

# Effective cost estimate and construction processes with 3D interactive technologies: Towards a virtual world of construction sites

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## Summary

The development of 3D technologies during the last decades in many different areas, leads us towards the complete 3D representation of planet earth on a high level of detail. On the lowest level we have geographical information systems (GIS) representing the outer layer of our planet as a 3D model. In the meantime these systems do not only give a geographical model but also present additional information like ownership, infrastructure and others that might be of interest for the construction business. In future these systems will serve as basis for virtual environments for planning and simulation of construction sites. In addition to this work is done on the integration of GIS systems with 3D city models in the area of urban planning and thus integration of different levels of detail.

This article presents research work on the use of 3D models in construction on the next level of detail below the level of urban planning. The 3D city model is taken as basis for the 3D model of the construction site. In this virtual nD-world a contractor can organize and plan his resources, simulate different variants of construction processes and thus find out the most effective solution for the consideration of costs and time. On the basis of former researches the authors present a new approach for cost estimation and simulation using development technologies from game software.

## 1 Literature Review

### 1.1 3D developments and interactive virtual worlds

#### 1.1.1 Digital earth as the basis for a worldwide geographical information system

In December 2000 NASA Digital Earth Office published a white paper (NASA, 2000) to explain the concept of 'digital earth'. According to this paper digital earth is defined by several arguments:

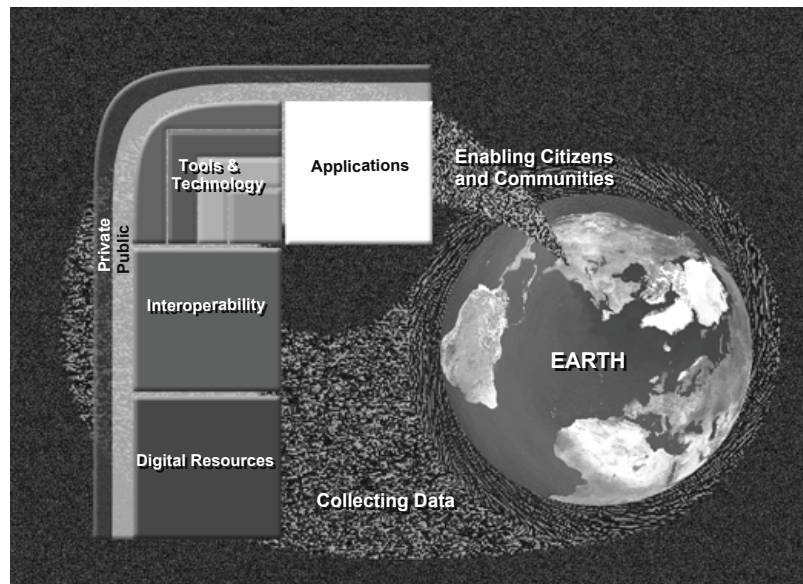
*(..) a way to obtain information about the Earth; a framework in which to publish information; a new market for data, software and services; a set of standards; a local, national, and international collaboration; a near-term "alpha version"; technology challenges for the long-term vision.*

These explanations show how the information about our planet will be handled in future. Even if many questions still remain unanswered we might imagine that the construction industry can profit from these ideas. For example the procedure how to get the necessary information about a new construction site is today linked with a lot of administrative work and field survey. In future there will be a central platform available, where all the necessary data is provided digitally.

Another important aspect is standardization. A central 3D model of the whole earth surface on a global level will have to be in a format shared by all different 3D applications with this model. This approach might become a governing aspect for the current heterogeneous 3D software

market. But it is still a question in which format the 'digital earth' should be visualized in order to be usable also in far future. Figure 1 shows the concept of 'digital earth'. A maximum number of digital resources containing knowledge about the earth are brought together. Different tools and technologies offer access to the digital resource on private and public level. Depending on the kind of request on the data different applications are possible. Here we want to use geographical and geological data for the preparation of a construction site.

Figure 1



Concept of 'digital earth' (NASA, 2000)

### 1.1.2 Geographical Information Systems (GIS) for use in the construction industry

GIS systems are one of the most rapidly developing technologies. In the beginning it contained only selected geographical data. In the meantime these systems have evolved to complex 3D environments with a lot of geo-referenced data (GIS, 2004) which can be used for example as a platform for Location Based Services (LBS). Taking these developments into account GIS systems may serve as a platform for site management in construction. One application may be to examine the soil quality of a specific site area if this information is available as geo-referenced data in the GIS system. It is also possible to use GIS systems as decision support systems in order to determine the best choice for investments in infrastructure projects. Looking at the scale of geometric data in GIS systems these are a blend situated somewhere between the holistic approach of the 'digital earth' concept and the 3D city models described in the next chapter.

### 1.1.3 3D city models as basis for communication with authorizing agencies

While GIS systems are widely used to represent continents, countries and regions, 3D city models rather represent local 3D environments (CASA, 2004). The huge amount of data in any highly detailed 3D model makes it necessary to implement Level of Detail (LoD)-technologies into software applications to be able to browse the model without overloading the hardware. LoD-technologies make sure that objects that are not in the view of the user are not rendered as accurately as the objects that are directly in the interest of the user. Thus the amount of data to be rendered is minimized when users want to navigate in real-time through the 3D environments. Figure 2 shows the 3D model of the city of Munich. Visitors can navigate in real-time through several parts of the historical city (Munich4D, 2004). In this context 'real-time'

means that the tram in the picture is actually moving while the user is walking through the virtual model. Also the textures on the buildings are rendered in real-time. This is possible by use of game software instead of common 3D CAD applications.

Figure 2



3D/4D city model of Munich (Munich4D, 2004)

Usually 3D city models are not provided in real-time as interactive 3D worlds because the amount of data in regular 3D city models would make any real-time rendering impossible. Therefore we have to accept a compromise with less interactivity but more information provided in the 3D model. The city of Berlin for example sells parts of the 3D city model as official digital documents for urban planners and architects. This is a big step forward as architects can directly integrate their own work into the existing 3D city model.

#### 1.1.4 4D simulation

Enhanced by these developments the simulation sector has increased efforts to use these models for its purposes. The city of Zurich uses interactive simulation software to visualize and optimize movements of the tram within the city (ZurichTram, 2004). As these solutions require real-time rendering and interaction while navigating through the virtual model the common CAD technologies known from the construction sector are no longer the adequate solution. They are used to design a 3D model and then import it into applications that are specialized on developing interactive virtual 3D environments.

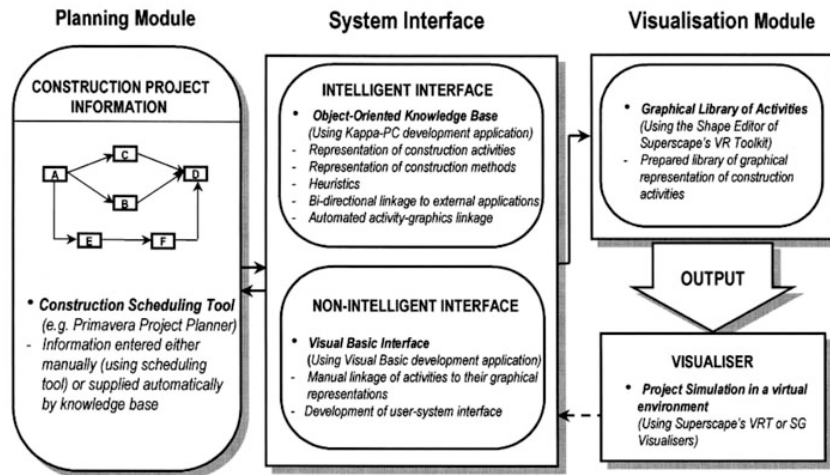
The software 'Mobility' (Mobility, 2004), which is based on the computer game 'SimCity', simulates the development and growth of traffic infrastructure in a city. Here the quality of the 3D model is not the determining factor. The proportion between buildings and cars for example has been chosen in a way so that the user can oversee a maximum of the traffic area. The system provides users with statistical data about infrastructure costs, loads of traffic, etc. It shows that today's systems have to be optimised depending on the interest or role of the user. Nevertheless this is a compromise as our hardware systems are not yet able to cope with the resource needs of a 1:1 real-time 4D model.

#### 1.1.5 Researches on 4D simulation in the construction sector

Object oriented programming (OOP) led to the development of new powerful 3D applications. Accompanied by these developments the first ideas about animating construction activities arose (Cleveland, 1989). In 1990 Arkady Retik showed the use of computer graphics as a scheduling tool (Retik, 1990) describing how the geometry of a building can be used for the

visualisation of the construction progress. In the following years the focus was set on the development of a simulation prototype for construction sites (Retik, 1999). Figure 3 shows the architecture of the prototype system.

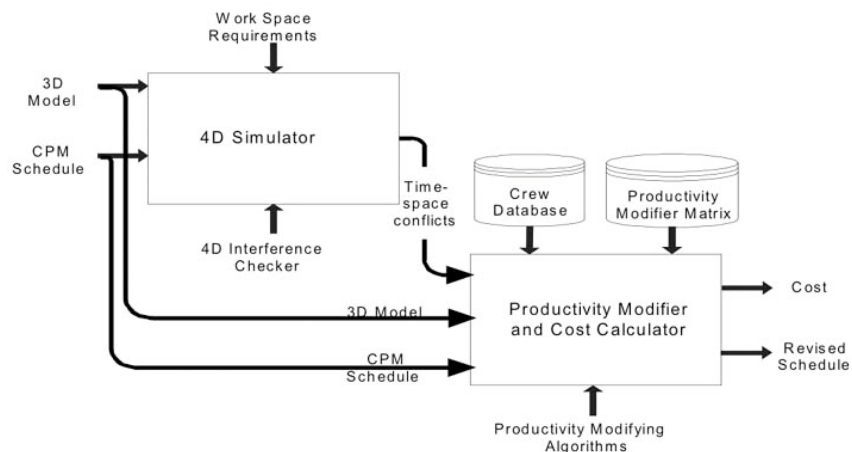
Figure 3



Simulation tool for construction site activities based on VR (Retik, 1999)

The system delivers the simulation of all planned processes in the virtual environment of the construction site. The chosen approach also tries to integrate CAD and Artificial Intelligence (AI) technology by proposing an intelligent interface for the links between activities and their geometric representations. Besides the user can choose between an intelligent and a non-intelligent interface that requires the manual linking of activities and the geometry. Differently to common CAD applications this prototype has various additional virtual reality (VR) functions like full interactivity, real-time navigation and the possibility to manipulate objects during runtime. In this context the research of Martin Fischer (Fischer, 1998) at Stanford University is of interest. While Retik leaves the alternative of a non-intelligent interface to users who doubt the use of artificial intelligence (AI) or knowledge based expert systems (KBES) in linking activities and geometry, Fischer favours the use of these more inventive systems. His approach foresees to avoid improper construction sequencing by using 4D models together with KBES to automatically examine the constructability of a specific construction.

Figure 4



Concept for constructability reasoning with 4D (Fischer, 1998)

The computer is supposed to optimize or 'debug' the construction sequence proposed by the engineer. Therefore an algorithm has to be developed to automatically detect time-space conflicts in the critical path (CPM) of the time schedule. The user then can change the construction sequence manually. But still the aim is to reroute this process to the machine as well. What is interesting for construction management is that he integrates crew information and costs into his reflections (Akinci, 1997).

As we can see from these explanations one critical point in further research seems to be the decision for or against KBES. In this article human decision making is considered as superior to KBES because some particular requirements in the construction sector such as prototype-building or the ever changing production site can yet be handled better by humans than by algorithms. In fact, KBES are good for simulating repetitive and routine activities (Retik, 1997). Besides, when different solutions for a specific problem have to be evaluated, the machine still loses against the sophisticated decision making of the human brain (Retik, 1997), (Hendrickson, 1989):

*„The success of any expert system depends on the system developer's ability to formalise and to represent the knowledge and problem solving procedures employed by a particular expert. Hendrickson and Au recognised that this expertise may consist of the ability to recognise a particular situation or pattern in the environment out of many thousands of possible solutions and that this pattern-recognition is difficult to emulate in a computer program. This is the situation in the field of construction delays, where disputes and claims of mitigation are concerned with a particular solution out of many thousands of possible solutions.“*

As the method of cost estimates varies from company to company and even from estimator to estimator a certain pattern-recognition is still difficult. As an alternative approach to KBES we suggest to profit from the advantages of the human decision making system and combine it with an optimized estimation process based on parallel virtual worlds with advanced interactivity as well as simulation and visualization techniques. Retik mainly focused on site layout planning and Fischer on constructability. Therefore we work on a related approach for the contractors' cost estimate and the cost simulation on site using the framework of professional game development software.

## **2 Concept for a parallel virtual world for use in construction**

### **2.1 Why a parallel virtual world?**

#### **2.1.1 Real-time environments for training purposes and process simulation**

Today there are several software products on the market that allow development and visualization of highly interactive virtual worlds (Virtools, 2004), (Quest, 2004). These products are used for training simulation, game development, advertising and deployment of multimedia information. Especially training simulation reminds on computer games and demands full interactivity for the user during playtime. Actually the 'player' has to act 100% like in reality, as every step of the process has to be accomplished in the virtual environment as well. As state of the art one can today develop a construction site as a virtual 3D environment with full interactivity and real-time animation in an astonishing quality to simulate the processes on site (VStep, 2004) in a level of detail that is almost comparable to reality. Figure 5 shows screenshots from the movie of such a virtual environment, a construction site in Amsterdam.

Figure 5



Construction site simulation in a virtual environment (VStep, 2004), © VStep BV, The Netherlands

Nevertheless there remain some specific topics that retain these solutions from being a one to one picture from reality:

- The virtual environment is built once and has to be updated manually
- It is conceived as an application that can be started and finished without being linked to the 'real time' in the sense of daytime
- Tracking of objects from reality is not considered. Most systems aim to simulate training under real conditions to avoid costly use of the real equipment and are not interested in the real-world feedback
- No real-time data analysis in terms of process costs and process duration
- No threading of the single variations of the played scenario (although possibility to 'record' played scenarios and review them afterwards)

### **2.1.2 Requirements for a parallel virtual world for use in construction**

The functionalities mentioned above have not been implemented yet in the current solutions. Nevertheless the software packages might be able to fulfil these requirements. This paper proposes the concept of a parallel virtual world for use in construction to meet the requirements from above in the following manner:

- 'Real' objects have a virtual corresponding object to which they are linked in real-time so that any change of position in reality is simultaneously visualized in the virtual environment; the virtual environment updates itself automatically to reduce the amount of manual processes to a minimum
- In connection with the use of product lifecycle management (PLM) and product data management (PDM) methods (Bargstädt, 2004) the construction site has to be documented throughout the whole lifecycle of the facility; any divergence of the virtual environment to the real world while being disconnected should be impossible; for that reason the virtual world should be kept 'alive' all over the lifetime of the facility
- The tracking of objects from reality with positioning technologies (e.g. GPS) is necessary for the simultaneous visualization

- The produced data of the virtual environment should instantly be used for efficiency analyses such as time and cost planning or quantity surveying; while looking at the 'live' play-back of the parallel virtual world the user can obtain an overview on time, cost and quality management of the specific project
- For documentation all knowledge involved in a certain project should be documented in linkage with the corresponding time thread; the different variants of a project developed in advance to the final decision for the as-built variant should be documented in separated threads; with these threads a management system is gained which is able to rerun variants without disturbing the actual progress of the parallel virtual world

Having set the requirements for a parallel virtual world a concept for its use for cost estimates is developed. The costs of a tendered project are determined while performing one simulated path of execution as an interactive computer game.

## **2.2 Cost estimation in construction using parallel virtual worlds**

### **2.2.1 Setup of the parallel virtual world**

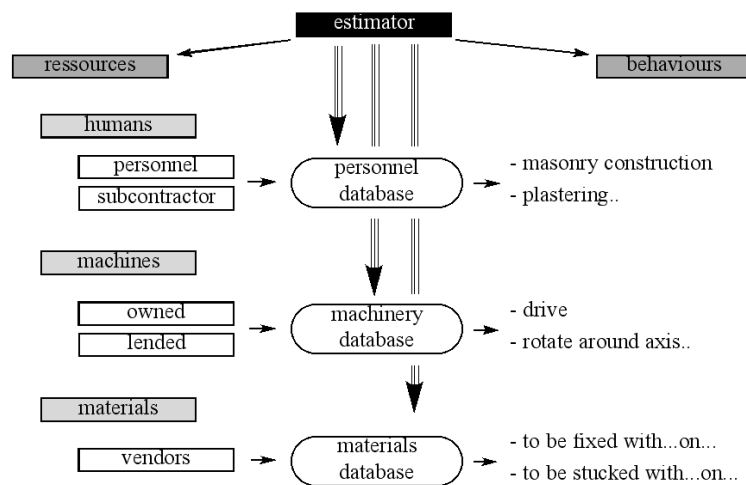
When setting up the virtual world of the site, the estimator first has to determine the global coordinates of the plot. The 3D model of the plot is part of the digital earth model. In order to reduce complexity only the used area needs to be adjusted without losing contact to the digital earth model. The GPS data together with the actual time at the plot location in the moment of plot determination is enough information to start the parallel virtual world. Now that time is running for the specific site, any change in the virtual world is recorded and documented. To be able to concentrate on the estimation method some further assumptions shall here be made to reduce complexity:

- The project is an industrially prefabricated construction
- The estimator has access to a 3D machinery database, personnel database
- The estimator has access to a 3D unit catalogue with the virtual 3D parts of the construction together with the tendering specifications (qualitative description)

### **2.2.2 Application of pre-defined behaviours to site objects**

When playing an interactive computer game the player is required to act to continue the game. These activities are based on pre-defined algorithms to be reused in many games or in different levels. A typical example for a pre-defined algorithm is a certain animation to be performed by a character in a game, incited by a certain event. Some game development SDKs come together with a broad range of commonly used pre-defined algorithms. It has been proven that the time effort for game development can be widely reduced when using these pre-defined algorithms. When using these game SDKs for simulation in construction, the number of behaviours available as pre-defined algorithms is not sufficient. Therefore construction specific activities have to be implemented as pre-defined behaviours to be able to link them to the virtual objects of the site. These activities can somehow be compared with the list of work unit items known from the estimation sheets. Figure 6 shows boundary conditions for the use of behaviours in cost estimation.

Figure 6



Access to behaviours of resources in the virtual site world

As behaviours only define possible patterns of site objects it is a huge task to define every possible pattern. Otherwise it will not be possible to use them. Therefore behaviours should be provided with the product itself for use in virtual worlds, as the developer of the product knows best about it. Out of the high number of possible combinations he can propose the appropriate ones for the work on site. The most significant difference between KBES-driven systems and the parallel virtual world system is the process of sequencing the single processes to be performed for site progress. The behaviours only define the boundary conditions for the use of resources. Instead of using a machine driven system for the sequence of the working processes the estimator has to play different scenarios using the resources and behaviours. The sequence of the processes is thereby defined by the estimator. While playing one scenario the virtual world system records the process sequence of the estimator as a specific thread in the database. Precious knowledge about process sequencing is thus recorded for later analysis and reuse. As an example the system provides information about repetitively used behaviours and rarely used behaviours, what gives an indication for the need and popularity of certain processes as well as for the constructability of constructions and the process knowledge of the estimator. As one result we can determine 4 steps in order to perform a cost estimation:

- Step 1: Setup of the parallel virtual world
- Step 2: Setup of resource scenario (as-planned 3D construction, resource teams, machines)
- Step 3: Apply behaviours to objects (3D part or part groups)
  - o Choice of process sequence
  - o Determination of time schedule
  - o Estimate of costs
  - o Overview on resources
- Step 4: Replay process sequence, optimization, comparison

In the following chapter step 2 and 3 are shown in a simplified example.



### 3 Example

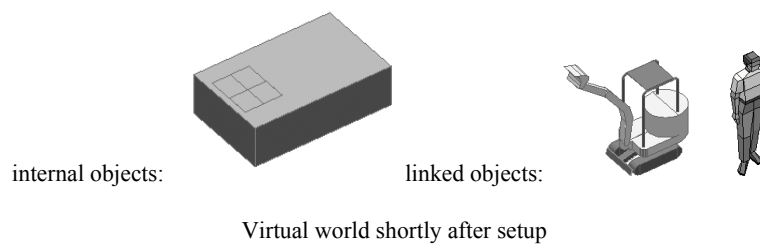
#### 3.1 Excavation of a hole

##### 3.1.1 Step 2: Setup of resource scenario

Even if the chosen example is quite simple, one can get an impression of the kind and amount of processes and decisions in construction projects in general.

A hole on a given plot has to be excavated. Resources in this project are the excavator and the driver. Figure 7 shows the parallel virtual world shortly after setup.

Figure 7



For internal objects of a linked virtual site it is true that their position is the same in the real world as in the virtual world. After having set up the resource scenario the estimator can choose behaviours to apply to the objects of the virtual world to start process sequencing. Now the different behaviours have to be listed which are necessary to obtain the costs for the excavation. The costs are calculated on the basis of pre-defined calculation algorithms known from standard calculation process models in construction industry (Bargstädt, 2004). For estimating the estimator applies behaviours to the objects in order to get the associated costs. The calculated costs are shown simultaneously to the process sequencing in the virtual world.

##### 3.1.2 Step 3: Behaviours to be implemented in the example

The behaviour description for human resources in figure 8 needs to be implemented once for the virtual world. It has been found that standard behaviours that come with the development kit of game development software tools do not fulfil the specific requirements of the construction sector even if some can be adopted. For example the movement of a worker from one site to another might be linked with extra costs if the site is far away from home and the contract of the worker foresees extra payments under these circumstances. Besides, to keep flexibility, the estimator might have the opportunity to manually determine how the movement of a worker effects cost structure.

Figure 8

Nr.	Applied to	Behaviour	Description	Effect
1	Driver	human move to	Requires to determine the new position of a human resource in the virtual world	Determines the position of the human resource at starting time of project; asks the estimator about boundary conditions for the human resource, e.g. hosting when away from home; determines the costs of the human resource
2	Driver	control machine	Links a human resource as an operator to a machine	adds the costs for the human resource to the cost of the machine; tests if the human resource is qualified for the operations of the machine

Behaviour descriptions for use with the human resource (driver)

As far as the machine resource is concerned the movement becomes even more complex as the machine does not come 'home' regularly but moves from site to site without a recognizable pattern. In this case there might be the necessity to develop new behaviours in a short time. This becomes profitable if the behaviours are reused in future. Behaviours thus represent reusable process know-how in a company. In this example the following behaviours might be of interest to be applied to the excavator:

Figure 9

Nr.	Applied to	Behaviour	Description	Effect
3	Excavator	machine move to	Requires to determine the new position of a machine resource in the virtual world	Determines the position of the machine resource at starting time of project; asks estimator about boundary conditions for the machine, e.g. equipment, transportation, etc.; determines the costs of the machine resource
4	Excavator	excavate	Requires to link the excavator to a certain object	Makes the excavator start to excavate the volume of the chosen object
5	Excavator	transport to	Requires to determine a position to set off the load	Determines frequency of load/unload

Behaviour descriptions for use with the machine resource (excavator)

## 3.2 Evaluation of the example

### 3.2.1 Problems in using virtual worlds for the estimation process

After the theoretical simulation of the necessary steps of an estimation process in a virtual world some questions remain that could not yet be answered appropriately because of the complexity of relations in construction processes. Some of these questions are:

- In which degree of detail has the estimator to 'play' the construction site to be able to determine costs accurately?
- How are behaviours supposed to be 'selected' from the list of all possible behaviours?
- How long takes it to play different estimation scenarios in big projects?

The above problems should be investigated by developing a prototype of a virtual construction environment, thus to analyse it in terms of repetitive behaviours, levels of detail in behaviours and methods of cost tracking in behaviours.

## 4 Final Comments

This article presents the use of parallel virtual worlds as a cost estimation method in construction. At first an overview is given on actual developments in the VR sector. 3D city models transform real environments into highly detailed virtual environments for use in the planning sector. It is shown how virtual environments can be used for the simulation of site activities and for constructability reasoning. To profit from the contemporary developments in GPS-based tracking the basic concept of the parallel virtual world is created as a 1:1 model from processes in reality. Finally, based on a parallel virtual world, a new estimation method is shown using the tracking functionalities of GPS together with the planned resources in a virtual site.

As a conclusion from the research it is shown that besides knowledge based expert systems (KBES) there are further computer-based approaches to re-engineer construction processes

without compromising with the moderate decision support ability of computers. When computers were not able to fulfil the building requirements of interactive virtual worlds the development would be stuck with unreal and unworkable pictures of reality. Today, with enough calculation power in almost every PC, the abstract virtuality should be increased in its similarity to the real world. This is in fact, on the way, when transforming a 2D plan of a city into a 3D interactive city model.

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