ENHANCEMENT OF VIRTUAL DESIGN AND CONSTRUCTION METHODS

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ABSTRACT

In this paper we report about a three-tier applied R&D approach for the Enhancement of Virtual Design and Construction methods at the Institute of 4D Technologies UAS, North¬¬western Switzerland (i4Ds). In collaboration with the CAD vendor and developer cadwork informatik AG our research focuses on technology, its intro¬duction into the market the effects and difficulties of the tool use and the induced process changes. We will describe the methodlogy, the expected outcomes of the enhancements, the research approach, initial findings and the further proceedings.
In the first tier cadworks introduces an intuitive integrated 4D modeler called (LexoCad or Baubit CAD) for contractors which is commercially available since one year. Analogue to playing with building blocks users create 3D building models and 4D phasing models for the construction of the building directly from 2D pdf drawings. The expected outcome are that the virtual building blocks serve as a test-bed for constructability analyzes, enhanced planning reliability, better coordination and communication, optimized procurement and wide-spread use in practice. The next two tiers of VDC enhancements are currently developed at i4Ds. For the second tier we introduce a semantic, flexible, database-backed, object-oriented data structure for hierarchically structured Product, Organization and Process models (POP models) with an enhanced intuitive 3D/4D graphical user interface for the rapid generation of design alternatives. Users can easily propagate information to related property sets of construction elements and assemblies. Behavior methods (scripts) can be assigned for a variety of tasks e.g. BOM creation, construction method modeling, creation of cost performance predictions etc. This approach technology-wise moves the model management from the modeler or viewer components to the data base domain. The flexible hierarchies not only allow users to manually restructure and rearrange the model to their needs but enable automatic AI optimizers to even alter the construction method e.g. timber element, precast concrete or masonry walls etc. The expected outcomes are a pro-active 4D planning, rapid generation, comparison and evaluation of POP- design- alternatives, derivation von case from existing designs, easy and effective integration of client information into POP models, creating performance predictions (quality, time, cost, risk, etc.) from this models, easy creation of 4D sub-models for knowledge transfer for inter-disciplinary cooperation.
In the third tier we introduce a novel process design concept which we named Process Design Patterns (PDPs). They are based on Christopher Alexander's (1977) concept of design pattern as a formal way of documenting successful solutions to problems and as templates describing how to solve problems of a particular domain. In a study, we called Process Archeology, we chose a recently finished four storey residential concrete building and reconstructed and re-modeled the over-all building processes with an inter-disciplinary team. Therefore we created the necessary 3D-, 4D- and process- and organization-models with commercial available modeling tools. We were able to derive one generic and seven specific PDPs for the whole erection of the building. We describe a strategy to apply PDPs directly on 3D building information models (BIM) to automate and optimize the planning process.

KEYWORDS

Virtual Design and Construction, 4D Modeling, Product, Process and Organization Modeling and Simulation, Process Design Patterns

1. INTRODUCTION

Fischer and Kunz (2004) define "Virtual Design and Construction (VDC) as a methodology, which utilizes computer-based multi-disciplinary performance models in the building sector which include the product (building, concept), the organization of the design, construction, operation teams, the processes and the economical outcome (quality, cost, time, etc) to support explicit and public objectives to integrate design, engineering, construction, operations and business strategies, etc. by design". These models are shortly referenced as product, organization, and process models or POP models.

Modeling of design alternatives in all three POP dimensions is a time consuming task and includes predominant manual operations. Currently available 3D and 4D software packages in the Architecture, Engineering and Construction (AEC) domain are lacking of intuitive tools which support this design process efficiently (Breit et al 2008).

Looking at the current situation in the AEC industry, we see that there is a need to evolutionary introduce new methodologies and to develop the corresponding supporting technologies. In the next three chapters we describe the introduction of the new processes for constructors and how the development of VDC technology through applied R&D prepare the software developer and vendor for the next generation of tools.

2. SERIOUS PLAY: VIRTUAL BUILDING BLOCKS FOR CONTRACTORS

Since one year cadworks has brought an intuitive integrated 4D modeler called (LexoCad or Baubit CAD) for contractors to market. Analogue to playing with building blocks user can create 3D building models and 4D phasing models for the erection of the building on site directly from 2D pdf drawings (Figure 1). The intuitive modeling capabilities of the software have been developed in iterative steps. User feedback from groups of professionals e.g. draftsmen, project manager, architects, engineers as well as art students and children have been integrated. So far we observed from the use of this integrated modeling package that creating the 3D model and phasing it to a 4D model is generally regarded as an intuitive work flow. It visually reveals design and planning errors as well as clashes at an early stage. Phased BOMs are appreciated as really helpful and better than the existing manual process for streamlining the procurement.

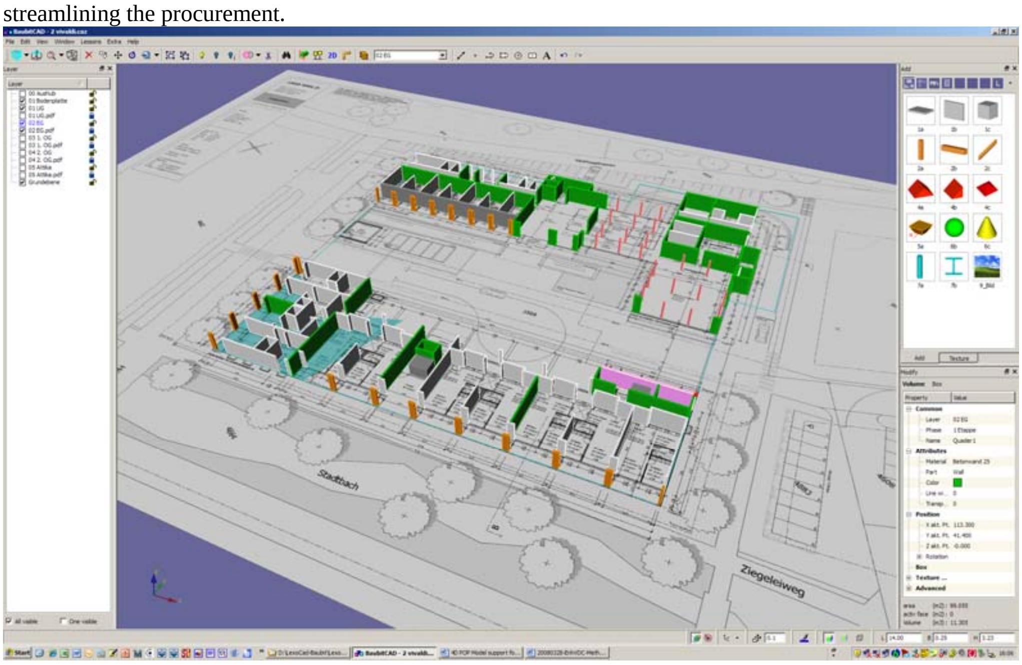

Figure 1: Intuitive 3D/4D Modeling with LexoCad/Baubit CAD based on 2D drawings

However, the creation of different variants of 4D construction models for a shopping center to demonstrate different traffic diversion scenarios in an old town was regarded as time consuming repetitive work.

Next we are going to study systematically the effects of the tool deployment in practice, the potentials that can be exploited, the difficulties, the communication and the processes changes.

3. RAPID CREATION OF DESIGN ALTERNATIVE IN POP MODELS

The design of buildings is a challenging interdisciplinary procedure and is only partly supported by today's ICT. The work flow is predominantly sequential in the order architects, engineers and construction managers. Most of the available 3D CAD systems do support neither the management of multiple design variants nor 3D model hierarchies that follow the planning processes in gaining more precision through the transformation from rough to detailed design. Tools for the creation of design alternatives need to handle the changing size, granularity and versions of the POP models. Project participants and stakeholders look at the same model from a different perspective. Typically, these views are organized in hierarchies. Such hierarchies are used to reduce the complexity on a specific point of interest and to maintain dependencies and relations to the remaining model. Establishing the "right" hierarchies is often essential to describe and predict design behaviors. Yet, experience shows that once a hierarchy is defined it is very hard to change - and thus the hierarchy itself becomes a main obstacle if the design objectives change or if a significant number of design alternatives have to be considered.

Hartmann and Fischer (2007) report about knowledge transfer in constructability review with the help of 4D models. To support decision making, which involve different stakeholders, a considerable number of sufficiently elaborated small sub 4D models need to be created. At the same time, these models need to be connected and integrated to the overall POP model of the project in order to keep them up to date.

In order to cope with the addressed requirements, we suggest in our second tier of development a flexible, semantic, database-backed, object-oriented data structure for hierarchically arranged POP models which will be described in the next chapter. We refer to the resulting prototype implementation Lexo4D.

We are going to describe our concept by describing use case scenarios shown in the pro¬duct model of Figure 2. We are dealing with the temporary state of a product model at a certain time which, in our example, is restricted to the structure and attributes of the buil¬ding elements. Different groups of stakeholders, using this model, want to compare the per¬formance behavior of two different construction methods and the revenue behavior of possible usages e.g. as office, hotel, residential or multiple purpose spaces. The challenge is to create meaningful 4D models in a project phase where typically only limited 3D buil¬¬ding models are available and thereby not preventing an integration of more elaborated and detailed 3D models later. To create sensible scenarios, meaningful data needs to be added to the building components. In a first step, this is to be done manually. As soon as sufficient data is available in the model, further data can be added automatically with search and propagation mechanisms.

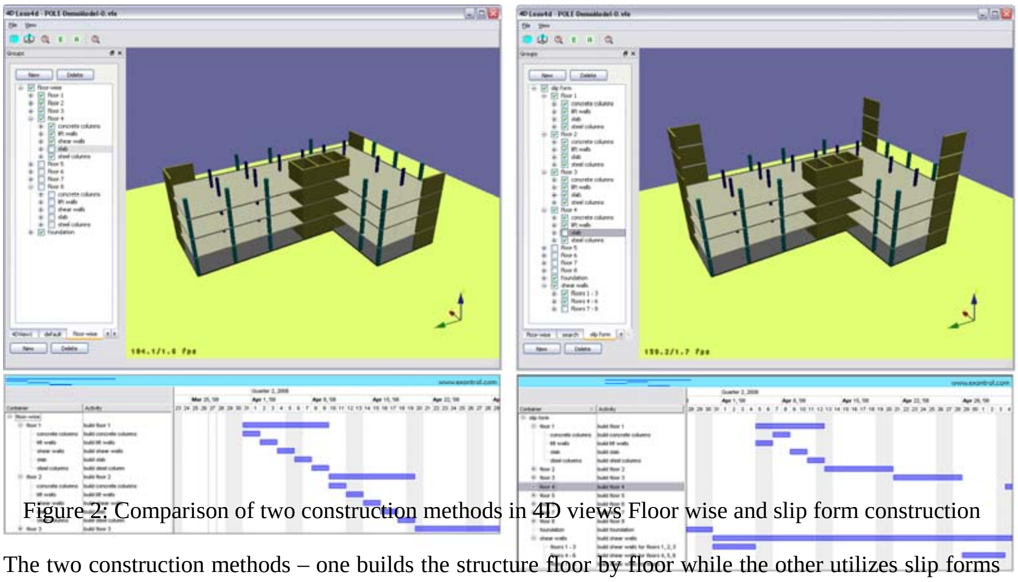

Figure 2: Comparison of two construction methods in 4D views Floor wise and slip form construction

The two construction methods – one builds the structure floor by floor while the other utilizes slip forms for the shear and elevator walls – structure the model into two different views. The floor wise method needs to group the structure into floors as shown in Figure 2 left. This can either be done manually by selecting the elements in the 3D GUI or with a search query, e.g. by looking for all steel columns of floor one. Because search statements can be stored independently, it is possible to re-use them in other projects.

The slip form construction method needs a modified 4D structure to assign the activities. It can be derived from the floor wise view through copying and re-arranging the wall segment groups. Assigning activities and resources to the 4D structure in the views can be done manually by importing a schedule and dragging the appropriate schedule items on the 4D structure elements. With the search propagation features, the activity assignment can be automated and offers some support when the building model becomes more detailed.

At the current project stage it is not yet possible to analyze the revenue behavior of different usages e.g. as office, hotel, residential or multiple purpose spaces, because there are no relating 3D building objects available. Therefore, the available building elements will be grouped floor by floor. This presumes the grouping containers in the view to become meaningful objects such as a "hotel floor". The assignment of related property sets e.g. number and quality of hotel rooms on the floor as well as further relevant economical parameters and behavior methods (small scripts) which calculate the performance predictions, the meaningful objects are further extended. These meaningful objects are a very flexible way to create even very complex design performance predictions. Existing objects can be modified and enhanced and therefore support the rapid generation of design alternatives. To evaluate a mixed usage of the available floor space as hotel and office rooms, the user may simply create a new view by copying the "hotel floor" and "office floor" objects and change the containing number of hotel and office rooms.

3.1 LEXO 4D - IMPLEMENTATION

The core implementation of Lexo4D bases on two common IT concepts: a service oriented architecture (SOA) and an object oriented data model. Bianco et al. (2007) define SOA as an "architectural style where systems consist of service users and service providers". A collection of published services are jointly used by several client programs. Services must be self-contained: to extend a SOA a new service can be added without interfering with existing services. This enables us to rapidly implement new functionality. The object oriented data model is ideally suited to model 4D POP data because we can enhance the hierarchical structure of a 3D building model. 4D data such as temporal activities, materials, prices, or dimensional information is imposed on a 3D model. The 4D data model is designed to provide different views of an existing 3D model such that different aspects of a building can be compared. An architect can calculate the costs of different materials for parts of a building while a scheduler can analyze the time impacts by using different construction techniques for certain parts.

Through the usage of SOA and an object oriented data model, Lexo4D became a very flexible and extensible framework for building second generation 4D modeling tools. In particular the different views of a building allow users to gain more control over the planning process of a building.

3.2 ARCHITECTURE

The SOA as implemented in Lexo4D bases on a three-tier architecture. As illustrated in Figure 3 the SOA service users are part of the client layer while the SOA service providers consist of the application and data layer. The client layer contains tools to visualize, analyze, search, and modify 4D POP data. The application layer holds the definition of service methods and their implementation. The data layer is responsible for provision of the object-oriented data model and its mapping to a relational database. Additionally, it provides facilities to search data.

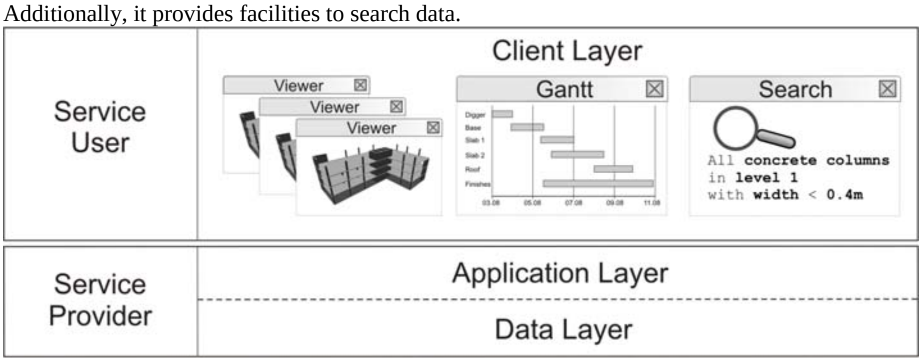

Figure 3: Service Oriented Architecture of Lexo4D
The SOA service users consist of various client applications, the SOA service

providers consists of the application and data layer.

In Lexo4D we have implemented client prototypes for different purposes such as visualization, reporting, and data provision. The most commonly used client is the viewer, a graphical user interface (GUI) to display the 3D model and to explore the associated 4D POP data. The viewer does all 3D rendering work, and provides selection and navigation tools for 3D and 4D POP models. The Gantt chart client analyzes the 4D POP data and creates a report in form of a project plan. A typical data provision client is the search and propagate tool. A set of data entities is selected through our search tool in conjunction with manual and graphical selection. This selection is further analyzed either manually or by algorithms and the gained result is propagated back as new information to the 4D POP data structure. An alternative client for data provision would be a batch script that periodically updates some 4D POP data like a bill of quantities, etc.

Lexo4D offers various kinds of services such as for data access, searching, or system maintenance. In addition users can add their own services to perform custom tasks. Any service has full access to the underlying 4D POP model as well as to other services. This enables experienced users to easily define new functionality. As an example a custom service uses an existing search service to query for all elements that match a certain criterion and then modifies some 4D POP data on the returned elements through an existing data access service.

The Lexo4D data layer manages the object oriented data model and its mapping to a relational database. The mapping is done through NHiberate (www.nhibernate.org). This has the advantage that we can work with object oriented data models while keeping the data in a non-commercial relational database.

3.3 DATA MODEL

The object oriented data model of Lexo4D is split into two parts: the 3D building model and on top of it a 4D POP model. The 3D building model is a data structure coming from a 3D design CAD package. Typically, it is a tree-like data structure consisting of hierarchically arranged elements which are the smallest physical entities in an architectural model (e.g. walls, slabs, windows, or doors). The 4D POP model is a fully object oriented data structure which is imposed on the 3D building model. It suits two purposes: first it provides more detailed description of the 3D elements, and second it is used to hierarchically structure or group 3D elements.

To bind the 4D POP model to the 3D building model we make use of unique IDs (see Figure 4). The 3D building model provides a unique ID for each of its elements. The 4D POP model contains a corresponding entity, called 4D POP element with the very same ID assigned. This approach has two significant performance benefits. For speed reasons the rendering engine can get a local copy of the 3D building model. For memory reasons the 4D POP model can use dynamic binding to load only required data.

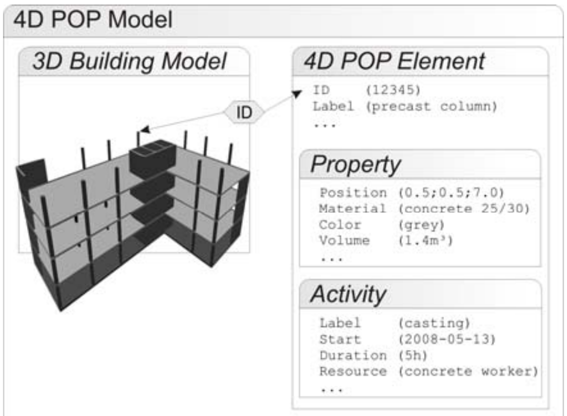

Figure 4: Bind 4D POP model to 3D model
Matching unique IDs in both models provide the gluing entity

To group and arrange the elements of the 4D model we introduced structural data entities (see Figure 5). Structural data entities base on a hierarchy of three core classes: Projects, views, and containers. A project holds a 3D building model. Additionally, it acts as parent entity for a collection of views. Views define a custom scenario for a 3D building model.

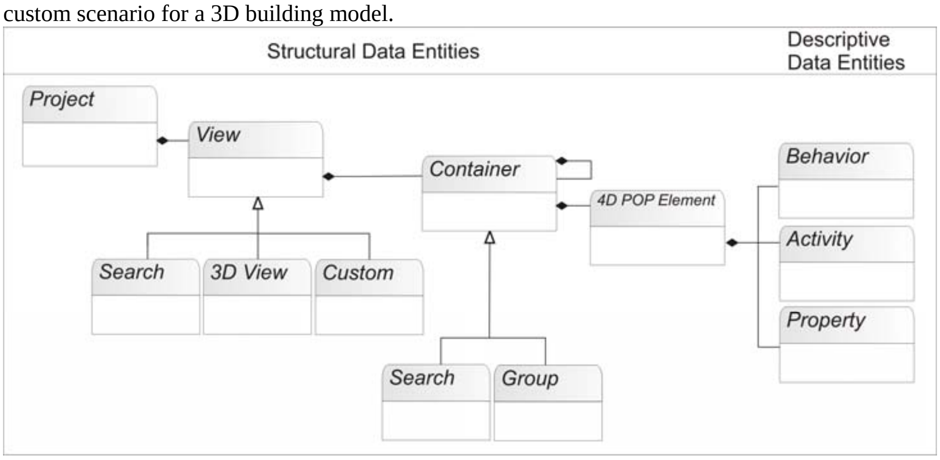

Figure 5: Structural data entities of the 4D model
Project, view, and container provide hierarchical grouping of 4D POP Elements

A site manager could create views for different design alternatives focusing on the planning process whereas a financial manager would configure his or her views having financial issues in mind. Each view is the parent entity for a collection of containers. The purpose of a container is to group 4D elements. A container could collect all walls of a building while another holds all elements of a specific floor.

Views and containers have been defined as abstract classes such that concrete implementations can serve multiple purposes. Lexo4D comes with a standard view to group element manually by dragging and dropping the elements. A special view has been defined to manage search queries and their results and one view reflects the hierarchy of the underlying 3D building model.

To further describe the 4D elements of a 4D POP model we introduced descriptive data entities. They are used to provide semantic information about a 3D building covering arbitrary domains. This enables us to extend our 4D POP models just by adding a new object and assign it to the 4D element.

Descriptive data entities can be divided into three groups: properties, activities and behaviors. Properties describe static attributes of an element such as type, purpose, location, volume, dimension, material, color, and part-number of 4D elements. Activities are temporal processes that add project planning capabilities to Lexo4D. Behaviors describe dynamic attributes of an element. They are typically implemented as small scripts. As an example the thickness of the ground floor may change depending on the intended usage of a building, e.g. as an office, a shop, or a restaurant. A behavior script calculates the optimal floor size.

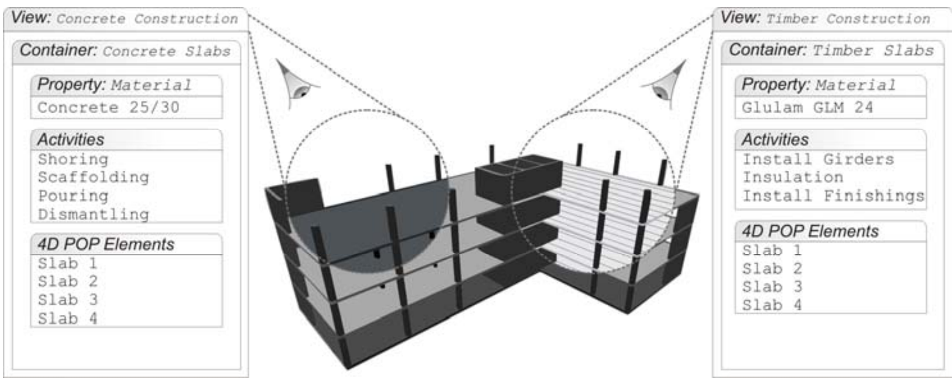

Figure 6: Comparison of two scenarios for a building

Furthermore the 4D POP model supports propagation of 4D POP data by assignment of descriptive data entities to a container. Therewith 4D POP values can be changed just for the current view rather than globally. An overriding mechanism ensures that a view always returns the value that is closest to the root of the according container tree. As illustrated in Figure 6 one view shows the building as it was made of wood, while the other shows the building made from concrete.

3.4 FURTHER DEVELOPMENTS, STUDIES AND OUTCOME

The flexible hierarchies not only allow the users to manually restructure and rearrange the model to their needs but enables AI optimizer to even alter the construction method e.g. timber element, precast concrete or masonry walls etc. We use rapid prototyping methods to include the feed-back of project managers and engineers which use and test the features. We will take selected projects which have been modeled with LexoCad before and study and compare how different user groups create, analyze and evaluate new POP design alternatives. We expect that these developments support pro-active 4D planning, rapid generation, comparison and evaluation of POP design alternatives, derivation from existing designs, easy and effective integration of client information into POP models, creating performance predictions (quality, time, cost, risk, etc.) from models, easy creation of 4D sub-models for knowledge transfer for interdisciplinary cooperation.

4. PROCESS DESIGN PATTERNS

In the third tier we introduce a novel process design concept which we named Process Design Patterns (PDPs).The application of PDPs on BIM are expected to create a step change in rapid creation, comparison and evaluation of POP design alternatives in VDC and a better exploitation of the solution spaces through AI methods for decision and process optimization.

4.1 DEFINITION OF PROCESS DESIGN PATTERNS

The idea to use patterns as formal descriptions of generic solutions to classes of commonly occurring problems was first introduced by the architect Christopher Alexander and has been adapted for various other disciplines (Alexander et al. 1977). A pattern records the design decisions taken by many builders in many places over many years in order to resolve a particular problem. Patterns may be collected together into a pattern language that addresses a particular domain. While the pattern language idea has so far had limited impact on the building industry, it has had a profound influence on software engineering (Alexander et al. 1977).

A design pattern is not a finished design that can be transformed directly into a solution to an individual problem. It is a description or template for how to solve a problem that can be used in many different situations.

In construction and planning process- design, we use process design patterns to formally describe actions or events leading the construction or planning process from one defined stage to the next. Preliminary studies by Häubi and Righeti (2005) proved that business processes could be described by a very limited set of process- elements, all performed in more or less equivalent steps and using the same sets of resources. This was the key to use the pattern- approach for describing business processes. Typically, such patterns are implemented on homogenous tasks, performed by specific taskforces using a given set of resources e.g. machines. Thus the scope of change caused by a certain pattern varies with the level of detail in the planning process. The concept of pattern based process design is therefore not limited to a certain stage or scale in the overall planning- process.

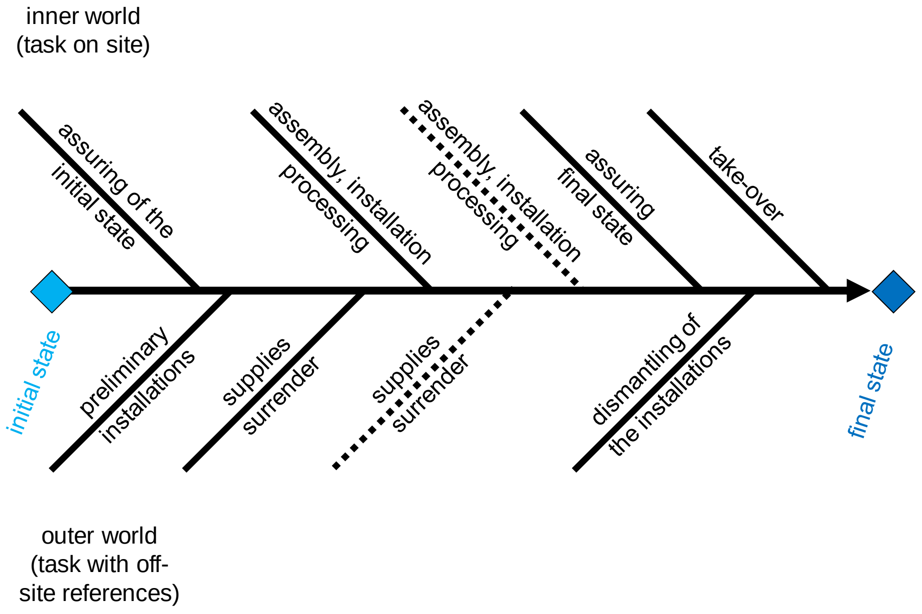

Figure 7: A possible generic process- design- pattern applicable to most construction processes.

4.2 PROCESS ARCHAEOLOGY AND THE DEFINITION OF PDPS

In a study, we called Process Archeology, we chose a recently finished four storey residential concrete building an reconstructed and remodeled the over-all construction processes with an inter-disciplinary team of two architects, a structural engineer, construction foreman, three process managers and a computer scientist. The team creates the necessary 3D-, 4D- and process and organization models with commercial available modeling tools.

Derived from the single generic top level pattern, we recognized seven second level pattern: ground preparation, forming elements by pouring, forming elements by assembling small unified components, assembling site- or project- specific pre- fabricated elements, assembling adjustable standardized elements or mechanical components, surface treatment and setting into operation.

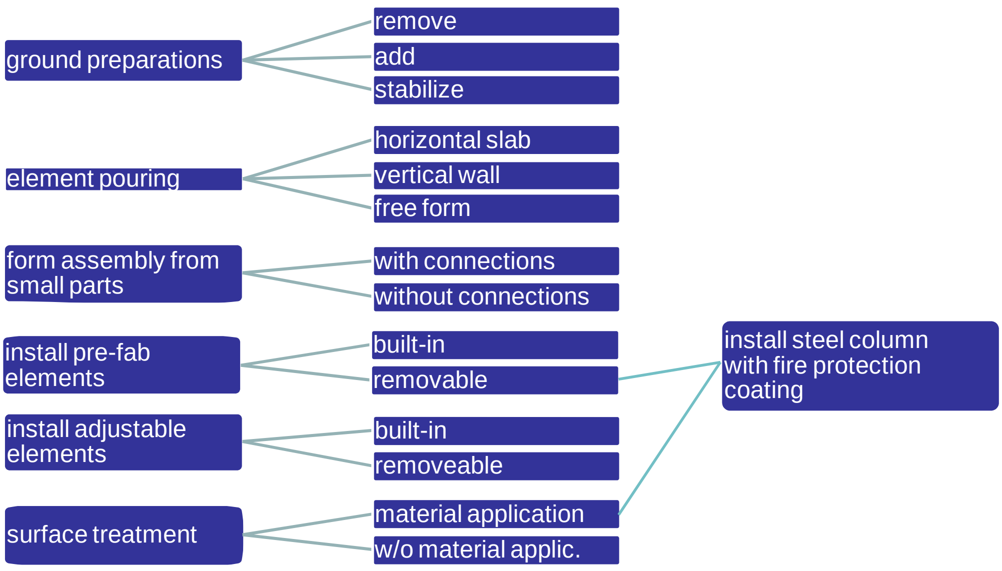

Figure 8: Types of second level Process Design Patterns, examples for the definition of third level patterns and one example of a combined fourth level pattern

The goal of our work is to create a comprehensive system for the description and definition of construction processes, where the level of detail in the description can be consistently varied up- and downwards according the questions related to the actual planning phase.

4.3 SYTHESIZING PROCESSES BY THE USE OF PATTERNS

PDPs define the rules for describing the transition process from one given building state to the next. The basic idea behind the pattern approach is to develop a system, which is able to create processes by applying pattern to the building information model (BIM). The overall process evolves in two steps from the building structure.

The first step produces a number of distinct process elements or sub-processes, generated by applying process design patterns on the building structure. The PDPs determine the type and order of actions or tasks to be performed and the BIM defines the quantities, shape and restrictions for these actions.

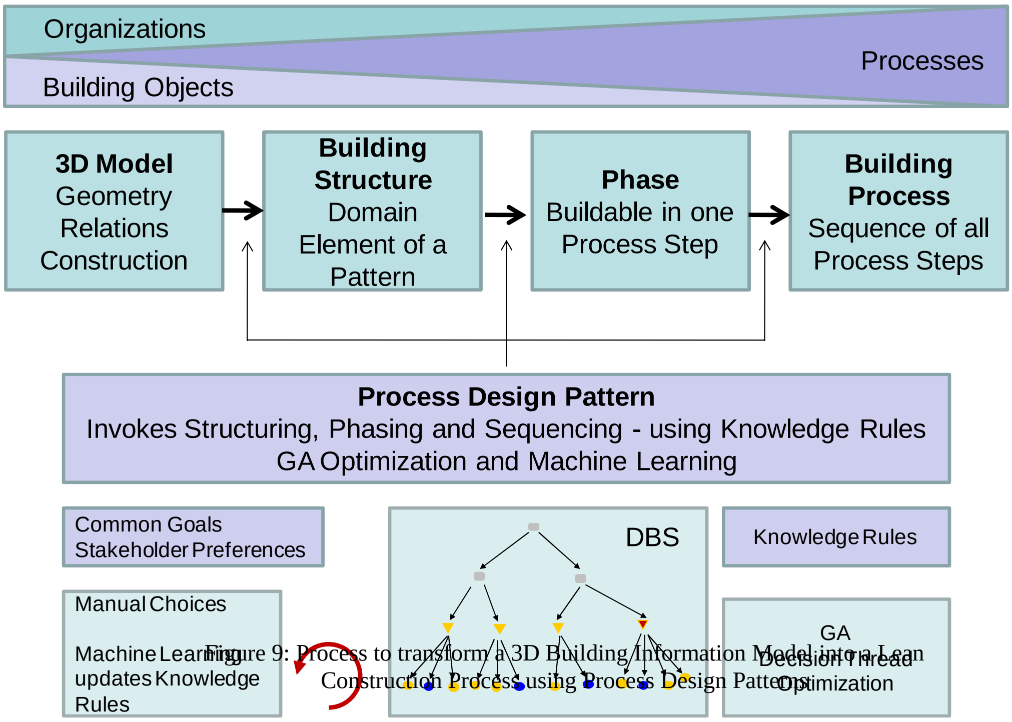

Figure 9: Process to transform a 3D Building Information Model into a Lean Construction Process using Process Design Patterns

These process elements or sub-processes are further decomposed into phases which are work-units which can be performed in one single step.

The overall process setup finally emerges from the integration of the sub-processes. Here again, the BIM defines the overall quantities and constraints for the process design and the patterns define the rules for the possible combination of sub-processes. Both steps mentioned foremost (see Figure 9) comprise of AI methods using rule-based approaches as well as decision break down structures (DBS), optimization thread optimization with GAs (Märki et al. 2008) and machine learning for updating of the knowledge rules from project to project. As PDPs are scalable the application of generic PDPs on the BIM generates more choices for the user to specify. We develop a user interaction schema which allows direct specification input combined with a DBS where the project stakeholders define their common goals as well as their own preferences. The decision threads optimization searches the solution space and suggests fitting design alternatives which automatically specify sets of choices. We are convinced that this approach will result in a far higher number of possible design alternatives than the current manual practice which allow only a very few numbers of alternatives to be studied.

The final design of the resulting over all process is subject to project management methods like critical path analyzes or linear scheduling methods like location-based scheduling (LBS) (Kankainen and Seppänen, 2003) but also to more advanced optimization techniques like GAPO (Märki et. al. 2004). GAPO stand for Genetic Algorithm Process Optimization and is a module which optimizes project plans in terms of time, cost and resource management - forming a multiple criterion (defined by weighted combination of fitness functions) optimized building process. We will take the use cases of the second tier and study how the application of PDPs simplifies and enriches the creation of design alternatives. Further objectives are their quality in comparison to manually created alternatives and the effects of machine learning steps on the enhancement of PDPs.

5. CONCLUSIONS

The rapid creation of design alternatives in 4D POP models and the prediction of their related performance behaviors are the main objectives for the enhancements of Virtual Design and Construction Methods. We suggest a flexible, semantic, database-backed, object-oriented data structure for hierarchically arranged POP models which allow different stakeholders like owners, investors, users, architects, engineers and construction managers to model their specific perspective and interest on the project. The actual implementation of the Lexo4D prototype proves so far that our concepts are working. Furthermore we defined Process Design Patterns which can automatically generate candidate process chains for a wide range of construction methods. At the current state we are beginning to implement PDPs in Lexo4D. As PDPs integrate problem solution and expert knowledge, they may have the potential to intuitively support the process-oriented approach in construction.

ACKNOWLEDGEMENTS

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