultaneously software developers were working with the 4D coupling module (API), and as the first samples of the API arrived 4D models were established in beta testing. About a year after the3D/4D initiative was taken, the requirements to the 4D model were fulfilled and videos and pictures were produced and used in the following planning, demolition and construction process (Kvarsvik 2004).

3.3 Stakeholders' Involvement

Statsbygg initiated the 3D and 4D modelling in 1998. There has been firm backing for the project right up to the very top of the organization both to go through with an ambitious urban ecology initiative and the 3D and 4D effort. The Graphisoft supplier in Norway, Arktis AS, built the 3D model. Graphisoft in Hungary achieved the contract to develop a program (called API) linking the 3D model to the schedule. A broad range of participants, including Statsbygg's own R&D director, Faculty of Architecture and Fine Arts at NTNU, the Pilestredet Park Project Manager, Oslo Municipality, and the R&D department of a large Norwegian constructor, were represented in the technical board



Before



After

Figure 1: 3D illustrations from the Pilestredet Park Project in Oslo, Norway

[1] Total reconstruction of an abandoned hospital area in the center of Oslo, 70,000 square metres urban site, with an agglomeration of hospital buildings from 1870 to 1990.

[2] Statsbygg – The Norwegian Directorate of Public Construction and Property

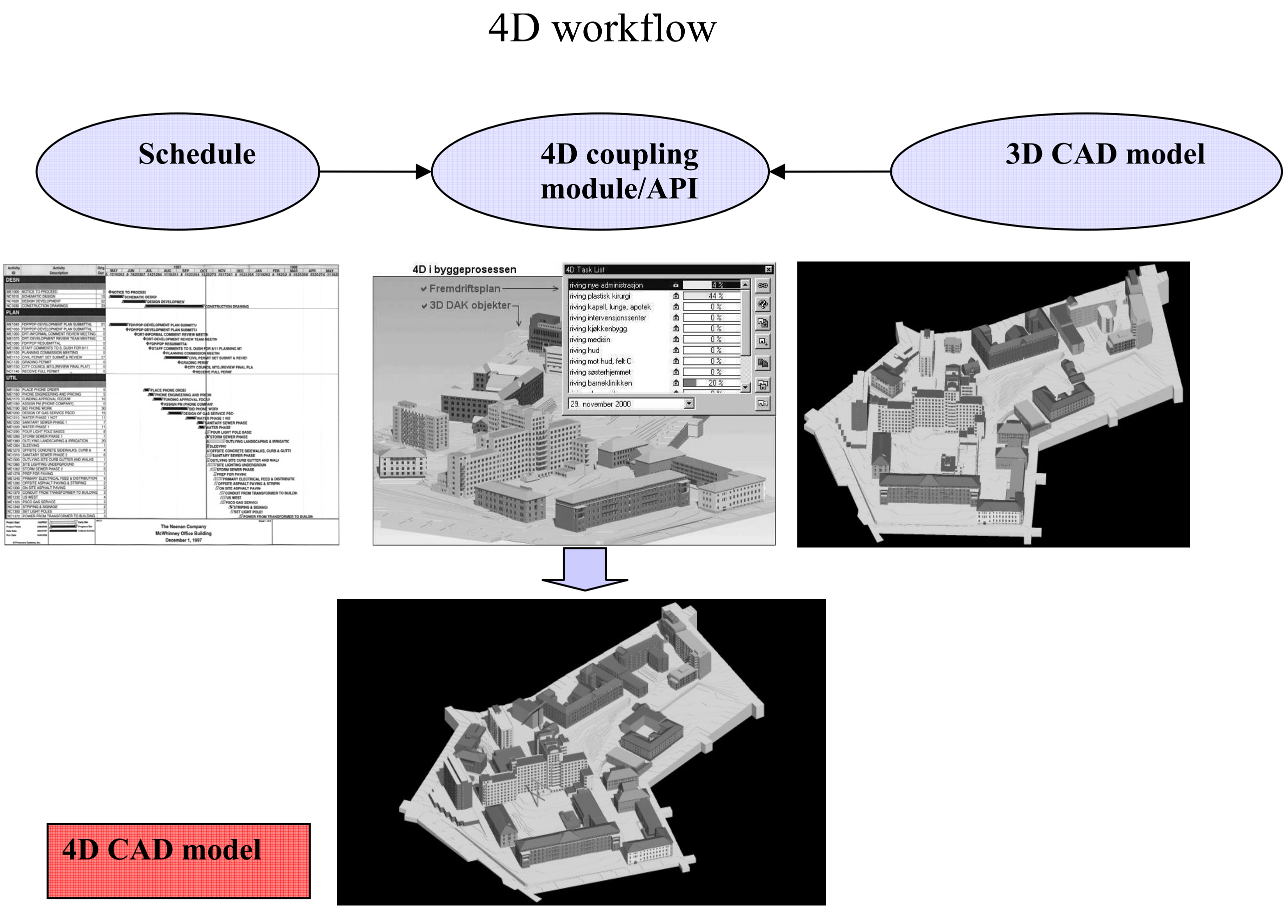


Figure 2: 4D illustrations from the Pilestredet Park project in Oslo, Norway. This figure illustrated the connection and dependencies between the 3D CAD software and the project schedule for the purpose of 4D modeling. Each floor in every building had specific dates for the start and end of construction, and the activities are color-coded for the visualization in 3D-movies. (Statsbygg 2001)

3.4 Modeling Tools

The requirements/specifications were established for the project in the first phase (Kvarsvik 2003):

1 The 3D model should represent the complete scope of the project that includes the site and buildings (exterior shell and interior floors). At that time, this was the largest 3D model built in Norway (onshore).

2 A coupling module (API) should be developed to enable the link between the construction schedule and the 3D model (Figure 2). The API had to be a part of or operated from the CAD tool.

3 The construction schedule has to be linked to the 3D model to produce a visual construction plan, i.e., a 4D model. In the construction schedule, each floor or object in each building must have dates for the start and end of construction.

4 The 3D model must be easy to use so that the professionals in the project management with limited modeling skills can utilize 3D and 4D tools on the job.

After establishing the modeling specifications, Statsbygg looked for suitable software solutions that could be operated within the project team. After market research, interviews and testing of a few existing 4D softwares, Statsbygg chose Graphisoft's ArchiCAD "Virtual Model" (a database) and Microsoft Project as the two programs used in the project. ArchiCAD was chosen because it is an object-oriented "intelligent" software (i.e. the objects can carry information). Microsoft Project was chosen because this was the most-widely used scheduling software in Norway at that time.

3.5 Modeled Data

- The different activities were colour-coded. In the Pilestredet Park Project, five different types of activities were illustrated: Build – (blue); Demolish – (green); Restore – (orange); Temporary (provisional activities on site, e.g., rigging, cranes, staging, etc.) - (light blue); Freeze (closed-off) - (red).
- The 4D model had a low level of detail which only modeled exterior shell and interior floors for every building

Modeling Workflow:

- The activities were defined, developed and edited in the scheduling program.
- Working with the 3D model in ArchiCAD the Construction Simulation API was started, and the schedule was imported. The activities could also be defined, developed and edited directly in the Construction Simulation tool (Kvarsvik 2004).

- The correct links between the 3D model and the activities were worked out by Statsbygg in the API.
- Statsbygg focused on how to improve the information flow and the communication among actors throughout the complete building process. Statsbygg tested and visualized the status of the project (the whole project or part of it) by a certain date or a particular construction phase, either in the elevation or the plan or in the 3D or 4D.

3.6 *Cost and Effort*

In collaboration with Statsbygg, Graphisoft developed their 4D "Construction Simulation" tool by analyzing and testing it in the Pilestredet Park Project. Two years after the project started, Graphisoft released "Construction Simulation" in the ArchiCAD 7.0 edition in 2001 world wide, which was an extremely short period from R&D to a commercial product. Statsbygg paid about 160,000 Euros to Arktis and Graphisoft for building the model, developing the API, and supporting the software in the Pilestredet Park project. One person in Statsbygg was in charge full-time for managing, operating and testing the 4D building model.

3.7 *Benefits of Supporting Product, Process and Organization*

3.7.1 *Process*

1 In a great number of meetings with participation of many people from different levels of organizations, the 4D model enabled project stakeholders to get a rapid insight and overall view of the challenges in the project.

2 On an urban site in the middle of Oslo, the 4D model played an important role in planning and managing the site. It illustrated different issues related to the building process with special respect to logistics in the phase of site demolition, i.e., the administration of storing, process and transporting material in and out of the site. Taking another example, Kvarsvik (Kvarsvik 2004) said in an interview that since all demolition materials were to be crushed and processed on site, the 4D model got project participants to realise the impact of different locations of the crusher on the surrounding areas and take steps to minimize the noise and dust from the demolition process.

3 Statsbygg maintained that more benefits would have been achieved by building the 3D and 4D models earlier in the project, when the old hospital area was considered to be demolished and planned for new use. In this way, the 3D and 4D models would have given quick feedback of different development scenarios to the planners.

3.7.2 *Organization*

The most obvious benefits of using the 3D and 4D model manifest themselves in working as a communication tool to engage all the stakeholders like architects, planners, consultants, builders, authorities, public communities. The 3D and 4D models gave Statsbygg insight in terms of cultivating an open and democratic culture in the project team for planning and building this project.

1 The 3D and 4D models gave the project team the input for important and future-oriented solutions, which supported the team spirit.

2 Kvarsvik also said that using 3D and 4D models attracted young and clever professionals.

3.7.3 *Overall Business Performance*

There are a number of benefits associated to costs. Experiences from the Pilestredet Park project showed that the 3D and 4D model contributed to lower the project costs on the following accounts.

1 More easily visualizing the project scope and soliciting insight to the project goals contributed to better communication and information flow, which allowed the accomplishment of project goals.

2 Detection of interferences during the design process provides opportunities for quality assurance in the construction phase (i.e. on site).

4 CONCLUSION

Experiences from the reviewed case projects demonstrated the benefits of 3D and 4D CAD for various modeling purposes in different project phases. These experiences acknowledge 3D and 4D CAD as a key driver and a primary enabler for better design of Product, more cohesive Organization, and more efficient Process that lead to project success. The case study on the Pilestredet Park Project in Oslo, Norway indicates that 3D and 4D CAD is not simply a question of investment but rather of appropriately planning and managing the implementation, i.e., understanding the appropriate *modeling purposes*, identifying the right *timing*, *people*, *data*, *tools* for doing it, and putting them in the right *workflow*. These are key controllable factors in the implementation process for realizing the expected benefits. Next, we will further look into how an appropriate control of these implementation factors can be translated into more benefits and what kind of metrics can be used to measure the implementation and benefits of 3D and 4D CAD.

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Appendix A: Various Uses/Purposes of 3D and 4D CAD and Reported Benefits on Case Projects

	Project Phase	Modeling Purpose	Benefit (Product, Process, Organization)	
3D	Conceptual/ Schematic Design	Briefing of project scope	**Org. (communication)**	Enable project players to better understand project scope
			Case Example	(2) (3) (8) (11) (4) (5)
		Evaluation of design forms vs. functions	**Product**	Improve quality of functional design
			Case Example	(5) (18)
			Process	Expedite evaluation of functional design
			Case Example	(5) (18)
	Design Development	Analysis of system options	**Process**	Enable development of multiple design alternatives early
			Case Example	(5) (11)
		Design discrepancy (constructability) checking	**Product**	Improve design accuracy, reduce design errors and inconsistency
			Case Example	(5) (11) (20) (21)
			Org. (communication)	Enable designer better understand field-related design issues
			Case Example	(11) (20) (21)
	Detailed Design	Detailed design coordination (MEP subs, fabricator, etc.)	**Product**	Improve design accuracy, reduce design errors and inconsistency
			Case Example	(2) (3) (7) (8) (10) (11) (14) (20)
			Process	Expedite detailed design coordination and shop drawing approval process
			Case Example	(2) (7) (14)
			Org. (coordination)	Engage CM/GC and subs earlier and more in the design phase
			Case Example	(3) (8) (11)
				Enable a collaborative project management context among GC and subs
			Case Example	(2) (3) (7) (8) (10) (11) (14) (20)
	Construction Documents	Drawing production	**Product**	Improve quality of design output
			Case Example	(14)
			Process	Expedite production of construction documents
			Case Example	(3) (5) (8) (11)
				Synchronize shop drawing production with material procurement
			Case Example	(14)
	Preconstruction	Automated quantity takeoff	**Process**	Expedite cost estimating/procurement process; Improve estimation accuracy
			Case Example	(2) (5) (7)
	Construction	Automated prefabrication	**Process**	Expedite fabrication process; Improve installation accuracy
			Case Example	(3) (8) (11) (14)
	Construction	Site dimension control	**Process**	Expedite site layout process; Improve surveying accuracy

	Project Phase	Modeling Purpose	Benefits (Product, Process, Organization)	
4D	**Schematic Design**	**Strategic project planning**	**Process**	Expedite work packaging
			Case Example	(4)
				Facilitate phased handover
			Case Example	(9)
				Support evaluation of multiple construction strategies
			Case Example	(9) (13) (15)
			Org. (communication)	Engage many project participants in project planning
			Case Example	(4) (16)
				Facilitate visualization of project scope and insights to project goals
			Case Example	(4) (16) (20)
	Preconstruction	**Proposal**	**Org. (communication)**	Show contractor's capability to execute the work
			Case Example	(11) (12)
	Preconstruction	**Bidding**	**Process**	Make construction bids closer in range
			Case Example	(4) (11)
			Org. (communication)	Brief bidders of owner/GC's intention
			Case Example	(4) (11) (12)
	Construction	**Permit approval**	**Process**	Expedite permit approval process
			Case Example	(8) (11)
	50% Construction Documents - Construction	**Master scheduling and construction sequencing**	**Process**	Improve schedule reliability and executability
			Case Example	(1) (3) (4) (7) (8) (9) (11) (19) (6)
				Synchronize facility operation and construction
			Case Example	(12) (17)
			Org. (communication)	Facilitate communication of the required sequence per specification
			Case Example	(10)
				Facilitate communication of construction status to end users
			Case Example	(12)
			Process	Enable early detection of potential site logistics and accessibility problems
			Case Example	(1) (3) (4) (5) (6) (8) (9) (10) (11) (12) (13) (14) (16) (19) (20) (21)
	50% Construction Documents - Construction	**Constructability review**	**Org. (communication)**	Externalize and share project issues
			Case Example	(1) (3) (4) (5) (6) (8) (9) (10) (11) (12) (13) (14) (16) (19) (20) (21)
			Process	Enable early perceptions of work scope and interference between trades
			Case Example	(2) (3) (7) (8) (11) (14) (19) (20) (21)
	Construction	**Trade coordination**	**Org. (coordination)**	Facilitate coordination between GC and subs
			Case Example	(2) (3) (7) (8) (11) (14) (19) (20) (21)