New Trends in Construction Site Safety and Management Based on Virtual Environments

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Abstract
This paper presents new trends in construction site safety management based on virtual environments. A virtual environment, named SIMCON+, which was developed as a test pad to have insight of the construction site, and to support decisions related to the management and safety during construction is presented in this paper. The SIMCON+ environment engages the user into a form of visual interactive simulation where different construction site configurations and scenarios of the surrounding environment (such as building components, materials, machines and workers) could be tested and analyzed during the planning process and earlier to the construction phase of the project. The paper also suggests a framework to conduct what-if analysis related to the safety of construction sites by expecting congested spots on the construction site at which collisions by machine-related resources are likely to occur. A case study for research validation is also presented. Finally, the paper outlines the most recent research effort in this area with highlights on some new trends of the Virtual Reality (VR) as a technology to be engaged in the area of construction planning and management.

Keywords*: virtual construction environments; virtual reality (VR), construction site safety.*

1 Introduction

During the last three decades research in the area of construction visualization and CAD has shown a quantum move from 2D sketching to 3D modelling and 4D CAD/Scheduling integration. Researchers have developed systems for 3D visual planning and scheduling of construction operations [2]; construction integration [7]; and design [9]. Previous visualization research efforts at the *project level* were motivated by the shortcomings of traditional scheduling and control techniques such as bar charts and CPM in being able to represent all aspects of construction necessary for project level planning [3]. As a result, recent research efforts were concentrated on integrating a 3D CAD model representing the design of the facility with a construction schedule [1]. This form of visualization has popularly become known as 4D CAD [3,11]. However, construction visualization at the *operations level* is a much more complex task. In addition of being visualizing the final product, the user must be able to view the interaction of the various resources as they build the product or perform a process. These resources must include temporary structures, materials, machine, and labour as they create the product. This research addresses this issue.

2 Construction Safety and Virtual Environments

There are numerous factors responsible for health problems and construction site accidents, and various researchers have reported that proper site management is vital for reducing hazards and accidents on construction sites [4]. It is a fact that several causes of construction site accidents and health hazards (such as falls, falling objects, site transportation, site layout, and hazardous substances) can be controlled through creating an efficient site layout plan [10].

An early study showed that the following are among the top human-related causes of accidents during construction: (1) operating equipment without authority and/or at unsafe speed, and (2) when equipment came into contact with a worker [14]. Similarly, research on hundreds of accidents has produced four distinct accident-prone situations during construction [5]. These situations are failing of temporary structure during construction, equipment coming into with worker and material, following unsafe practices or perform an operation with negligence, and operating with hazardous materials. This paper focuses on the type in which workers and material or workers and equipment came into contact.

3 Virtual Environments in Construction

The term virtual reality (VR) is defined as the technology that enables real-time viewing of, and interaction with, spatial information. Similarly, there are other words used in the literature to describe same groups of technologies, and similar concepts including virtual environments (VEs) [8,15,16], and visualization, interactive 3D (i3D) [7]. Similarly, SIMCON [12] is a 3D VE developed as a test pad to have insight of the construction site during the pre construction phase. The SIMCON application simulates machine-based construction processes such as: material handling, earth removing and crane operations in real-time object-oriented graphical environment. The main objective of the SIMCON research was to develop a tool by which safety in construction could be enhanced by having a test pad to graphically conduct what-if analysis for different scenarios of building, machine and site configurations, and provide a high level of user interaction, refer to Figure 1 in the appendix. The new SIMCON+ application was updated in 2003 to become a stand-alone application, and the ability to store the state of the visual simulation in a data file where information could be retrieved later for further analysis. Original development of the SIMCON application was done using the Sense8-WorldUP virtual reality authoring tool. Further information regarding the WorldUP tool could be retrieved from reference [17].

3.1 SIMCON+: Visual Interactive What-If Analysis Tool for Improving Construction Site Safety

The latest version SIMCON+ was developed based on the WorldUP ActiveX (OCX) control and Microsoft Visual Basic. Figure 2 in the appendix presents the most recent stand-alone SIMCON+ application. In this version more than 36 application modules written in Visual Basic and Basic Script were embedded into the SIMCON+ application to control the overall user-simulation interface on the Window-XP operating system.

The two key components of the SIMCON+ application are the internal *Scheduler* and *Simulation Manager.* These two components manage and control the resulted 3D visual simulation. The internal *Scheduler* of the SIMCON+ application is the main element by which the user is engaged into an interactive 3D graphical simulation once the application is launched. The *Scheduler* consists of a 3D CAD Data Base, a Process Control Module, and a Building Assembly Module. These modules within the SIMCON+ application are the heart by which many different scenarios of construction site configurations could be tested and analyzed with respect to the available site space. Additionally, the user has the ability to interactively interact with machines to analyze their impact on the overall safety of the construction site in a visual interactive format. Figure 3 in the appendix presents components of the SIMCON+ *Scheduler* and *Simulation Manager* modules.

3.2 3D CAD and Building Assembly

In the SIMCON+ application the 3D CAD Data-Base contains all 3D CAD object definitions such as: building components, machine prototypes, terrain etc., and these 3D CAD objects are retrieved into the simulation based on object-oriented nature. This means that these objects are reusable and feature inheritance within the simulation. Once the simulation is started the building assembly module (PCM) is fired and all 3D visual objects are placed within the environment based on their 3D CAD definition or user input. Figure 4 in the appendix presents the mechanism of building/objects assembly in SIMCON+.

3.3 Process Control Module (PCM)

When the SIMCON+ application starts the *Scheduler*'s PCM retrieves information regarding four different machine prototypes (truck, excavator, crane or mobile crane), stations within the construction site, and the type of operation needed to be performed.

This information is stored as a script file loaded into the application upon user selection. The process control module PCM manages the sequence of executing these scripting files during the simulation. Additionally, simulation of machine processes using the SIMCON application could be done through what is called a non-autonomous mode. In this mode of operation user-simulation interaction is done based on user inputs to the simulation through a number of 2D and 3D input devices.

3.4 SIMCON+ Simulation Manager (SM)

The Simulation Manager (SM) in SIMCON+ manages all of the real-time simulation tasks necessary to for the Interactive Visual Simulation. Within the simulation manger (SM) both machine and labour dynamics are achieved through General Problem Solving (GPS) and collision-detection algorithms. The GPS algorithm consists of five different actions to be done by each object in the following sequence: (1) find target and move towards it, (2) if obstacle exists on the path move opposite from the target direction, (3) rotate towards a free-obstacle orientation, (4) move forward, and (5) find target and move towards it. Figure 5 in the appendix shows this embedded GPS algorithm. Similarly, machine and worker objects are checked against collision every cycle once the SIMCON+ application is started. This is done through a general collision-detection algorithm applied to all machine, worker and building objects. Therefore, once the SIMCON+ application is started the user has the ability to record from and play back motion paths for any machine and/or labour objects within the simulation and collision checks are fired every simulation cycle.

5 Simulation Scenarios and What-if Analysis

This section presents a framework for conducting what-if analysis based on the SIMCON+ data output. This framework is illustrated in Figure 6 in the appendix. The methodology of this framework is concentrated on the fact that the SIMCON+ application is able to retrieve 3D CAD objects representing the actual construction site in terms of building structures and actual site dimensions. Typically, these 3D CAD definitions are regular scaled-down outcomes from the design process during the pre construction phase. As shown in Figure 7, once the simulation starts the user has to define one scenario, and activate one machine object at a time. The user then should naturally engage him self into the simulation by activating a number of machine and labour-based animations. The SIMCON+ application at any time during the simulation will record data with respect to collision incidences took place by the driving machine, locations of these collision incidences, and the type of each collision incidence.

The recent SIMCON+ application added a new feature for storing and retrieving data representing different simulation scenarios. This feature stores simulation data with respect to the number of collision incidences occurred during the simulation. Additionally, this feature stores the exact location of these collision incidences on the construction site terrain, and the construction site objects caused these incidences. Similarly, SIMCON+ stores a new variable representing the construction site zone based on user definition during the simulation. A sample output of SIMCON+ collision data file will be presented in the case study section of this paper.

6 Case Study

The case study in this section represents a small size turn-key residential building project in the city of Doha, capital of the State of Qatar. The total value of the project is approximately $2.82 million (QR 8,330,000) based on a lump-sum contract type. The project is located in Bin-Mahmoud area with a total built up area of 7200 sq-m distributed on five identical floors and one basement. The total project duration as agreed in the contract was 13 months. The main contractor of the project is a local Grade (B) contracting company with an approximate total value of annual projects equal to $5.5 million. This project was investigated with respect to construction site safety using the SIMCON+ application during summer and fall 2005. The main focus was to study the available construction site space with respect to the pre-planned operations before construction. Figure 7 presents a 2D CAD (drawn in Autocad 2004) representing the construction site space with respect to the surrounding environment, and a plan view representing the final building object as considered in the SIMCON+ application.

This case study was tested in SIMCON+ considering one building location scenario due to the city of Doha building regulations, and few other scenarios were considered based on different site configurations with respect to machines, location of temporary site structures and zones for workers-based operations. Figure 8 presents a sketch of a typical scenario considered using the SIMCON+ application.

As mentioned earlier that a number of scenarios were tested for this case study using the SIMCON+ application. Figure 11 presents one scenario output data resulted from the SIMCON+ application. These results show the total number of collision incidences recorded during the visual simulation run, and in this particular scenario they were equal to 22 incidences resulted from 3 different collision types. Similarly, the results show the average for each collision incidence type with respect to the total number. The analysis shows that the highest number of collision incidences where based on an impact of a working machine with a temporary site object on the construction site terrain. Additionally, the analysis shows the exact special location of each collision incidence within the virtual construction site space created on the SIMCON+ application. These locations represents exact points on the construction site terrain since the original 3D CAD file representing the case study was imported into SIMCON+. The output column representing the truck machine type is simply indicating the virtual machine used by the user during the simulation cycle in a non autonomous mode (fully interactive) in order to drive through the virtual constructed site.

Moreover, the SIMCON+ output produces a 2D graphical representation of the collision incidence locations within the virtual site as shown in Figure 9. Finally, this analysis suggests that a decision rate equals to 63% should be given to consider the safety of machine-based operations with respect to the temporary site objects virtually simulated within the simulation. Similarly, a decision rate of 31.8% should be given to consider the safety of machine-based operations with respect to other machines.

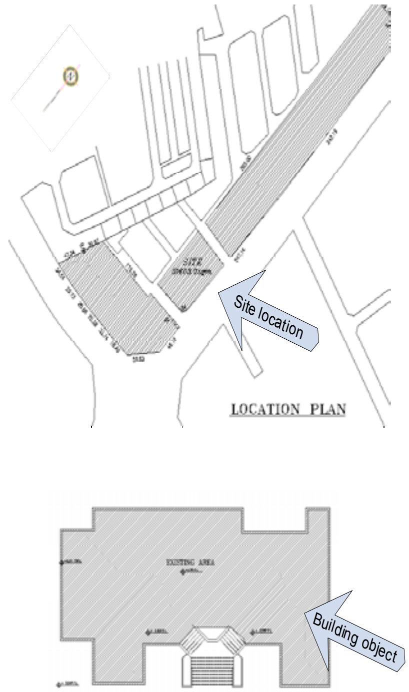

Figure 7: Construction Site Location and the Case Study Building Object.

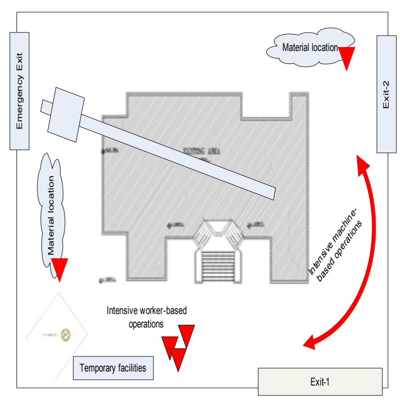

Figure 8: Case Study Typical Scenario as Tested in SIMCON+.

SIMCON+ Visualizer
Collision Incidences Data
....
Total collision incidences = 22
Total collision due to machine-machine = 7
Total collision due to machine-worker = 0
Total collision due to machine-material = 1
Total collision due to machine-building = 0
Total collision due to machine-site object = 14
Total collision due to machine-traffic = 0
Average Collision Incidences Data by Type
....
Average collision due to machine-machine = 0.3181818
Average collision due to machine-worker = 0
Average collision due to machine-material = 4.545455E-02
Average collision due to machine-building = 0
Average collision due to machine-site object = 0.6363636
Average collision due to machine-traffic = 0

Senario	**Zone**	**Collision_Type**	**Incidence**	**Machine_Type**	**X_Location**	**Z_Location**
Scenario-A	West side	machine-machine	1	truck	-2252.206	2039.103
Scenario-A	West side	machine-site object	2	truck	147.5826	3461.46
Scenario-A	West side	machine-machine	3	truck	-3939.83	-1312.644
Scenario-A	East side	machine-machine	4	truck	-1854.226	-2491.14
Scenario-A	East side	machine-site object	5	truck	2655.586	-3771.665
Scenario-A	East side	machine-site object	6	truck	1910.277	-3793.611
Scenario-A	East side	machine-machine	7	truck	-757.6066	-2557.025
Scenario-A	East side	machine-machine	8	truck	-856.5674	-2509.952
Scenario-A	East side	machine-site object	9	truck	156.902	-3768.048
Scenario-A	East side	machine-site object	10	truck	2638.12	-3759.712
Scenario-A	East side	machine-site object	11	truck	3163.762	-3768.588
Scenario-A	East side	machine-site object	12	truck	1754.696	-3763.658
Scenario-A	East side	machine-site object	13	truck	508.2935	-3781.838
Scenario-A	North side	machine-site object	14	truck	4767.698	-2418.307
Scenario-A	North side	machine-site object	15	truck	4798.963	-2302.45
Scenario-A	North side	machine-site object	16	truck	4789.249	-3367.854
Scenario-A	West side	machine-site object	17	truck	2296.533	3483.143
Scenario-A	West side	machine-site object	18	truck	3790.958	3487.943
Scenario-A	West side	machine-site object	19	truck	1517.989	3527.857
Scenario-A	West side	machine-material	20	truck	-2288.88	2742.03
Scenario-A	West side	machine-machine	21	truck	-3225.151	871.5676
Scenario-A	West side	machine-machine	22	truck	-3225.151	871.5676

Figure 9-a: Case Study Data Output File

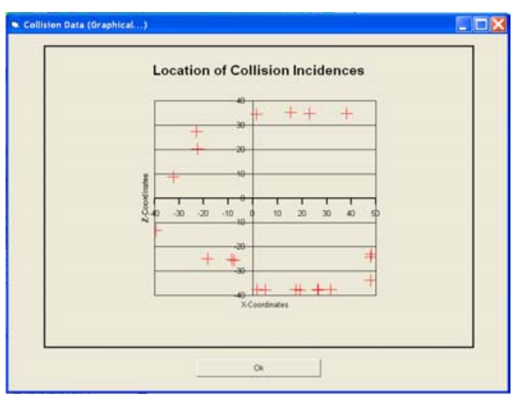

Figure 9-b: Case Study Graphical Output Data

7 Current Research

The motivation driven by today's modern visualization and visual simulation tools and techniques has taken this research effort to the following phases: Phase [1], exploring modern visual simulation and virtual reality authoring tools such as the EON's Visual Studio graphical environment which yields to a more realistic visual simulations, Phase [2], adding realistic material flow representation for enhancing the realism of the overall system, as well as some other visual simulations such as smoke, fire and explosions, Phase [3], enhancing the SIMCON+ application by including routines and algorithms that incorporates the dynamic deformation of terrain and material objects as the simulation progresses, Phase [4], incorporating more portable and dynamic file formats related to the building industry such as the IFC 2.x file formats. Up to date this research is still in Phase [1] due to the complexity involved in migrating most of its embedded routines and codes in SIMCON's+ Sense8-based interface to the new EON VR authoring system.

8 The SIMCON+ Environment Based on EON VR Authoring Tool

The latest version of the EON studio (version 5.2) [6] is a complete GUI based authoring tool for developing 3D visual simulations and visualization applications on the Windows-XP operating system. The development process of any application consists of the following major steps:

1. Model creation and/or import from various 3D modelling tools such as Autodesk, Alias, VRML…etc., in which visual attributes such as colors, shades, and textures could be added to each element using a separate model editor , named EON CAD. Additionally, in this step various model reduction and visual enhancement techniques could be done to accelerate the real-time content and enhance the overall performance of the developed application.
2. Behaviors association, in which simulation attributes such as move, rotate, grasp, un-grasp…etc. could be added to each element of the developed application. Also in this step, the overall application appearance such as dialogs, messages, menus etc. could be added through an integrated scripting language.
3. Application distribution, in which the application could be designed to be distributed as a stand-alone application or content over the internet, or embedded within another application.

Since the evolution of the visual programming interfaces in early 1990s such as Microsoft Visual Basic and Visual C, C++, and Java, the programming paradigm has moved from the typical sequence-driven applications to what is called an event-driven. This programming paradigm changed as well the nature of many computer graphics and animation applications. In the early Sense8's virtual reality authoring tool or the latest EON system, applications developed are built based on a number of events and triggers that either responds or act upon these events.

Additionally, the object-oriented nature of the EON system facilitated the idea that a typical graphical scene is to be constructed based on what is called a number of nodes representing graphical objects, simulation properties, behaviors, control and navigation etc. Furthermore, an EON application is constructed by arranging and connecting node*s*, EON's basic components. EON Studio has more than 90 nodes that can be used to add elements and features to an EON application. Each node has a unique assortment of properties displayed in each node's properties window. By entering information in the properties windows, a developer can define how the node will perform in a simulation. All nodes also have a default name that reflects its particular task in a simulation, and a node has no effect on a simulation until it is placed in an environment where it can interact with other nodes. Interaction between nodes is made possible by arranging the nodes in the *Simulation Tree* hierarchy as shown in Figure 10 and by making logical connections among 3D graphical objects in what is called the Routes window (refer to Figure 11). Figure 10 presents a typical Simulation Tree for a machine in SIMCON+ showing all logical machine controls during the simulation, and the associated physical properties of each machine. Figure 12 presents the SIMCON+ virtual environment as being designed in the EON VR authoring tool.

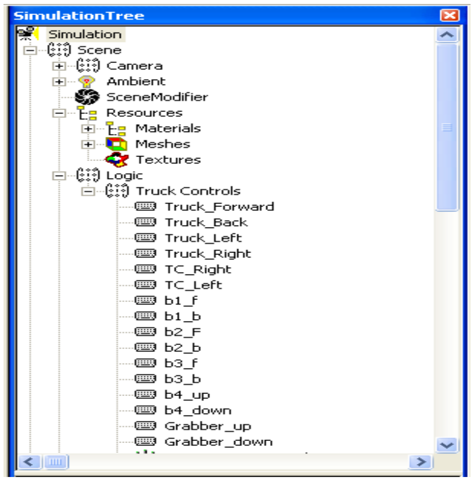

Figure 10: Simulation Tree of a Typical Scene in SIMCON+ (EON development environment)

The latest version of the EON VR Authoring Tool includes some advanced features which allow the simulation of real object physics. Such features will have enormous capabilities in advancing the area of construction simulation and virtual construction creations. For example, within the latest version of the EON system machine prototypes would be able to be simulated more realistically based on their physical properties such as speed, resistance, breaking forces, terrain resistance…etc. Therefore, it would be possible in the very near future to have virtual environments which would yield to a correct prediction of machine-based operation times and/or delay times. This feature would be considered a quantum leap in all research done in the area of construction planning and scheduling based on simulation models and techniques.

8 Conclusion

This paper presented some new trends in construction site management based on virtual environments. Additionally, a framework for investigating construction site safety based on virtual construction environments was presented. The paper presented an analytical approach to conduct what-if analysis based on true spatial information and dimensions of the construction site using an interactive visual simulation tool. The SIMCON+ application not only considered the actual size of the building structure, but also all other relative construction site entities such as machines, workers, temporary site facilities and materials. A graphical representation of possible collision incidences that might take place in the actual construction site was also presented in this paper. Additionally, the concept of generated simulation scenarios and recording data of these scenarios in order to aid in the decision making process related to the safety of the construction site was presented. Finally, the paper validated the presented tools, techniques and methodologies through a case study from the real construction world.

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APPENDIX

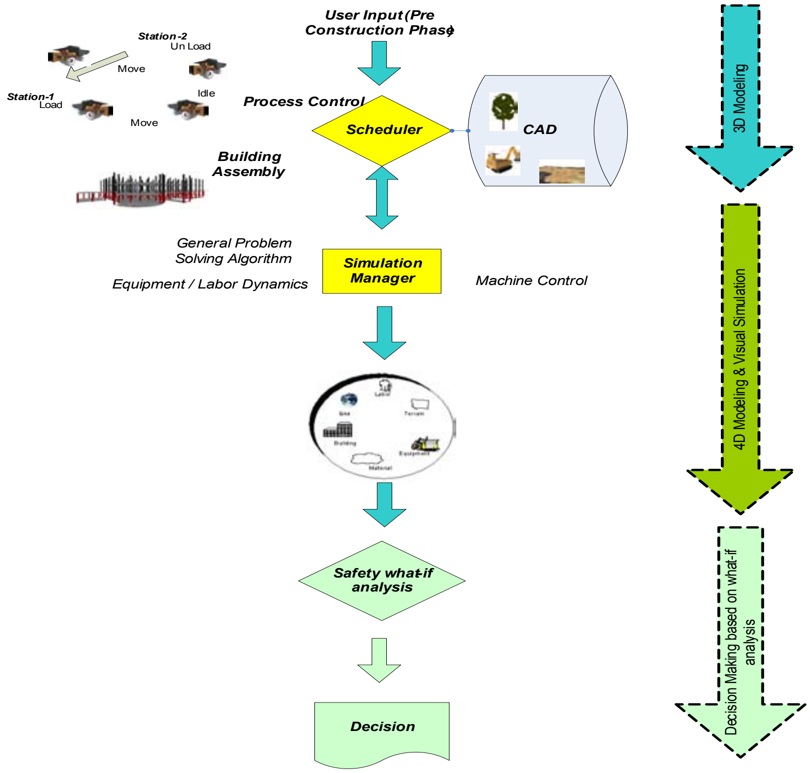

Figure-1: Frame Work of the SIMCON+ Application

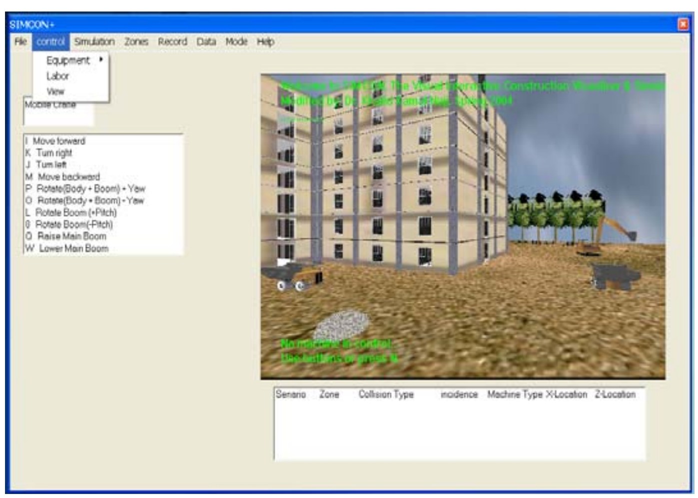

Figure-2: SIMCON+ Graphical User Interface on Windows XP

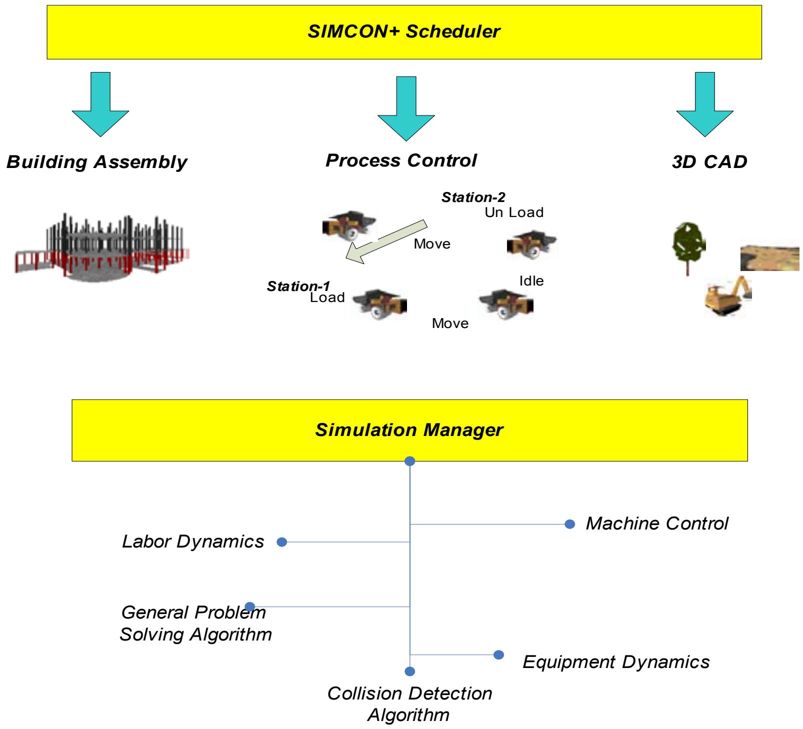

Figure-3: SIMCON+ Graphical Internal Components

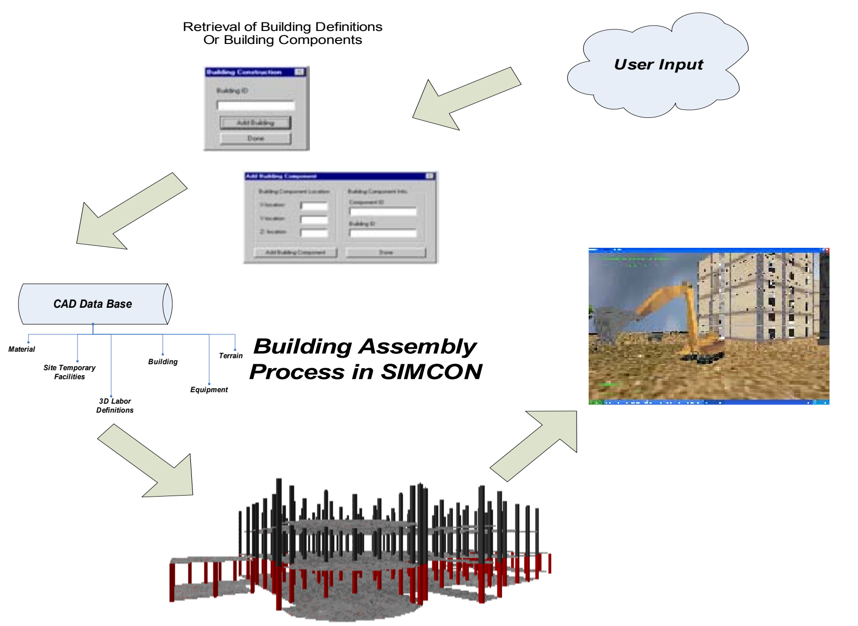

Figure 4: Building/Objects Assembly in SIMCON+.

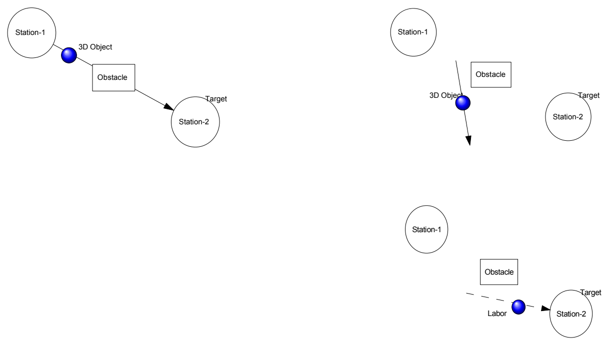

Figure 5: Steps of the GPS algorithm in SIMCON.

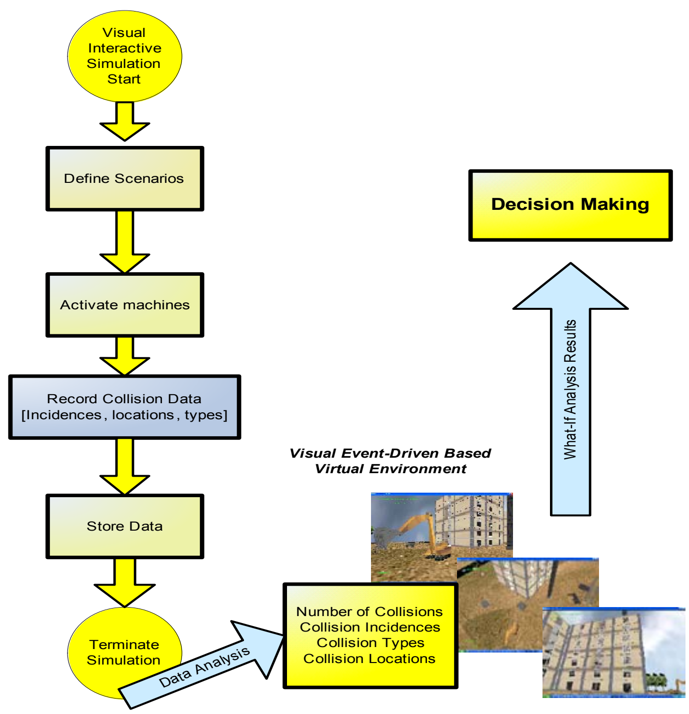

Figure 6: Framework for Conducting What-If Analysis based on SIMCON+.

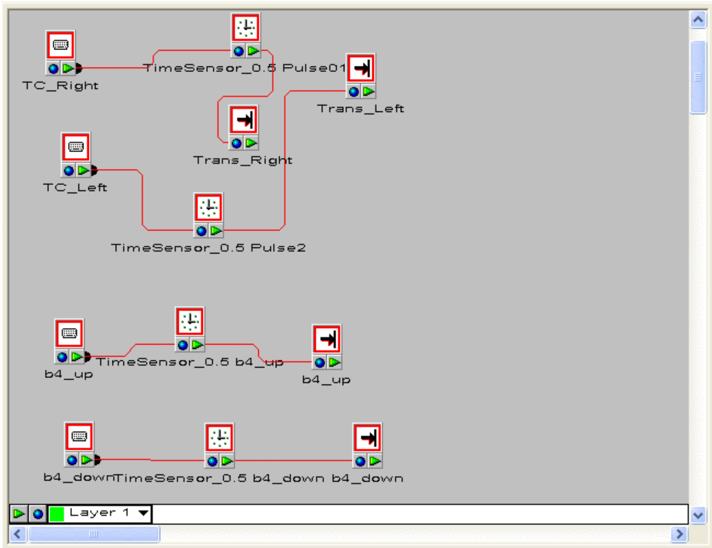

Figure 11: Routes Window in EON Showing the SIMCON+
Typical Machine Control Logical Relationships

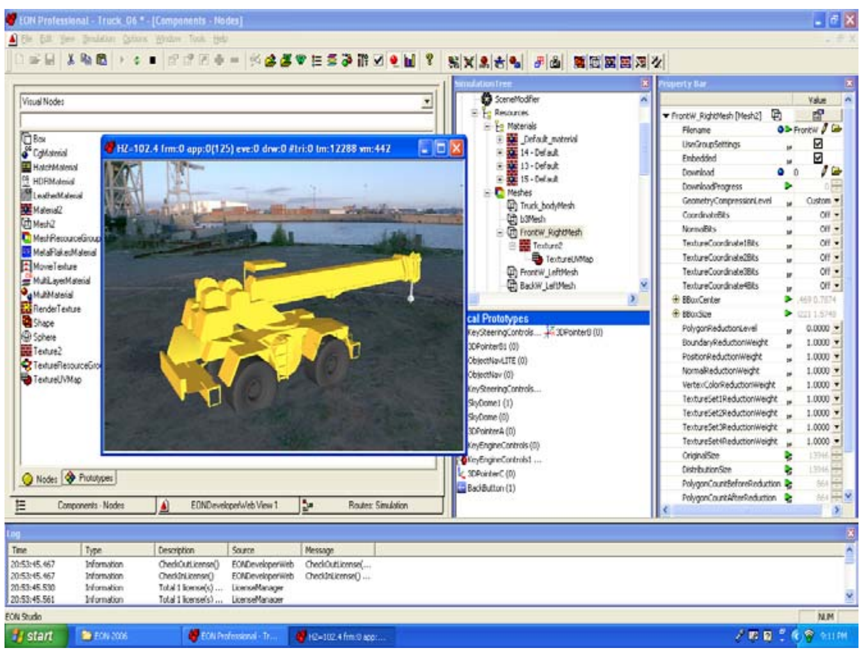

Figure 12: SIMCON+ Virtual Environment at Design Time within the EON System.