MULTIDIMENSIONAL MODELING: A MECHANISM FOR IMPROVING CONSTRUCTION PROJECT MANAGEMENT

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ABSTRACT

"Multidimensional Modeling" is an automated, visual and digital representation of various dimensions of a project which uses availably commercial software or an exclusive computational tool. A "Dimension" is any variable that a professional needs to know and analyze in order to manage a construction project, and which can be used during the whole life cycle of the project, from the design stage all the way to the operation stage. The modeled dimensions were the surface, space, time, constructive sequence and the execution strategy, quantity takeoff, cost, safety, and activities performance history.

Performance indicators were used to evaluate the use of the model which was proposed as a mechanism for improving construction project management. The validation and evaluation of the multidimensional modeling was performed using the foolproof method for three case studies (Chilean building projects).

The use of the multidimensional modeling increased transparency during project execution and simplified the coordination, control and planning processes. This was accompanied by improvements in availability, consistency, accessibility and reliability of information from the project, and with a decrease in uncertainty regarding project scope and performance. Additional observations included improvements in speed and in the decision making process, and improvements in communication among project participants.

KEY WORDS

Information Technology, Lean Construction, Multidimensional Modeling, Construction Management.

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INTRODUCTION

Information Technology (IT) is a knowledge group commonly referred to as information production, distribution, storage, recovery and use. The three most important elements of IT are tools (e.g. software and hardware), people (e.g. facilitators and users) and work processes that are necessary to efficiently implement and use IT to manage construction projects (Rischmoller and Alarcón 2005).

A building professional uses traditional tools and documents (sheets, technical specifications, Gantt diagrams, 2D sketches, "S" curves, etc.) to predict, understand and communicate the scope and performance of the project to various participants of the project. The amount of information for a project and the way in which it is represented and organized influence the complexity and uncertainty of the project. Due to this fact, usually the traditional management practice is not the most efficient way to plan, control and coordinate the activities of a construction project. A digital construction model which describes all of the aspects of the project: design, operation and construction (Bertelsen 1992) can greatly contribute to improve construction management practices.

Currently, models that digitally represent project information and the knowledge of professionals (e.g. digital 3D and 4D models) are investigated, developed and/or applied, to accurately and promptly predict the scope and performance of a project, and to facilitate the decision making process during the initial stages of the project.

MULTIDIMENSIONAL MODELING DURING THE EXECUTION STAGE OF THE PROJECT

Multidimensional Modeling is an automated, visual and digital representation of several dimensions of a project, which uses commercially available software or an exclusive computational tool. A Dimension is any variable that a professional needs to know and analyze in order to manage a construction project, and can be used during the whole life cycle of the project, from the design stage all the way to the operation stage. Some dimension examples are: space, time, quantity takeoff, cost, safety, resources, habitableness, etc. (Izaguirre 2006).

Currently, at least two research lines related to Multidimensional Modeling should be identified: "nD Modeling" developed in Salford University-UK and "Virtual Design and Construction" developed in Stanford University-USA. The first research line has the goal of creating a multidimensional model based on an exclusive computational tool (SCRI 2003) and the second one seeks to develop multidimensional models using commercially available software (Fischer and Kunz 2004). Both research lines promote the development of models early in the design stage to maximize the benefits for the participants of the project (e.g. client, designer, constructor, etc.). However, there are actors in the construction industry that are reluctant to implement the model from the design stage because they do not visualize the potential benefits of its use.

The second approach was selected for this research due to practical reasons: the research was carried out working with companies that had access to commercially available software; limited time to carry out research in existing projects; nD software from Salford is not readily available for this type of applications. This article reports on three case studies where models were developed during the execution stage of the project.

LEAN CONSTRUCTION: A CONVENIENT THEORETICAL FRAME USED FOR INVESTIGATING THE INFORMATION TECHNOLOGY

Lean Construction offer a convenient theoretical framework to address the practical experiments and investigation of IT during the design, planning, construction and supply processes of the project (Rischmoller and Alarcon¸ 2005).

The existing complexity and uncertainty regarding the scope and performance of a project creates variability during the construction processes and leads to waste during project execution (e.g. delays, suspensions, redone work, etc.). Some IT tools contribute to the application of some Lean Construction principles. For instance, simplification and transparency are two principles that can be easily applied using multidimensional modeling to counteract existing complexity and uncertainty in a project. From a Lean Construction perspective, multidimensional modeling works as a buffer of information and knowledge represented in a digital and visual way, that can be used to simplify and to increase transparency in the coordination, control and planning processes. The expected improvements can be summarized in the following four points.

- An increase in the availability, consistency, access facility and reliability of the project information.
- A decrease in the uncertainty that a professionals and workers in general have regarding the scope and performance of a project during its execution.
- An increase in speed and process quality during decision making.
- An improvement in the understanding and communication among participants of the project.

RESEARCH SCOPE

Researching and applying the IT was carried out keeping in mind to seek local benefits (e.g. in every sector) not necessarily for all the construction industry (Eastman et al. 2002). For this reason, the research primarily focused on implementing multidimensional modeling on Building projects, during the execution stage (PULL approach). Nine dimensions were modeled and studied: "Surface" (First 2 dimensions), "Space" (First 3 dimensions), "Time" (fourth dimension), "Execution Strategy and Constructive Sequence" (fifth dimension), "Quantity Takeoff" (sixth dimension), "Cost" (seventh dimension), "Safety" (eighth dimension) and "Activities Performance History" (ninth dimension). Dimensions five and eight are modeled together with the time dimension.

Two types of multidimensional models were developed during the research; one of them had a digital 3D model (space) as a base and the other had a digital 2D model (surface). Based on those models, new dimensions were incorporated (4th, 5th, 6th,…, 9th dimension).

Commercially available software was used to elaborate multidimensional models: a quantity takeoff and modeling software[3], planning and control software[4], virtual navigation and

[3] Autodesk Architectural Desktop (ADT)
[4] Primavera Project Planner® (Primavera P3)

visualization software[5], spreadsheet software[6] and database software[7]. The integration of the information from the different modeling dimensions was achieved by using the functionalities of each software. For instance, the navigation software integrates design and scheduling information, the planning and control software can be easily linked with the spreadsheet and database software. These functionalities allowed easy updating and integration of information of the different dimensions.

USING CASE STUDIES TO VALIDATE AND EVALUATE MULTIDIMENSIONAL MODELING

Validating a structure and operating a multidimensional model meant conforming that it correctly represented and displayed available information and knowledge of each of the case projects. Both processes were carried out using foolproof methods in three case studies. The following performance indicators were used to evaluate the impacts:

- Number of design changes performed in advance.
- Number of incongruities found in the design documents.
- Degree of difficulty of predicting and imagining the scope of the project.
- Speed and process quality during decision making.
- Effectiveness in communications among the participants.
- Efficiency in handling project control information.
- Precision in project quantity takeoffs.
- Efficiency in handling project quantities and costs.
- Predictability of safety risks.
- Number of changes made during construction and the execution strategy.
- Ability to detect non planned elements of the project.
- Level of automation of the information upgrade process.

Quantitative indicators were directly measured and compared with similar projects in the company experience. Qualitative indicators were measured using interviews to professionals involved in the projects that required them to compare the indicators of the current project with those in similar projects in their past experience. All the companies participating in the research have had recent experiences in similar projects and this fact contributed to their interest in participating in this research.

[5] SmartPlant Review (SPR)
[6] Microsoft Excel
[7] Microsoft Access

CASE STUDIES

A multidimensional model was used in each of the three case studies (Building projects) in order to improve construction project management. The results obtained are discussed below. The implementation approach required close interaction between the researchers and each of the project teams. The research team visited the site twice a week and participated in planning meetings providing modeling support.

Case Study Nº 1: Americo Vespucio Station – 2nd Line of the Santiago Subway

The scheduled project duration was 560 days and the budgeted cost was 16.9 million dollars. Two types of multidimensional modeling were implemented for this project. One type, based on a digital 3D model, was developed to manage construction of the frame structure. A second type, based on a digital 2D model, was used to manage and improve the visualization of the finishing work. The dimensions modeled to manage the frame structure of the project were[8]: the first three dimensions that represented space (a 3D view of the project), time, the construction sequence and the execution strategy, the quantity takeoff, cost and safety.

Figure 1 shows the scope of the project digitally and in 3D, and the quantity takeoff of concrete extracted from each of the drawn elements.

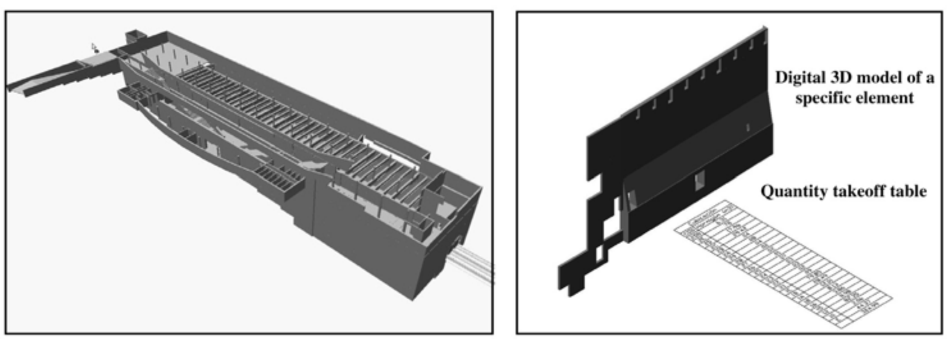

Figure 1: A Digital 3D Model of the Subway Station and the Quantity Takeoff of Concrete

The quantity takeoffs were exported to the spreadsheet software where the structuring of the project activities was carried out, and then were loaded along with the costs into the planning and control software. The planning and control software had the potential of filtering and organizing information, and showing the histogram of the costs and quantities over time (see Figure 2).

[8] The "activities performance history" dimension was not modeled for lack of time during implementation.

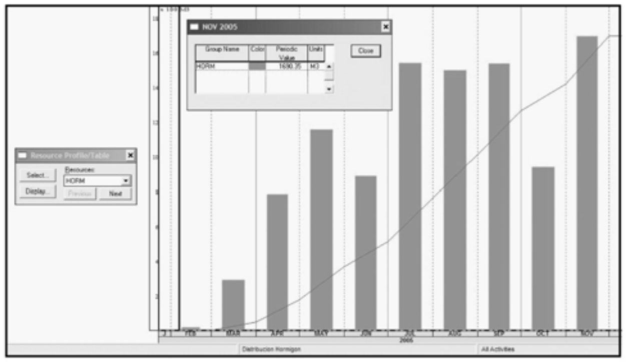

Figure 2: Monthly Histogram of Concrete in m^3

The "time" dimension was modeled by linking the start and end dates of the activities of the construction program with the elements of the digital 3D model ("database" and "visualization" software were used). The development of project activities overtime (4D Planning and Scheduling) was displayed in 3D using colors and textures. One use of 4D visualization was visual control and tracking of project progress, as shown in Figure 3.

"Safety" and "execution strategy and construction sequence" were modeled by default with the "time" dimension. Table 1 summarizes the benefits obtained from using the multidimensional model to manage construction of the frame structure of the project.

Table 1: Benefits Obtained in Construction of the Frame Structure from Case Study Nº1

CASE STUDY / DIMENSIONS USED	CASE Nº1: AMERICO VESPUCIO SUBWAY STATION — COSTRUCTION OF FRAME STRUCTURE — Benefits that were Obtained
Space (First 3 Dimensions)	Detected 2 incongruities found in the project bue prints which were due to interferences.
	Explained 2 conexion details among the elements.
	Design changes in order to simplify the constructive process and standardize the selection of the prefabricated beams. Virtual scanning was carried out throughout the 3D model.
	High speed and high quality decision making process; used by professionals in order to build complex conexion details.
	High effectivess in communication and understanding among diverse participants of the project, during the communication process of work scope and complex construction details.
Time (4th Dimension)	High effectiveness in detecting non scheduled elements of the project. These represented close to 389m3 of reinforced concrete (a loss of US$195,000 due to the fact that they were not budgeted and the project was a lump sum).
	Automation of information updating process. Any change performed in the construction program was automatically updated in the digital model (e.g. the duration of the activities).
	High effectiveness in communication and understanding among diverse participants of the project, during the review of actual and scheduled progress of the job using a digital 3D display.
	High efficiency in the process of understanding information coming from the tracking and control of the project. A planning engineer used a digital 3D display to corroborate the calculated progress percentages and in to detect delays.
	High speed and quality in the decision making process; used by professionals to visually analyze and determine (in 3D) the activities of the project that should have been implemented.
Execution Strategy and Construction Sequence (5th Dimension)	5 changes were made in advance during the construction sequence of the project, due to incongruities found in the construction procedures.
	Automation of the information updating process. Any change performed in the construction schedule was automatically updated in the digital model (e.g. construction sequence).
	High effectiveness in communication and understanding among diverse participants of the project, during the analysis of the construction procedures used on the job.
	High speed and quality in thedecision making process; used by professionals to plan and reschedule the project activities, using a digital 3D display.
Quantity Takeoff (6th Dimension)	High precision in quantity takeoffs extracted from the digital 3D model. Approximately US$40,385 in estimating errors were detected due to inaccuracies in original quantity takeoff.
	High efficiency and effectiveness in handling project quantities. The planning engineer summarized and filtered information of the work quantities in a reliable and fast way.
	High speed and quality decision making process. Management decided to subcontract the execution of one sector of the job, when they detected early that they did not have enough capacity during an specific period of the project.
Cost (7th Dimension)	High efficiency in handling the project work costs. The planning engineer summarized and filtered information of the project costs in a reliable and fast way .
Safety (8th Dimension)	Increased effectiveness in detecting and predicting risky situations of the job, reducing the probability of accidents and the costs associated with them (suspensions and personal damages).
	Increased effectiveness of the decision making process; used by a risk preventionist to take preventive measures . The professional used a digital 3D display.

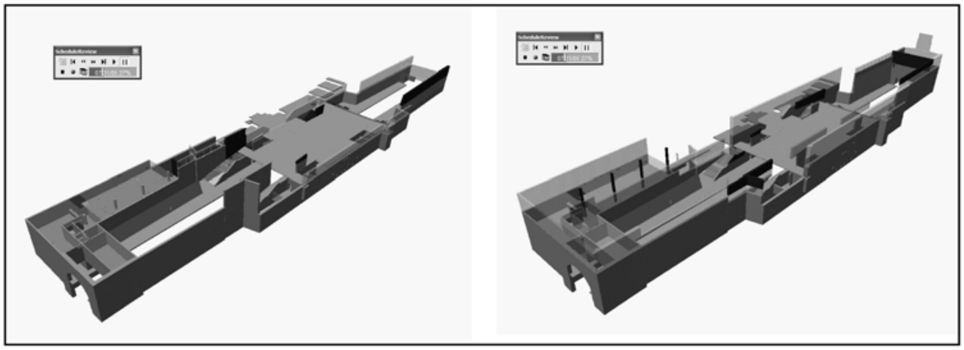

Figure 3: Visual Control and Tracking of the Frame Structure

The dimensions that were modeled and used to manage the finishing work of the project were[9]: the first two dimensions that represented the surface (2D floor plan of the project), time, the execution strategy and construction sequence, and the performance history of the activities. A first attempt to use 3D models for the finishing work showed practical limitations of the visual representation, elements of the superstructure overlapped with representation of the finishing work, making more difficult to visualize the work.

Figure 4 shows one of the 2D models elaborated to manage the finishing work. The floor plans were made using the modeling software and the activities in progress were assigned color codes. The floor plans were subdivided by colors according to the amount of work performed in each area.

Figure 4: A Digital 2D Model of the Service Level of the Station

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9 The "safety" dimension was not modeled because it only works with a digital 3D model. "Quantity takeoff" and "cost" dimensions were not modeled for this stage of the project.

The 2D models, linked to a finishing schedule, were used to display the progress state of the project in different moments in time. Figure 5 shows the completed activities in grey and the activities in progress in other color codes. The actual progress percentages of the activities are presented along with the corresponding color codes. These figures served, among other things, to perform the visual control and tracking of the project.

The models were also used to determine the number of crews that would be working simultaneously in a floor area. This information was used to analyze possible interferences that could occur and to explore solutions in advance (e.g. changing implementation strategy). Furthermore, the models allowed that visual tracking could be carried out over time and space for each crew or each subcontractor. The model was used as a mechanism for reducing work interruptions and produce continuous work flow. This was very effective in preventing subcontractors from removing resources temporarily from the project and avoiding the risk that resources could arrive late when needed and produce instability on the job. (e.g. delays and suspensions) (Sacks 2004).

The benefits that were obtained after using the multidimensional model to manage the finishing work of the project are summarized in Table 2.

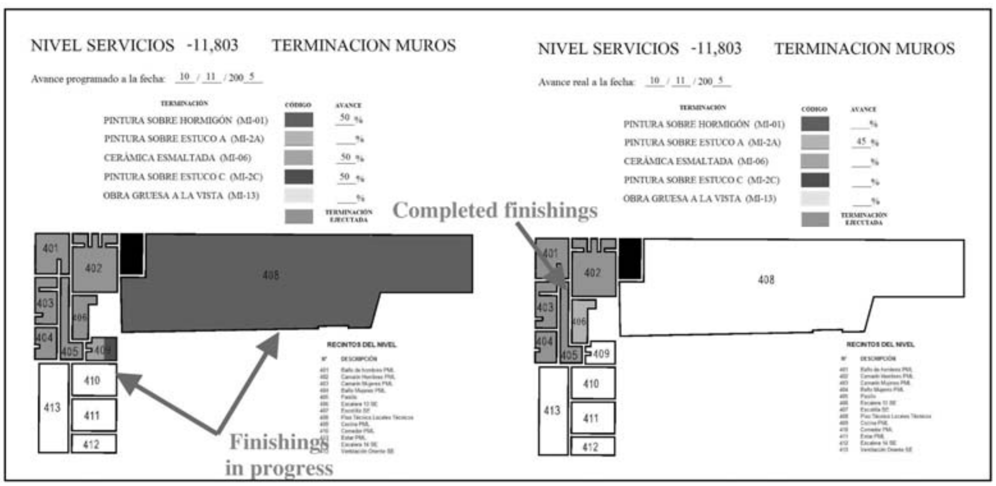

Figure 5: Visual Control and Tracking of Finishing Activities (Detection and Solution of Delays)

Table 2: Benefits Obtained in Finishing Work from Case Study Nº1

CASE STUDY / DIMENSIONS USED	CASE Nº1: AMERICO VESPUCIO SUBWAY STATION FINISHING WORK Benefits Obtained
Surface (First 2 Dimensions)	Increased effectiveness in communications among diverse participants of the project, during the transmission process of the ground location of several project finishings.
Time (4th Dimension)	Increased effectiveness for detecting non scheduled finishings of the project. A non scheduled finishing was detected in the project.
	Automation of the information updating process. Any change performed in the construction program was automatically updated in the digital model (e.g. activity durations).
	High effectiveness in communication and understanding among diverse participants of the project, during the review of actual and scheduled progress of the job using a digital 2D display.
	High efficiency in the process of understanding information coming from the tracking and control of the project. A planning engineer used a digital 2D display to corroborate the calculated progress percentages and to detect delays.
	High speed and quality in the decision making process; used by professionals to visually analyze and determine (in 2D) the activities of the projectof finishings that should have been implemented.
Execution Strategy and Construction Sequence (5th Dimension)	7 changes were made in advance while analizing the execution strategy of the project, due to incongruities in the chronological order in which the execution of the project was scheduled.
	High automation of the information upgrading process. Any change performed in the construction schedule was automatically updated in the digital model (e.g. construction sequence).
	High effectiveness in communication among diverse participants of the project, during discussion of execution strategies used on the job.
	High speed and quality in the decision making process; used by professionals to plan and reschedule activities of the project using digital 2D display.
Activities Performance History (9th Dimension)	Automation of information updating process. Any change performed to the database of the system was automatically updated in the performance history of the corresponding activity.
	High speed and quality in the decision making process; used by professionals to reduce or avoid repeating causes of non compliance of activities.

The dimension called "activities performance history" was modeled using a spreadsheet software and consisted of a "traditional" automated control system, which provided descriptive information, progress percentages and reports about causes of non compliance of the activities. This type of control was complemented with the visual control explained earlier. Figure 6 shows information regarding one of the project activities. All of the activities were coded (e.g. XXX-YY-ZZ) and in order to display information of another activity it was only necessary to change the code.

Ingresar codigo de actividad de la forma XXX-YY-ZZ, con:
XXX: Nº del recinto (Ej. 107)
YY: Tipo de terminación (PI= piso, CI= cielo, MI= muro)
ZZ: Especificación del tipo de terminación (Ej. 2A, 01, etc.)

Control de Terminaciones
Estación Vespucio

Tipo de Actividad	Terminación Piso	**Ubicación**	Acceso Sur
Código	101-PI-2A	**Recinto**	Hall Acceso Sur oriente
Descripción	Baldosa microvibrada negro		
Contratista	0		
Cubicación	0	0	

Resumen de Control

Control	Fecha de control	% de Avance	Cumplimiento	Razón
Nº 1	10/10/2005	10%	No	Cambio en la planificación
Nº 2	15/10/2005	70%	SI	
Nº 3	00/01/1900	0%	SI	
Nº 4	00/01/1900	0%	SI	

Programado

Fecha de inicio	22/07/2005	**Duración**	4 días
Fecha de término	27/07/2005		

Real

Fecha de inicio	**09/10/2005**	**Duración**	8 días
Fecha de término	**17/10/2005**		

Figure 6: Performance History of Activity 101-PI-2A

Case Study Nº 2: Dávila Clinic

The scheduled duration of the project was 510 days and the budgeted cost was 16.5 million dollars. A 3D model (a 3D view of the project) was created, from the 2D project blueprints, and used to manage the installations of the project[10] . Figure 7 shows some of the interferences found among the installations of the project, detected using a digital 3D model that was made based on the original 2D design drawings.

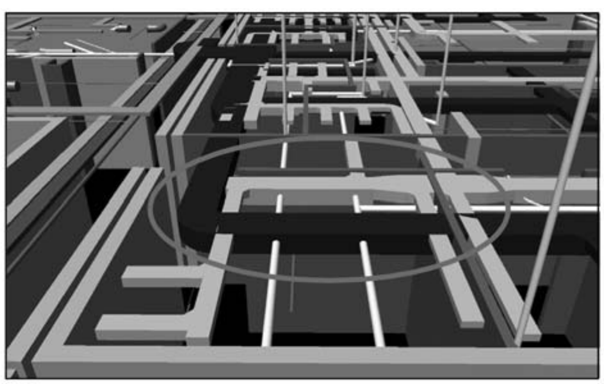

Figure 7: Interferences found among the Installations of the Project

[10] Other dimensions were not modeled due to time pressures during implementation.

The benefits obtained after using the multidimensional model to manage the installations of the project are summarized in Table 3.

Table 3: Benefits that were Obtained upon Managing the Installations from Case Study Nº2

DIMENSIONS USED \ CASE STUDY	CASE Nº02: DAVILA CLINIC — PROJECT INSTALLATIONS — Benefits that were Obtained
Space (First 3 Dimensions)	Detection of 287 incongruities in the projectblue prints due to interferences among the installations. Savings estimated by the contrator in US$ 32,100 in production cost (rework) and a 20 day in schedule (saving in general costs). A construction engineer used actual cost and duration information to perform the analysis.
	High speed and quality in the decision making process; used by professionals to efficiently solve interferences detected using the digital 3D model.
	High effectiveness in communications among diverse participants of the project, during the discussion of project scope and solutions for solving the interferences detected.

Case Study Nº3: San Pablo Condominium – First Phase

The project scheduled duration was 240 days and the budgeted cost was 1.3 million Dollars. The multidimensional model was based on a 3D digital model (first three dimensions) the additional dimensions modeled were[11] : time, execution strategy and construction sequence, and quantity takeoff. Figure 8 shows project progress in 3D visualization. Table 4 summarizes the benefits obtained in this Case Study.

Table 4: Benefits Obtained upon Managing the Frame Structure from Case Study Nº3

DIMENSIONS USED \ CASE STUDY	CASE Nº03: SAN PABLO CONDOMINIUM – FIRST PHASE — CONSTRUCTION OF THE FRAME STRUCTURE — Benefits Obtained
Space (First 3 Dimensions)	High effectiveness in communication among diverse participants of the project, during the project scope review.
Time (4th Dimension)	Automation of the information updating process. Any change performed in the construction schedule was automatically updaded in the digital model (e.g. activity durations).
	High effectiveness in communication among diverse participants of the project, during reviews of actual and scheduled progress status of the job, using a digital 3D display.
	Increased efficiency in understanding information coming from the project tracking and control system. The planning engineer used a digital 3D display to corroborate the daily progress.
	High speed and quality in the decision making process; visual analysis (in 3D) of project activitiesthat should have been implemented.
Execution Strategy and Constructive Sequence (5th Dimension)	Automation of the information updating process. Any change performed in the construction schedule was automatically updated in the digital model (e.g. construction sequence).
	High effectiveness in communication among diverse participants of the project, during the discussion of the constructioin procedures used on the job.
	High speed and quality in the decision making process; used by professionals to plan and reschedule activities of the project using a digital 3D display.
Quantity Takeoff (6th Dimension)	Improved accuracy of quantity takeoff extracted from the digital 3D model. There was close to a 0.5% difference with the values obtained using the traditional approach.
	Progress reports were supplied to the project manager; however, he didn't use it as intended to because he relyed more on the information coming from his traditional work approach.

[11] Other dimensions were not modeled for lack of time during implementation.

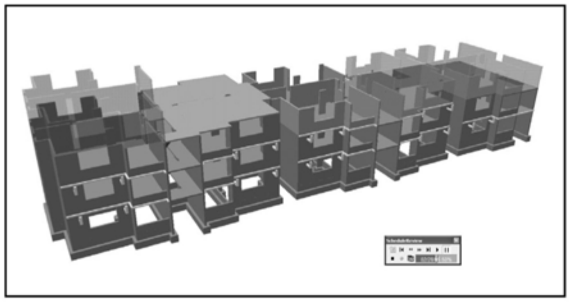

Figure 8: Progress of the Frame Structure

CONCLUSIONS

The use of multidimensional modeling increased transparency during project execution and simplified the coordination, control and planning processes. In general, the changes observed in performance indicators showed:

- An increase in availability, consistency, accessibility and reliability of project information.
- A reduction in uncertainty regarding project scope and performance.
- An increase in speed and quality in the decision making process.
- An improvement in communication effectiveness among project participants.

As a result of this improvements, the projects benefited from reduction in variability of construction processes eliminating potential delays for lack of clear and precise information, interruptions due to unsafe situations and/or accidents, interferences on the job and rework.

The ideal implementation of the multidimensional model is during the design phase; however, it was proven that a late implementation (during the execution phase) still provides significant benefits that should motivate owners and contractors to adopt this approach even in this late stage. However, owners and designers should promote multidimensional modeling during the initial stages of the project to capture high leverage opportunities available early in the project.

ACKNOWLEDGEMENTS

The writers would like to thank the Production Management Center of the Catholic University of Chile (GEPUC) and the Construction firms that provided the project case studies for the research.

REFERENCES

Bertelsen, S. (1992). "The Mouse's Opinion on the Building Design Documents." *NIRAS Consulting Engineers and Planners*, Denmark.

Eastman C., Sacks R. and Lee G. (2002). "Strategies for Realizing the Benefits of 3D Integrated

Modeling of Buildings for the AEC Industry." NIST SP 989, International Symposium on Automation and Robotics in Construction, 19th (ISARC), *Proceedings National Institute of Standards and Technology*, Gaithersburg-Maryland, USA.

Fischer M. and Kunz J. (2004). "The Scope and Role of Information Technology in Construction." *Centre for Integrated Facility Engineering*, Stanford University, USA.

Izaguirre L. (2006). "Proposición de la Modelación Multidimensional como un Mecanismo de Mejora para la Gestión de Proyectos de Construcción." M. Sc. Thesis, Catholic University of Chile, Santiago, Chile.

Rischmoller L., Alarcón L.F., Koskela L. (2006) Improving value generation in the design process of industrial projects using CAVT. *Journal of Management in Engineering, ASCE*, April, 52-60.

Rischmoller L. and Alarcón L. (2005). "Using Lean Principles as a Framework to Study Information Technology in Construction." *Proceedings IGLC-13,* Sydney, Australia.

Sacks R. (2004). "Towards a Lean Understanding of Resource Allocation in a Multi-Project Sub-Contracting Environment." *Proceedings IGLC-12,* Denmark.

SCRI (Salford Centre for Research & Innovation) (2003). "Developing a Vision of nD-Enabled Construction." *Construct I.T. Centre of Excellence The National Network for the UK,* England.