QUALITY MANAGEMENT IN CONSTRUCTION PROJECT DESIGN AND MANAGEMENT

Conradie D.C.U[1], Roux E[2]

[1] Built Environment Unit, CSIR. dconradi@csir.co.za Tel. No. 012-8412218
[2] Built Environment Unit, CSIR. eroux@csir.co.za Tel. No. 012-8413007

ABSTRACT

Purpose of this paper - The aim of this paper is to propose the use of simulation to improve design quality and to introduce new opportunities to use quality management throughout the various development stages of construction projects. The paper will attempt to identify the opportunities and implications of quality management with specific emphasis on construction project management during the feasibility study, design, construction planning and construction building life cycle phases.

The construction industry has been slow to introduce the benefits that can be offered by various advanced predictive simulations.

Methodology/Scope – The scope of this paper is limited to the exploration of the problems of architectural design with reference to precedent research and to two recent case studies undertaken by means of a recently developed computational simulation tool used to improve the various building life cycle phases.

Findings – Simulation validates and tests various design assumptions long before construction begins. Better evaluation of design alternatives by means of simulation will contribute positively to construction project design, quality and management. Many lesser known manufacturing techniques can contribute significantly to the improvement of the life cycle phases of a building.

Practical implications – Improved quality will ensure that the design of buildings is significantly improved leading to less construction waste and to optimum performance of the building operation and management stages. This will lead to significant cost savings both with regards to the project cost and to the cost to the environment.

Value - The use of appropriate quality techniques supported by predictive simulation will ensure that the design solution space for a given set of design constraints for a specific building is sufficiently explored.

Keywords: simulation**,** design, quality management, construction project management

1 INTRODUCTION

The aim of this paper is to propose the use of simulation to improve design quality and to introduce new opportunities to use quality management throughout the various development stages of construction projects. The authors reason that appropriate simulations might be one of the best ways to evaluate various design solutions. The extensive use of simulation in the recently completed New York Times building and the Federation Tower in Moscow illustrates the point. The main advantage of simulation is that different solutions can be evaluated and design problems can be detected well before construction. This will reduce the cost of design mistakes while at the same time improving quality. Simulation offers a way to evaluate and test new high performance

construction materials and finishing techniques. Simulation can advance the use of renewable energy sources and natural materials such as wood. On-line simulation systems such as the Massachusetts Institute of Technology (MIT) Design Advisor are already able to assist designers and contractors with regards to comfort, energy, natural ventilation, day lighting and life cycle cost of energy and CO_2 emissions. Simulation will make required quality improvements visible and will also make acceptance decisions easier.

Vitruvius's principles of architecture, as originally published in his ten books on architecture (Morgan, 1960) between 80/70 BC – 25 BC, are still relevant today. He asserted that the fundamental principles that a structure must exhibit are *utilitas* (purpose and use), *firmitas* (material and construction) and *venustas* (proportion and scale) (Blaser, 1990). The world has changed significantly since then. Modern designers are confronted and have to come to terms with numerous requirements and constraints that should inter alia lead to greener and innovative buildings, sustainable designs, efficient energy use and accessibility/inclusive design.

A building is a special artefact or product. The design of buildings is an activity that integrates the bodies of knowledge present in the arts and sciences (Pugh, 1996). However, the balance between art and science for a fossil-fuelled power station, family house, textile fabric, sculpture, painting and textile loom differs significantly.

One of the important production tools in the architectural design office is Computer Aided Design (CAD). Unfortunately over the past 35 years commercial CAD systems have had little impact on the early, conceptual stages of design. This is the phase where the maximum benefit over the life cycle can be realised at the minimal cost. This inadequacy is further exacerbated by the pressing need to follow a total life cycle approach to architectural briefing and design. Eastman (1999) indicates how many efforts have been put into developing databases to support architectural design and construction. Except in special cases, these efforts have not been very successful.

Since approximately 1990, in an attempt to address the shortcomings of CAD, architectural CAD researchers have been focussing their attention on the cognitive aspects of the architectural design process. They have been constructing models of architectural design knowledge and reasoning. They developed data structures to represent them computationally. Although the models are unique to the discipline of architectural design they were borrowed and adapted from other disciplines such as Artificial Intelligence (AI) and product development.

Due to the complexity of design, systems for design have often defined the task with artificial narrowness (Hinrichs, 1991). In the past, progress in AI was made by limiting the universe of discourse or even closing it in an attempt to simplify the enormous complexity of design problems.

Kolodner (1993) is of the opinion that engineering and architectural design are almost entirely a process of adapting old solutions to fit a new situation or merging several old solutions to do the same. Carrara *et al.* (1994) agree with this viewpoint when they characterize design as:
1. Defining a set of functional objectives that ought to be achieved by the design artefact.
2. Constructing design solutions which, in the opinion of the designer, are (or should) be capable of achieving the predetermined objectives.
3. Verifying that these solutions are internally consistent and that they achieve the objectives.

Richens (1994) strongly disagrees with this point of view when he claims that architectural objectives usually include functional ones but are dominated by less definable intentions. Flemming (1994) states that attempts to introduce machine innovation and creativity are red herrings. Oksala (1994) expresses the opinion that it is realistic to design machines that work as architectural design assistants and are capable of re-designing work according to given rules.

To implement the systems the following four typical approaches were used (Hinrichs, 1991):

- *Selection.* Select components to instantiate a skeletal design. Selection problems are typically constraint satisfaction problems in which all variables to be satisfied are known ahead of time. The components are given as if from a catalogue.
- *Configuration.* Arrange a given set of components. Configuration is related to selection, however, it concentrates on the relationship between components rather than the components themselves.
- *Parametric.* Fix numeric parameters. Parametric problems are similar to selection problems except that the components are quantities and the task is usually to optimise or partially satisfy constraints.
- *Constructive.* Build up design from components. Constructive design is analogous to planning in that components take on the role of operators or actions. Typically, the space of components is fixed throughout the design process.

In CSIR researchers of the Built Environment unit initially followed abovementioned research and had useful precedents where attempts were made to improve architectural design in projects such as Architectural Evaluation and Design System (AEDES) (Conradie *et al*, 1999), Architectural General Object System (ARGOS) (Conradie, 2000) and a space norms research system created for the Department of Public Works, ESPACE, (Republic of South Africa, Government Gazette Vol. 483, 2005).

Knowledge-age drivers have a significant impact on the product development process. This suggests that the construction industry needs to be improved in general and the architectural briefing and design specifically if it is to remain competitive and appropriate. Although there are similarities between product development and architectural design there are also significant and problematic differences (Conradie, 2000).
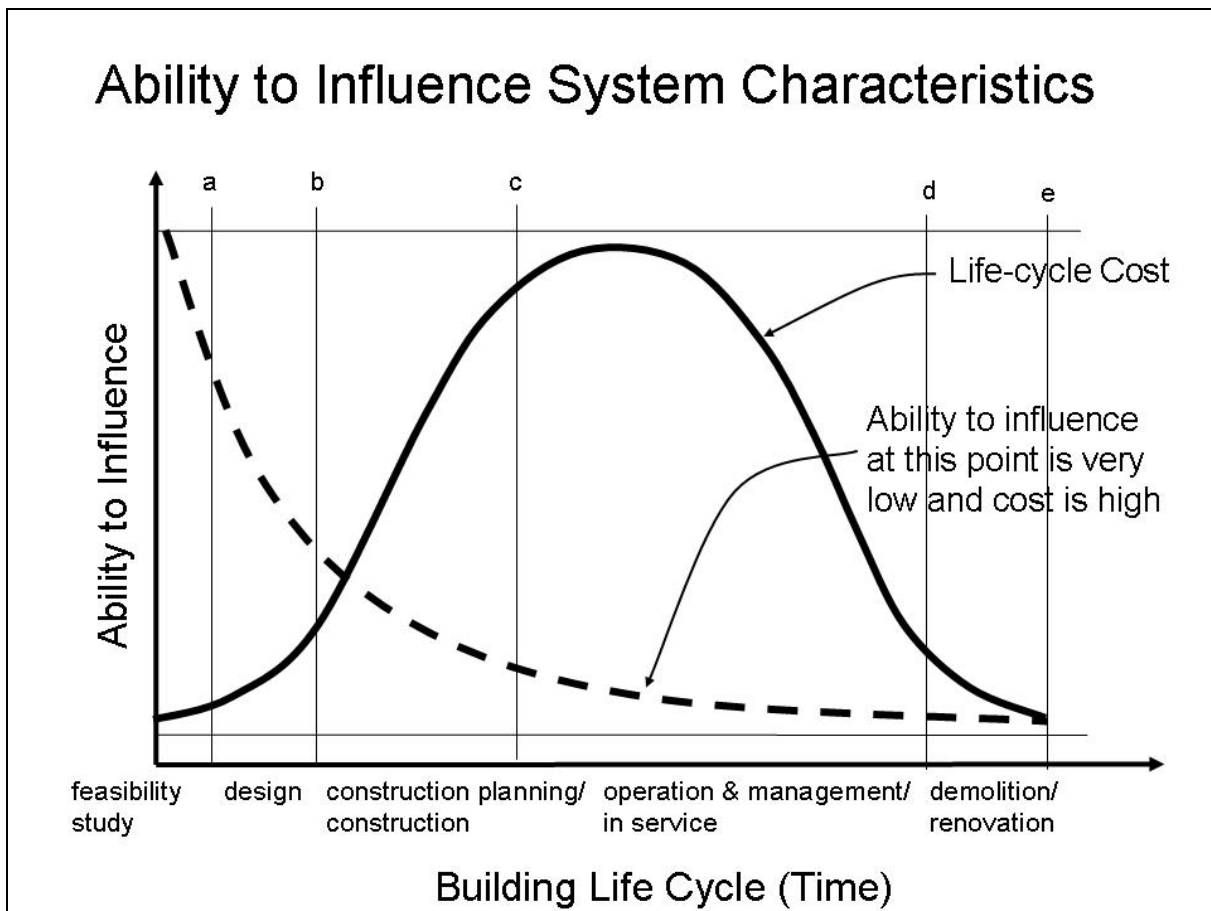
Figure 1: Ability to influence system characteristics (Based on Sparrius, 1998).

The global drivers of the new market place are (Agility Forum, 1997):
- Ubiquitous availability and distribution of information.
- Accelerating pace of change in technology.
- Rapidly expanding technology access.
- Globalisation of markets and business competition.
- Global wage and job skills shift.
- Environmental responsibility and resource limitations.
- Increasing customer expectations.

These challenges imply the need to design and develop families of products by networks of firms on compressed development schedules. The designer of the artefact must have increasingly more knowledge regarding the life cycle costs of a product at the conception of the design problem. At this stage few decisions have been made and little cost has been committed to production. Designers are under pressure to apply state-of-the-art upstream design techniques to improve quality while decreasing downstream costs. Sparrius (1998) postulated that in service problems experienced downstream are symptoms of neglect upstream. Upstream problems can only be solved upstream. The ability to influence a system's characteristics diminishes rapidly as the system proceeds from one phase of its life cycle to the next (Figure 1).

Although architectural practitioners have not traditionally been seen as being in the business of manufacturing products, research publications (Pugh, 1996), (Anumba *et al.,* 1997) indicate strong similarities between the construction industry and the manufacturing industry. Both industries design and build physical artefacts/products to satisfy specific client requirements in a specific environment. They also follow similar design-build processes.

Hinrichs (1991) stated that architectural design tasks take place in an open world. An open world is a problem-solving situation in which knowledge is incomplete or inconsistent. A designer's knowledge can be incomplete in several ways:

- *Open categories*. The set of possible solutions for a particular design problem is open.
- *Incomplete domain theories*. In architecture the designer's theory of his domain is incomplete. He/she may not know or be able to retrieve all the causal relationships and facts relevant to a given problem.
- *Under-specified problems*. Design problems that are under-specified have solution criteria that are incomplete. This means that the class of solutions forms an open category. If a problem is under-specified the solution needs to be satisfactory rather than absolutely correct. The ability to determine when a design solution is adequate is critical.

The generation of plausible solutions for a given design problem is problematic. The generation of a solution is difficult for the following reasons (Hinrichs, 1991):

- *The design problem spaces are not enumerable*. There is no function that permits a designer to generate the next possible design. This implies that application guides, standards and norms will not necessarily lead to quality design but can only attempt to improve design.
- *Design constraints are not constructive*. The constraints of a design problem do not directly suggest solutions. Constraints on most design problems rule out an infinite number of possible designs and possibly still permit an infinite number.
- *Categories in the design vocabulary are fuzzy and subjective*. Design problems are not described by necessary and sufficient conditions but by experience and perceived client expectations. The design solutions of today are often characterized by designs we have known from the past. Hinrichs (1991), being an artificial intelligence researcher, thought that this indicated that creative designs should be generated from experience such as the use of Case-based Reasoning (CBR) and not deductive rules.
- *Problems may be barely decomposable*. It is sometimes possible to break problems down into smaller sub problems. However, these sub problems tend to be highly inter-constrained. Researchers in the Artificial Intelligence field of CBR thought that this indicated that new designs should be based on previous proven designs in order to expedite the design process. The reason is that these previous proven designs could be modified when required saving a significant amount of design time. This ignored the creative or art aspect of design mentioned above.
- *Design occurs in multiple problem-spaces*. Because it is sometimes necessary to decompose a problem the designer must work at different granularities such as the design of a door or an entire airport.

2 PRECEDENT SYSTEMS

Research undertaken at CSIR in 1999 resulted in providing a rudimentary framework for a holistic total life cycle design methodology. CSIR wrote a prototype software system called AEDES (Conradie *et al*, 1999). In 1999, the results of this research were presented at the Eleventh Symposium on Quality Function Deployment (QFD) in Detroit (Conradie *et al.*, 1999).

AEDES was a first attempt to create an Integrated Project Environment that could span the entire life cycle of the facility. The system managed to use aspects of QFD, Systems Engineering and Concurrent Engineering. These are advanced manufacturing/product development techniques. The research team succeeded in creating a system that enables the designer to start with a raw client requirement and progress to the component level. Functional decomposition was used extensively.

The most significant shortcomings of the system were:

- An over emphasis of the functional decomposition (transformational approach) aspects led to a very rigid system that is very prescriptive to the creative people that were supposed to use it.
- It was difficult to map multiple functions from different main template categories identified in AEDES to physical structural elements.
- The team never fully achieved the objective of creating starter kits (cases at various levels of specificity) to expedite future designs. This was due to the fact that the benefits that AI could offer and specifically CBR were not known at the time.

A starter kit is a simple architectural CAD drawing that contains a complete ideal layout of, for example, a hospital ward and could be used to rapidly design a hospital. This approach is useful in South Africa where there is currently a shortage of skilled designers.

Another prototype CBR-enabled intelligent component system, called ARGOS, was developed for a doctoral thesis (Conradie, 2000). This system facilitates the storage of design information in cases that can be used on desktop computers over the total life of the facility. A life cycle information infrastructure based on Extended Mark-up Language (XML) was used as a basis for ARGOS. The storage of CAD drawings by means of the Internet standard, XML, was explored in detail.

Due to the generic nature of ARGOS the range of possible applications is potentially large. The relationships of ARGOS to other intelligent data sources were also explored.

A detailed parametric ARGOS graphical object was developed with the ability to switch between 2D and 3D modes. Internally the ARGOS design case could contain four main types of design information consisting of both alpha-numeric and graphic information. A short hypothetical run-through, including empirical response tests, of how the ARGOS system might be used were described (Conradie, 2000). Empirical response tests were also conducted for a blackboard (spreadsheet) with 25, 50 and 100 ARGOS objects on different types of computers. This indicated that the ARGOS blackboard type of systems architecture that uses a spreadsheet is effective. Although exciting breakthroughs with the discovery of an intelligent component that could be used to bridge structured design methodologies and the creative aspects of design were made in this study, there were unfortunately a number of shortcomings such as:

- At the time of this research XML was not being used as a means to structure design knowledge. Subsequently XML became one of the most important standards to store design knowledge.
- ARGOS was very orthogonal and made the design of organic free flowing forms difficult. It was impossible to say if designers would accept this new type of blackboard autonomous component in design.

3 METHOD FOLLOWED

Due to the generally unsatisfactory solutions offered by all of the abovementioned, the CSIR research team decided to study visual simulation and modelling in depth. This led to the establishment of a generic simulation platform called KRONOS based on a Building Product Model (BPM). KRONOS was the Greek god of time revered at the ancient Greek site of Olympia where the Olympic Games started in 776 BC. BPMs were originally developed to facilitate collaboration between different architectural and engineering design systems such as CAD. The KRONOS platform operates at three distinct levels, i.e. the model level that provides the static virtual world, the steering level that handles the movements of agents and the cognitive level where it is decided what the Belief-Desire-Intention (BDI) of the agents would be and how they are going to react to collisions (Bratman, 1987). Modern thinking in simulation recognizes the importance of

understanding complexity, inter-relatedness and correlation between various systems. Simulations in the built environment require both static and dynamic simulations. At the moment many static type of simulations such as energy evaluation, shading simulation, structural design, acoustical simulation and fenestration simulation are widely used in academia and industry.

Two different case studies were undertaken to test the platform. The first study simulated people and vehicular movement for a new 7100 seat mega church. This property experienced severe traffic problems due to inadequate vehicular exits. The other case study was very different from the first one because there was no real perceived problem. The opportunity was used to observe first hand the behaviour of members of the public at the Stellenbosch Traffic Department (Figure 2) which is a public service centre with many service counters. The two case studies highlighted many deficiencies, such as inadequate support for complex queues, in the simulation software. Currently more advanced capabilities are being added to KRONOS to support traffic safety assessment simulation. In an attempt to improve the effectiveness of design in new buildings other simulations are currently being researched, for example, the simulation of sun and shade including natural daylight.
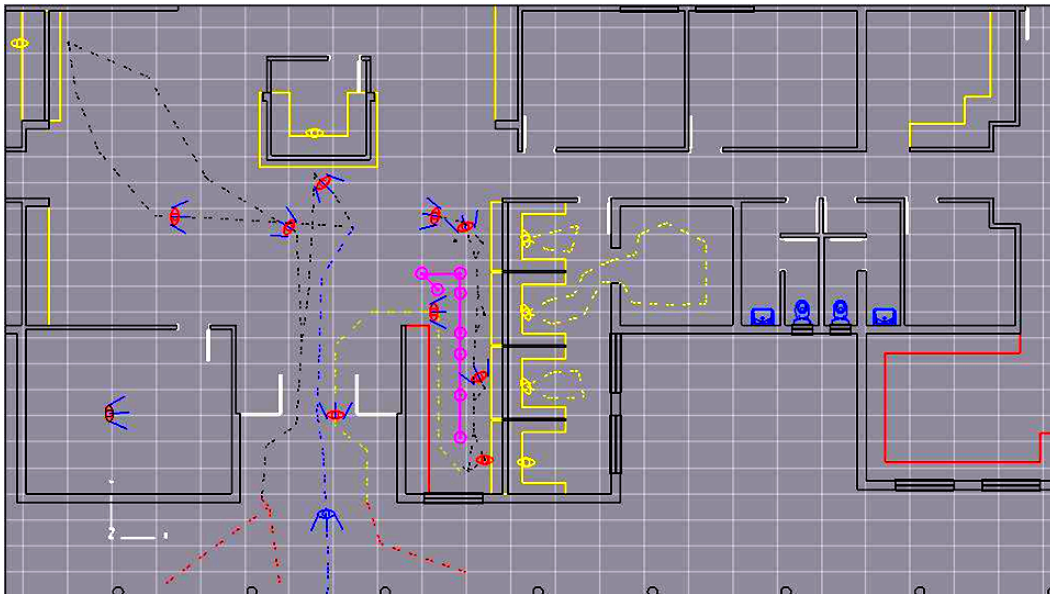

Figure 2: A typical 2D simulation of the Stellenbosch Traffic Department

4 SIMULATION

4.1 Introduction
One of the most exciting opportunities to improve design quality or even simulate the construction process is the use of modelling and simulation. The full potential of simulation to improve design and construction quality has not yet been realised. Although mathematical modelling has been used for many years we are now alluding to the new generation of visual type of simulations. The recent significant progress in computer hardware, particularly high speed graphic hardware and software, greatly facilitates what can be achieved with this type of simulation. An important advantage of simulation is that it is non-prescriptive and does not force a designer to follow a specific method or rationale. It enables the designer to test what the effect of specific designs will be long before construction. This he can do without following the rigid methods of the transformational approach to design such as in formal systems engineering. In the case of 4 Dimensional (4D), i.e. 3 Dimensional (3D) and real time type of simulations, the different stages of the construction project can be rehearsed before the actual construction work starts. The following main types of visual simulation can be distinguished:

- Computational Fluid Dynamics (CFD).
- Energy evaluation.
- Shading simulation.
- Structural design.
- Acoustical analysis.
- Fenestration analysis (Evaluating fenestration product for zero net energy construction).
- Miscellaneous multi-purpose simulations.
- Construction process simulation.

4.2 CSIR research

Over the past two years, extensive research has been undertaken at the CSIR to establish a generic Computational Building Simulation (CBS) platform to support the design and evaluation of complex built environments (Conradie *et al*, 2007). To study or predict building performance requires both advanced static and dynamic capabilities. The CSIR research team created a modelling and simulation environment based on a BPM. Within this environment agents and props were placed to dynamically simulate and predict user behaviour.

A KRONOS agent has the following characteristics:
- Real time free roaming or predefined movement.
- Reports observed phenomena.
- Support space-time experiments.
- Can communicate with each other and props.
- Programmable characteristics.

An agent can be a person, vehicle, animal, pedestrian, in fact any entity that normally moves. A prop has the following characteristics:
- Physical shape.
- Mostly static.
- Observable by agents.
- Programmable characteristics.

Props can be any static entity such as construction elements, furniture, notice boards, traffic signs or even the sun. The latter is an example of a super specialized prop because it moves slowly on a daily and annual basis. Complex mathematic formulas and ephemeris tables are used to calculate its movement.

The data from the two case studies mentioned above which used KRONOS indicated that the approach is feasible. In an attempt to reduce the current high fatality rate on the Moloto Road in Mpumalanga, current work being done concentrates on the simulation and prediction of accidents. Other research includes the accurate modelling of the sun's movement with a view to generate accurate real time or accelerated real time shadows and solar penetration analysis on various surfaces. This will form the basis of the improved use of daylight in buildings and the design of heliostat fields and the receiver for solar power generation (Figure 3).
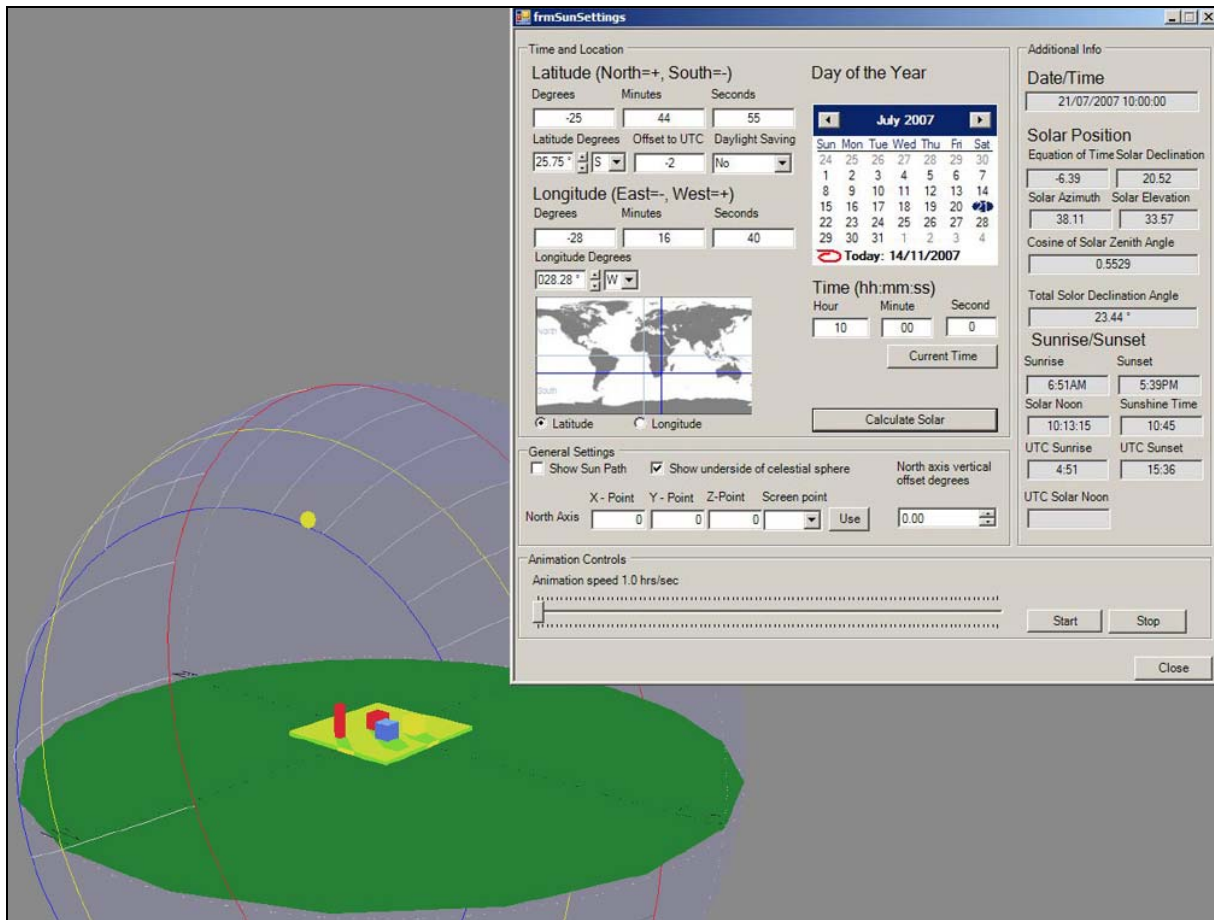
Figure 3: The accurate simulation of solar diurnal and annual movement and projected shadows in KRONOS.

4.3 Advantages of simulation

The following are advantages of simulation:

- Designs can be validated and explored before construction.
- 2 Dimensional (2D) documentation will gradually be replaced by integrated information in Building Product Models (BPMs).
- Design alternatives can be compared.
- The modelling of multiple physics becomes feasible.
- The use of photo-realistic real time animated architecture may be used.
- Immersive environments (virtual reality) can be used for design reviews.
- Multi-disciplinary BPMs are becoming commonplace such as ISO-STEP, CIMSTEEL, COMBINE on the basis of international standards such as International Association of Interoperability (IAI).
- Life cycle planning (Athena Institute. *Impact Estimator* and *Eco Calculator*) (Athena Institute, Accessed 18 February 2008) may be done.

5 FINDINGS

Improvement in quality of the upstream building life cycle phases such as architectural feasibility study, design and construction planning and construction life cycle phases is not a trivial matter. Over the past 35 years, commercial CAD systems have had little impact on the early conceptual stages of design. However, it did improve the quality of production drawings significantly.

QFD and Kansei Engineering (KE) can significantly improve the quality of the conceptual stages of design. Teoriya Resheniya Izobretatelskikh Zadatch (TRIZ) (Kaplan, 1996) when combined with simulation can lead to significant improvements of design solutions because the technique is a powerful catalyst for out-of-the-box thinking.

6 CONCLUSION

The use of predictive simulation will ensure that the design solution space for a given set of design constraints for a specific project is sufficiently explored. Improved quality will ensure that the design of buildings is significantly improved leading to less construction waste and optimum performance of the building operation and management stages. This will lead to significant cost savings both with regards to the project cost and to the cost to the environment.

BIBLIOGRAPHY

Agility Forum. 1997. *Next-generation manufacturing*. Bethlehem, PA: Agility Forum.

Anumba, C.J., Baron, G. and Evbuomwan, N.F.O. 1997. Communications issues in concurrent life-cycle design and construction, in *BT Technology Journal*, 15(1), Jan. 1997.

Athena Institute. No date. *Impact Estimator* and *Eco Calculator*. Available from: <http://www.athenasmi.ca/tools/ImpactEstimator/> [Accessed 18 February 2008].

Blaser, W. 1990. *Richard Meier Building for Art*. Basel: Birkhäuser Verlag.

Bratman, M.E. 1987. *Intention, Plans, and Practical Reason*. Cambridge: Harvard University Press.

Carrara, G. and Kalay, Y.E. 1994. *Knowledge-based computer-aided architectural design*. Amsterdam: Elsevier.

Conradie, D.C.U. 2000. *The use of Software Systems to Implement Case-Based Reasoning Enabled Intelligent Components for Architectural Briefing and Design*, (Pretoria: Ph.D. thesis Faculty of Engineering, the Built Environment and Information Technology), South Africa: University of Pretoria.

Conradie, D.C.U., Gibberd, J., Mentz, F and Ras, H. 2007. Towards a Continuum of Computational Building Simulation Tools to Support the Design and Evaluation of Complex Built Environments. In *Conference Proceedings of CIB World Building Congress, Construction for Development*, Cape Town: 14-17 May 2007.

Conradie, D.C.U. and Küsel, K. 1999. The use of QFD for architectural briefing and design, in *Transactions from the eleventh symposium on Quality Function Deployment*. Novi, Michigan: QFD Institute.

Eastman, C.M. 1999. *Building product models: computer environments supporting design and construction*. New York: CRC Press.

Flemming, U. 1994. Artificial Intelligence and Design: A mid-term Review, in *Knowledge-based computer-aided architectural design*. Amsterdam: Elsevier.

Flemming, U. 1994. Case-based design in the SEED system, in *Knowledge-based computer-aided architectural design*. Amsterdam: Elsevier.

Hinrichs, T.R. 1991. *Problem Solving In Open Worlds: A Case Study In Design*. PhD thesis, Atlanta: Georgia Institute of Technology.

Kaplan, S. 1996. *An introduction to TRIZ: the Russian theory of inventive problem solving*. Michigan: Ideation International, Inc.

Kolodner, J. 1993. *Case-Based reasoning*. San Mateo, California: Morgan Kaufmann Publishers.

Mazur, G. 2001. *Theory of Inventive Problem Solving (TRIZ).* Available from: <http://www.mazur.net/triz/>. [Accessed: 13 November 2007].

Morgan, M.H. 1960. *Vitruvius: the ten books on architecture*. New York: Dover Publications, Inc.

Oksala, T. 1994. KAAD: Evolutionary and cognitive aspects, in *Knowledge-based computer-aided architectural design*. Amsterdam: Elsevier.

Pugh, S. 1996. *Creating innovative products using total design*. Reading, MA: Addison Wesley.

Republic of South Africa. Government Gazette Vol. 483. 2005. *Space planning norms and standards for office accommodation used by organs of state.* Notice 1665 of 2005. Pretoria: The government printing works.

Richens, P. 1994. Does knowledge really help? CAD research at the Martin centre, in *Knowledge-based computer-aided architectural design*. Amsterdam: Elsevier.

Sparrius, A. 1998. Specification Practices, in *Course documentation*, *Ad Sparrius System Engineering and Management (Pty) Ltd*. South Africa: Armscor Training Centre.