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Integrating Virtual Prototyping and Cad Technologies in Construction Project Planning: A Review

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ABSTRACT

This paper reviewed the construction planning process and available CAD-based planning methods, in a bid to proposing integrated technological improvements, towards improved productivity of the global Architecture, Engineering and Construction (AEC) sector. Through a mixed research method involving a review of literature published in the last 40 - 50 years; including 12 Books, 52 peer-reviewed articles, 13 conference proceedings, 1 Technical Report and 2 Theses; and subject matter expert validation workshops. This research projects the planning phase of the construction project life-cycle as holding the key to creating a more effective and efficient project delivery, by the integration of computer-aided virtual reality and prototyping, in the delivery of construction projects. This review paper contributes to existing literature by bringing new insights into the practice of Construction Planning through the proposal and validation of a **PR**ototyping and **VIR**tual **I**nformation **S**ystem **(PR-VIRIS)** framework. PR-VIRIS is proposed to combine case-based reasoning techniques and virtual prototyping in the simulation of alternative construction methods, to boost productivity and aid decision-making by governments, policy makers and project managers on large capital projects.

Keywords: Construction Planning, Virtual Reality, Virtual Prototyping, Computer-Aided Designs, PR-VIRIS

INTRODUCTION

A comparison of productivity data between other sectors and the construction sector, is interesting and revealing. Figures I and II respectively reveal that country specific and global trends/statistics are the same, as the manufacturing and other sectors record annual improvements in productivity, while the construction sector continuously declines or remains flat.

The above phenomenon is a global one and according to [52], this phenomenon may be explained by the following three differences between both industries;

1. The construction industry does not have the ability to *try-before-build*, as easily obtainable in the manufacturing industry;

2. The construction industry does not have a fixed production line; and
3. The construction industry does not have an effective platform to capture and re-use knowledge generated in design and construction stages. These differences inform the necessity for this study.

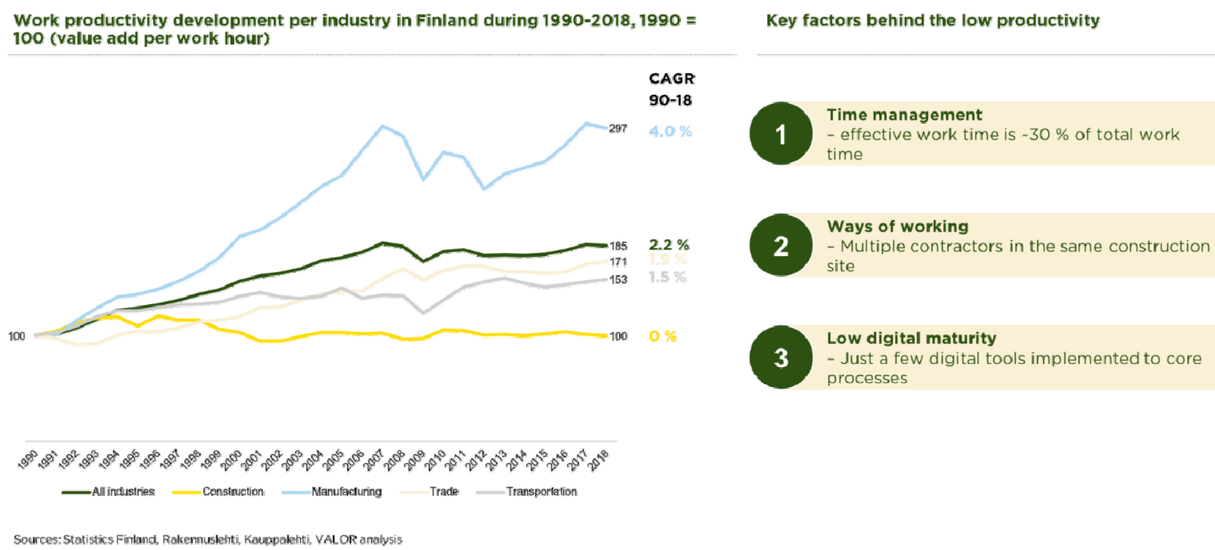

FIGURE I. PRODUCTIVITY COMPARISON BETWEEN THE CONSTRUCTION AND OTHER SECTORS (FINLAND)

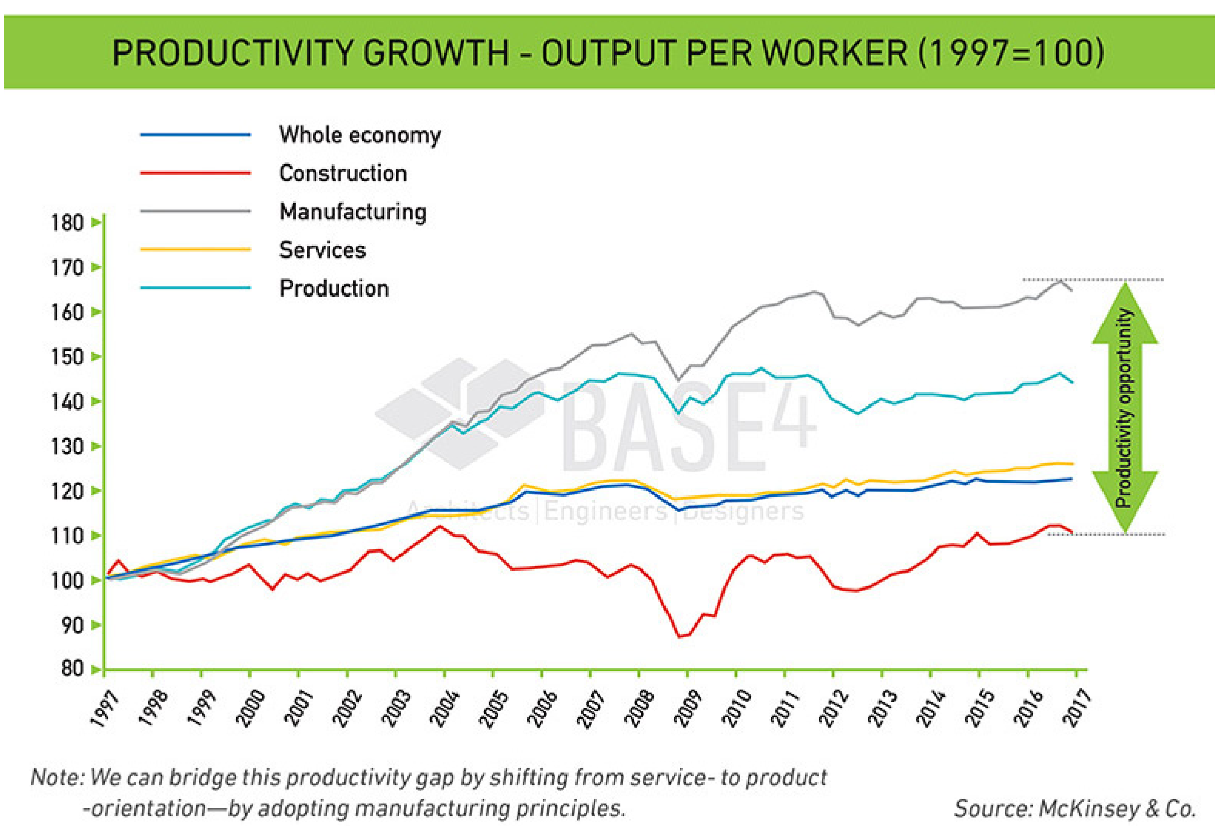

FIGURE II. PRODUCTIVITY COMPARISON BETWEEN THE CONSTRUCTION AND OTHER SECTORS (GLOBAL)

A construction project is, to a very large extent, an experimental process guided by design and planning information which in most cases is full of incompleteness and mistakes. As a result, many projects are completed at the expense of ubiquitous time and cost overruns, hence the lack of the ability to *try-before-build* makes construction a very risky business [52].

The manufacturing industry has a fixed production line [5], which makes the speed of machinery simple and determines the productivity, whereas the construction industry does not have a fixed production line and project team members and participants have to exercise personal judgements in order to find the best way to complete set tasks and work packages.

Current trends in Information and Communication Technology (ICT) are yielding a wide range of new computer-based tools to support the architecture, engineering and construction sector (collectively referred to simply as *the construction industry* in this study). These tools, particularly those associated with Building Information Models (BIMs) for construction project modelling and integration, promise great increases in the effectiveness and efficiency of designing and managing construction projects. However, these improvements require more than just technical solutions; their full potential cannot be realised without corresponding changes in the work tasks and skill sets of the project participants.

[25] categorised trends in construction ICT into three eras. The first era of construction ICT (now more than 4 decades old and continuing) focused on developing stand-alone tools to support specific work tasks such as Computer-Aided Designs (CAD), structural analysis tools, estimating, etc. These tools are well established within current project management practice. A more recent era (from the mid-1990s) of construction ICT has focused on computer supported communications such as E-mail, the World Wide Web (www), document management systems, etc. This is a less mature field, with new tools and core features still emerging, and business processes still adapting. Much of the construction ICT research and development over the past decade has pursued a third era of construction ICT, focused not on individual applications or transactions, but on the potential for uniting all these as a cohesive overall system through integration, building modelling, etc. This emerging ICT has seen some impressive innovative use in industry but has yet to reach mainstream potential.

This paper is structured to first identify the literature that is the basis for this research, describing the CAD-based Virtual Prototyping and technologies as well as the global practice of Construction Planning. The paper then introduces some applications of these technologies to Construction Planning and then makes a case for improved integration by proposing an all-inclusive system architecture that seeks to revolutionalise the construction planning process. The paper further discusses the findings of validation workshops and the implications of the proposed system for practice, theory and future research. The paper concludes with a call for further collaborative research in what is as yet, an error-prone but important aspect of construction, planning.

Justification of Study

With the disruptions of the world's largest ecosystem, and its prevalent wasteful nature as compared to the

Manufacturing and Services sectors, technological disruptions across construction value chains, may reshape and transform the AEC sector. Evolving the Construction Planning process into a 'try-before-build' process, similar to the highly productive manufacturing sector, will aid the transformation towards a more productive AEC sector, especially through the combination of product and information modelling capabilities. Following a literature review, the proposed system architecture presents a framework for future improvements in the construction planning process, through the combination of virtual reality/prototyping and case-base reasoning information modelling techniques, with efficient reporting and documentation for productivity tracking.

METHODOLOGY

Literature Review

Without a strict bibliometric analysis, a critical review of existing body of literature is carried out, comprising 12 Books, 52 peer-reviewed articles, 13 conference proceedings, 1 Technical Report and 2 Theses, all published over a 50-year period, is presented to gauge the changes and evolution of subject matter systems.

Proposal of System Architecture

With findings from literature, a state-of-the-art system architecture, which combines the key features of virtual reality simulation and prototyping, is proposed, fulfilling adaptive, integrative and stochastic characteristics of modern-day construction planning systems.

Validation Workshops

Validation workshops were convened with subject matter experts and project management practitioners to validate the findings of the review and the proposed framework/system.

VIRTUAL REALITY AND PROTOTYPING

This section presents and briefly highlights the characteristics of the virtual reality and prototyping technology, as an advanced technology utilised towards the improvement of efficiency and productivity of the AEC sector.

The ever-increasing role of computers and advanced technology in business and our everyday lives has not, until a few decades ago, reached the construction industry, because of a lack of adequate software designed specifically for the construction industry, and the reluctance of the industry to try new and unproven methods of doing business. Competition, increasing personnel and construction costs, and falling productivity levels have made advanced computer technologies essential for large construction firms, while medium and small-size firms are finding it a necessity rather than a luxury to acquire a computer [21].

Following the lead of the non-farm industry, the construction market has been flooded in the past few years with sophisticated and versatile computer packages which deal with various aspects of the building and construction process: structural analysis and design, cost control, estimating, scheduling, financial management, etc. For this reason, potential users are faced with two major problems; (1) the difficult task of identifying their needs; (2) the problem of locating and selecting the appropriate software packages that best suit their requirements due to the slow spread of the simulation and modelling techniques in construction [4].

Virtual Reality (VR) [or Virtual Environment (VE)]

Virtual Reality (VR) refers to a computer simulation that creates an image of a world that appears to our senses in much the same way we perceive the real world, or physical reality. In order to convince the brain that the synthetic world is authentic, the computer simulation monitors the movements of the participant and adjusts the sensory display(s) in a manner that gives the feeling of being immersed or being present in the simulation.

It refers to immersive, interactive, multi-sensory, viewer-centered, Three-dimensional (3D) computer generated environments and the combination of technologies required to build these environments [18]. A more formal definition of virtual reality would be a medium composed of interactive computer simulations that sense the position and actions of the participant(s) (or associated elements), providing synthetic feedback to one or more senses, giving the feeling of being immersed or being present in the simulation [67].

In engineering, virtual reality holds the potential to revolutionize the way in which humans interact with computers. Engineers strongly rely on the use of computers to build, test and verify designs and virtual reality now offers a new and innovative way to interact with the complex engineering data and designs [77]. Some of the areas where virtual reality can contribute to increase engineering productivity are in the areas of design, prototyping, design for maintenance and assembly, factory planning, networked design, concurrent engineering and most recently integrated construction project planning.

Virtual Prototyping (VP)

In engineering design, the Virtual Prototyping (VP) technique has been studied and implemented in recent years, but with a rather slow implementation in the construction industry. Due to the irregularity in the studies leading to confusion, when Virtual Prototyping (VP) is mingled with Virtual Reality (VR) or Virtual Environment (VE), the extent of confusion continues. Hence this section will seek to present a clarification to the definition of the virtual prototyping (VP).

Virtual Prototyping refers to the process of simulating the user, the product and their combined (physical) interaction in software through the different stages of product design, and the quantitative analysis of the product [68].

According to [27], VP is a relatively new technology that involves the use of Virtual Reality (VR) and other computer technologies to create digital prototypes.

GLOBAL CONSTRUCTION INDUSTRY APPROACH TO THE CONSTRUCTION PLANNING PROCESS

This section describes the fundamental aspects of the construction planning process and the generic stages in the development of a construction plan. The aim is to present the complexity of the planning process, thereby establishing the context and need for integrated planning through the use of multidimensional virtual reality and prototyping techniques.

Past research on the development of the construction industry and the effort to implement the research findings, both have the broad aim of solving the problems of the construction industry, while also improving its performance [60]. The construction industry in both the developed and developing countries may be viewed as that sector of the economy which, through planning, design, construction, maintenance and repair, and operations, transforms various resources into constructed facilities. These physical facilities play a critical and highly visible role in the process of development.

[30] stated that while estimating evaluates the use of resources in terms of cost, planning evaluates the use of resources in terms of time, and putting both together is necessary to obtain cash flow. Additionally, these are used for production planning, cost control and valuations if a development or construction contract is won. Thus, the calculation of a realistic duration and cost is a key aspect in the successful completion of a contract.

Developing the Construction Plan

The planning of a construction project is generally resolved by the correct application of parameters (time and costs) that have already been extensively applied and proven for the specific project type, with each parameter backed by rapid and efficient evaluations of a technical and economic nature. [10], having acknowledged the increasing nature of complexity of construction processes, has suggested that conventional methods of construction planning may need to be refined, given the existence of several complex conditions, amongst which are;

- Considerable economic and technical repercussions resulting from incorrect implementation of projects that cover essential infrastructures of an integral system or programme of projects;
- The influence of external factors beyond human control, like the environment;
- External influence due to the limited availability of resources on the market;
- Limitation or unavailability of experience: in which case it is necessary to use extrapolations or simulations of hypothetical conditions.

Construction planning can be considered a goal-oriented task that evolves through several stages within the construction period, with the evolution of the planning process regarded as a problem-solving task [48]. The first stage involves problem definition; the second stage involves the provision of a solution while the third stage involves monitoring and controlling the execution or application of the solution provided. Any deviations from the plan, either through internal or external influences would require that the construction planner revisits the plan with a view to revising the planned solution.

Gathering Project Information

With the purpose of supporting the planning of construction work into a plan that becomes more fully inclusive, gathering of project information is regarded as the first step, and sometimes referred to as stakeholder requirements, [19] opines that the true purpose of planning is collecting and collating of information for decision-making purposes and this requires great effort, skill, sometimes experience and competency in data collection techniques. [47] acknowledge that with a broad spectrum of information required, a majority of the information eventually used for developing the construction plan is at best incomplete, insufficient or sometimes inaccurate.

In general practice and as stated already, the process of information gathering enables the construction planner to make certain decisions on issues such as; (1) Identifying the types of construction activities (what should be done?); (2) The available construction methods (how should the activities be carried out?); (3) The appropriate type of resources (who does what and with what means?); and (4) The dependency factors governing the sequence of all the construction activities (when should the activities be carried out?). However, with very limited time available to comprehensively process all aspects of the construction project information, [3] indicates that the construction planner normally develops deterministic construction plans based on pure guesswork data, in order to speedily produce the construction plan under pressure.

Defining Construction Activities

Past studies by [54], [31] and [57] have unified the opinion that the level or degree of detail to which construction plans are prepared, plays a significant role in the effectiveness of construction project planning. However, [3] notes that there is still much confusion about what should be considered an adequate degree of detail when developing and presenting a construction plan. This explains why the Prince 2 methodology of the Office of Government Commerce suggests that plans for a subsequent stage are rather produced towards the end of the preceding stage, as it is generally suggested that plans should be prepared at the lowest possible degree of details towards the execution and implementation stage, where the uncertainty factors are never considered to be highest [47], and which makes the representation of the construction activities appear in a varying degree of details.

Selection of Construction Methods

In calculating the time and cost estimates for each of the construction activities in the construction plan, construction planners work collaboratively with other project participants to select the best methods of construction required by the various tasks and work packages in the construction project, with this collaborative work being as a result of some participants having the required experience or knowledge of available resource [17].

Several evaluation criteria have been used to aid the decision in selecting the best construction methods. In a survey conducted by [14] of U.S. experienced practitioners ranging from clients/developers, engineers and contractors to precast concrete manufacturers, a total of 33 sustainable performance criteria (SPC) were identified. These were grouped into seven dimensions, namely; economic factors: long-term cost, constructability, quality and first cost; social factors: impact of health and community, architectural impact; and an environmental factor: environmental impact. These factors are;

- Long-term Cost
- Constructability
- Quality
- First cost
- Impact on health and community
- Architectural impact
- Environmental impact

The resultant list of sustainable performance criteria (SPC) provides team members a new way to select a construction method, thereby facilitating the sustainable development of the built environment. However, due to limited time available while formulating a construction plan, the selection of the construction method is mostly decided based on the experience of the estimators, recommendation, previous construction records or the intuition of the planner [23].

Sequencing of Construction Project Activities

Previous studies by [9] and [38] have sought to address and establish the factors that dictate the sequencing of construction activities for a project, using project management techniques such as the Critical Path Method (CPM) or Program Evaluation and Review Technique (PERT). The determination of these dependency factors requires experience or the knowledge of construction principles and project management techniques, as the dependency relationships developed would determine whether the construction activities are overlapped or performed in sequence. In support of the findings of the above studies, [28] and [41] have identified the following factors as having a greater influence on the creation of the dependency link between construction activities. They are;

- Structural
- Resources
- Space and regulation
- Environmental
- Production technology
- Specific preferences

Resource Allocation

Resource allocation problems such as finding out optimal allocation policies have been studied by researchers through mathematical approaches such as integer programming [72], dynamic programming [26] and branch-and bound [71]. However, these methods require a great deal of computation effort, and developing mathematical models may be difficult due to the variance of the model for different systems, especially large-scale projects or those having a lot of repetitive activities [80].

Resource allocation for construction activities in a network plan can be either limited or unlimited. Limited resource allocation is performed to assess the impact of the resources to the project duration, while unlimited resource allocation is conducted to obtain optimum level of resources to achieve a given target of project duration. Depending on resource availability and the time required to complete a construction project, both methods of resource allocation can be applied [1].

Optimising the Construction Plans

Careful planning, proper executions and established techniques are three critical factors that make construction projects successfully completed [52]. Critical path method (CPM) and bar charts are commonly used to enable construction projects to be done in a systematic way. This involves the project team allocating the different resources needed and associated with the major construction method selected, and decided on the appropriate sequence of activities or assemblies. However, project planners face many uncertain and complex tasks and work packages during the construction period, e.g. due to design errors and mismatch of what is planned and actual demand [52].

Producing a construction plan with an optimum allocation of project resources is the main objective of the construction planner. The optimal allocation of resources would allow a predetermined limited number of resources to be allocated to the various levels of construction activities to realise a successful project completion without any negative effects on projected costs and project duration. Optimal procedures in previous studies developed over the years are divided into linear programming and enumerative procedures as well as other mathematical techniques [1], [40].

APPLICATION OF VIRTUAL PROTOTYPING AND CAD TECHNOLOGIES TO CONSTRUCTION PLANNING

This section presents the application, in literature, of the virtual reality and prototyping technology in the construction planning process, in the areas of Construction Process visualisation, Resource Planning, Analysis and Allocation, Site Layout Planning and Utilisation and Information Modeling and Management, using the Case-base technique.

Construction Process Visualisation

Collaborative technologies for the Architecture, Engineering and Construction (AEC) industries centering on component-based CAD models support architectural and structural perspectives only. The construction perspective is often neglected because a key factor and important dimension for construction project management − time − has been missing in previous simulation models, causing construction planners to abstract CAD model building components into schedule models representing time. The Virtual prototyping (VP) technology, through 4th-dimensional CAD (3D-CAD + time) removes this abstraction process by creating a link between a 3D building model and a schedule model through associative relationships [58].

The concept and development of 4D-CAD in the construction field can be traced back to the mid-1980s, when 3D-CAD models were combined with the project timeline to form 4D models [16] and previous studies by [37] and [6] had presented cases for the development of systems linking 3D-CAD models to schedules.

The area of visualisation in construction project management has significant opportunities, especially for the integration of advanced interactive tools in support of a diverse range of construction project management functions. However, only limited effort has been expended by previous researchers on this subject. Studies by [58], [70] and [69] have shown that the field of visualisation has been instrumental in representing how physical artefacts are to be built from constructability reasoning and construction method workability perspectives, the literature fails to reveal any tangible information about the visualisation of heterogeneous multi-source, multi-dimensional, and time varying data in the context of construction project management.

Resource Planning, Analysis and Allocation

Errors and mistakes in the construction planning schedule frequently occur in practice, as the compilation of schedules depend to a large extent on the limited knowledge and experience of the project teams [78]. This makes every successfully tendered construction project a potential gamble due to the inability of the main contractor to predict whether the project outcome will result in a profit or loss well in advance of the construction.

A major limitation for several projects is the lack of an effective computer-assisted technology for resource allocation, planning and management. Due to project complexity and the large number of factors involved, computers can be an efficient tool for project planning. Such existing basic computer aids as bar charts and the critical path method (CPM) are quite limited as they are 2-dimensional (2D) and are unable to provide spatial construction features or resource and working space requirements [46], [12], whereas more sophisticated methods combine the three traditional techniques of resource allocation, resource levelling and time-cost trade-off analysis. For example, [11], [32] and [50] combine resource allocation and levelling using genetic algorithms (GAs); [51] propose genetic algorithms (GAs) for time-cost optimisation problems; [33] combine a flowchart-based simulation tool with the genetic algorithm (GA) technique. [79] developed a 4D Management for Construction Planning and Resource Utilisation system which links a 3D geometrical model with resources to compute project resource requirements.

While presenting an intelligent scheduling system (ISS), [85] Chen integrates construction factors such as schedule, cost, space, manpower, equipment and material, simultaneously in a unified environment, which produces optimal schedules. The ISS was developed under the environment of Simphony (NSERC/Alberta Construction Industry, University of Alberta), a general-purpose simulation language that provides the flexibility of user-written simulation codes. [86] considered the problem of multi-project resource allocation which was solved by simulation models, through the use of a general purpose simulation language (GPSS), leading to statistical results.

Site Layout Planning and Utilisation

With growing concerns on the effects of spatio-temporal conflicts on constructability within the Architectural, Engineering and Construction (AEC) industry, there is a need to investigate the subject of construction space planning and utilisation. The integration of site-related activities into the planning and scheduling of construction projects has received quite little attention in practice, albeit a very important area. Some construction firms either defer the consideration and treatment of these activities until the commencement of construction works, or provide for them in an unplanned manner.

Site experiences indicate that managing the utilisation of construction space can improve productivity, prevent costly temporary facilities, better protect finished works, save transportation costs, and reduce reworks. The effective planning and scheduling of such site-related activities demands a clear understanding of how they are generated [34], and the benefits will ultimately reduce the delivery time and construction costs with improved building quality.

To improve space management, previous studies have proposed various concepts to represent the space system and developed several models to program space utilisation. [75], [76] represented workspace as critical construction resource and incorporated space programing into construction planning. [64]; and [65] studied construction space decomposition and categorised space assignment patterns for detecting interference. [29] detected spatial conflicts by analysing the patterns of the space conflicts, and developed a strategy to resolve the conflicts. The 4D studies of Fischer incorporated the time description into the 3D CAD model by referencing the process schedules, and [2] proposed a pair-wise analysis between the spaces occupied by two activities for detecting time-space conflicts in a construction schedule.

Information Modelling and Management

In practice, construction planning and control processes depend on large-scale project and corporate data repositories, which are often unstructured and poorly managed, and the construction phase of a construction project involves diverse disciplines and personnel who require different pieces of information at various times and most times in different formats. This results in the production of complex information in large quantities which are often poorly managed. In order to improve efficiency and enhance the integration of information within the construction industry, an appropriate and robust information framework is required, with the adoption of a central database/

repository where the integrity and reliability of information can be monitored and maintained.

The Case-Based Reasoning (CBR) Technique and Information Modeling

CBR has played a very important role in the development of artificial intelligence and expert systems and used to address tasks including planning and design [45]. In the architectural, engineering and construction (AEC) sector, CBR was used to solve problems such as building design [7], [55] and contractor prequalification [59].

According to [63], CBR is a technique for solving new problems by adapting solutions that were used to solve previous ones. It involves matching new and current problems against previously encountered cases stored in a case-base, and where one or more similar cases are retrieved, reused and tested for success [73]. If the retrieved case is not a close match, the solution is further revised producing a new case that may be retained and applied. Like most CBR systems, the model proposed by [22] (CasePlan) utilises CBR as a means to reuse knowledge specific to individual projects, with its unique feature being its ability to tackle planning problems in construction and its ease of use of product models as the basis for case organisation.

Compared to rule-based systems, CBR has the following advantages;

- When a problem is presented to an expert, past similar problems are mentally replayed, thus CBR is closer to actual human decision processes.
- In CBR systems, it is easier to automate the process of incorporating new knowledge into an existing knowledge database. New rules are created and entered into the knowledge base when a rule-based system fails to obtain a desirable solution to a problem, whereas the CBR system will automatically utilise this additional knowledge for the solution of future problems.
- The creation of a case base is usually a more rapid process than the creation of a knowledge base. With rule-based systems, the expert is questioned by the knowledge engineer to obtain and ascertain the rules behind the reasoning of the expert; quite a very labour-intensive process. With the CBR system, the task is to identify, store and index the key features of the previous problems so that these features can be recalled. The process of collecting cases for a CBR system may not take much time because several project-based and led organisations have already documented their previous cases, and a typical example is the use of the *lessons learnt* documentation in the PRINCE 2 (Projects In Controlled Environments) methodology, albeit a less robust retrieval system.
- In running a large rule-based system, invoking the applicable rules from the knowledge base could be a difficult. In the CBR system where there is no need to invoke rules, similar cases from the past are simply identified by their indices and with a high speed of running the CBR systems, information retrieval can be quite rapid.
- Finally, CBR can be used in problems with poorly understood domains, whereas a rule-based system is not that flexible and appropriate if contradicting rules apply in different situations [42].

CBR is an effective tool in areas where experience is rich but mathematical models are difficult to obtain. Despite the easy knowledge acquisition, learning and retrieval capabilities of CBR, current literature only describes how CBR can be utilised in machining process planning [81], and non-destructive testing (NDT) defect classification [82], with applications in virtual prototyping still quite novel.

In the area of construction planning and product development, the case base which is a part of the synthetic information bases, can be used to store information of previous projects with similar attributes and characteristics, while the case base management system performs the reasoning of management of case bases. The scheme case information will contain detailed description of specific construction planning attributes, with the system being implemented by combining Virtual Reality Modelling Language (VRML), Hypertext Markup Language (HML) and Java, with the VRML giving the system a sense of immersion, HTML supplying an economic and convenient way of inputting data and parameters, while Java is used to perform complex calculations [83].

An attempt to integrate CBR and VR was designed as an event-based link between the CBR tool and VR environment, where every action in the CBR with an influence in the VR case (and vice versa) would be communicated to either via Dynamic Data Exchange (DDE) links. At this stage, geometric objects are created in 3D CAD and imported into a VR tool, converting them into an object-oriented language, with the subsequent addition of worded attributes, emulating features of VR cases. In designing the VECTRA framework, [84] further attempted the integration using only the VR environment to support the application, with the downside being the inconveniencing processes of programming the data retrieval mechanism and inputting case descriptions, and the advantage of a straightforward case modelling in VR.

In acknowledgment to [22], [15] suggested that due to growing quantities of product models currently being created for use in the construction industry (as a pre-requisite for optimal project planning), there is also a growing need to create flexible retrieval methods for model reuse.

PROPOSED SYSTEM ARCHITECTURE OF VP AND CAD MODELING PACKAGE FOR INTEGRATED CONSTRUCTION PROJECT PLANNING (PR-VIRIS)

With the above review of global construction planning practices and the efficiency derived from integrating the virtual reality and prototyping technology, this section proposes and presents a theoretical framework and system architecture, for a system having the stand-alone capabilities of integrating product and information modelling technologies towards improved productivity of the construction planning process of the AEC sector.

Since the initiation of the 4D-CAD and the VR/VP technologies over a decade ago, researchers have proposed studies and applications based on an independent system for project planners and managers. There has been a consensus on the foundations of the severally proposed systems and this has been to link an inputted 3D model with an existing project schedule. This simply involves linking the Product-Based Structure (PBS) - an element of a 3D model, with the tasks of the schedule - the Work Breakdown Structure (WBS). A dynamic sequencing or simulation of the construction planning process can then be generated to support the planning process while another process of modelling, archiving and retrieving construction information is run alongside to support decision making on construction projects.

Previous models have proposed and defended the introduction of a third-party toolkit that manages the simulation and modelling operation, but the problem of a fragmented working process is obviously inconvenient and adds to the already-existing problems of the fragmentation of the construction industry. As a focus on the functional aspects of this study and with reference to the preceding sections, the authors introduce the basic requirements for an all-inclusive integrated PRototyping and VIRtual Information modelling System (PR-VIRIS). A description of the system is presented showing the basic components that make up the proposed system.

Requirements of Proposed System Architecture

Considering the breakthrough in previous studies, research recommendations for future studies and current requirements of the construction industry, an ideal system architecture to aid the planning and decision-making processes would be considered to be adaptive, integrative and as well as stochastic [36].

The need for an Adaptive Model

With the risk and error-prone nature of construction practices, there is a great need to apply adaptive and flexible models. Past researchers and industry professionals have stressed the need for a system that enables continuous feedback between planned schedules and actual schedules of a project [8], [66]. Another reason is because current planning tools and models do not function effectively in dynamic project environments [32].

Adaptive models can guarantee the consistency of data stored in case libraries even when a model is modified. Adaptive models can also aid the automatic propagation of change events, in order to save Users, the time that would have been used to manually adjust the model. This simply means that in designing an adaptive model, all independencies between model elements must be considered.

The need for an Integrative Model

Project data comes in different formats and models, e.g., requirements, plans, designs, risks, resources, etc., and is also stored in several sub-models. For building construction projects, research efforts are being made to enable and support the integration of different sub-models, like the integration of design and building codes (International Code Council, 2008), and the integration of design and life-cycle costs [44]. Considerable progress has also been recorded in the areas supporting the integration of design, estimating and scheduling information [24].

In the reality of construction practice, there is a huge possibility of a change in requirements in the course of a project [43], hence it is recommended that the simulation model should be such that CAD models are linked via activities to construction method models. A major function of these integrated models would be to generate and sequence the necessary activities and determine resource requirements.

The need for a Stochastic Model

A stochastic model incorporates uncertainty by allowing a certain range of possibilities for inputs, and the estimation of probability distributions of potential outcomes [36]. Thus, a stochastic model could aid in the estimation of the outcomes of actions and proposed changes to work-packages and project deliverables, before the functional relationships between the components of the project are redefined in the design and planning stage, and prior to the construction of these project components.

Description of Proposed system architecture

The proposed system, as illustrated in Figure III, will be described with simple and non-complex system components aimed at presenting an all-inclusive system with integrative, adaptive and stochastic properties.

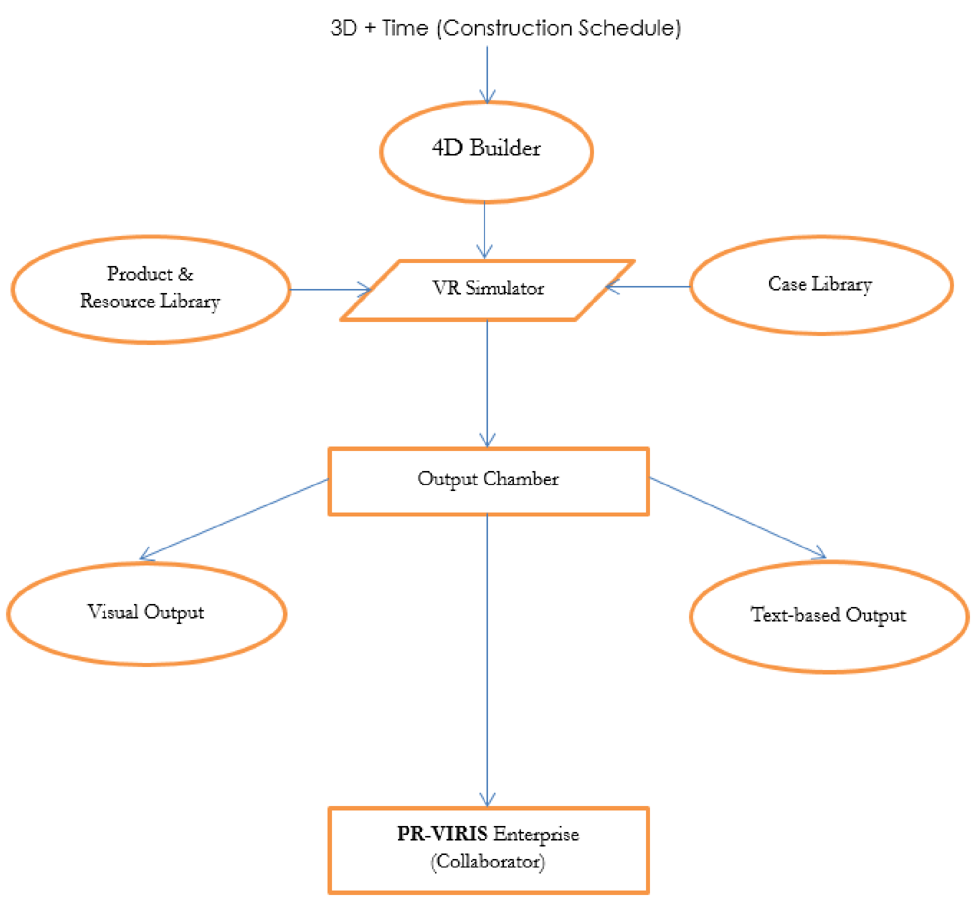

FIGURE III. PROPOSED SYSTEM COMPONENTS AND OPERATION OF THE PR-VIRIS

The 4D Builder - 3D + Time (Schedule)

The 4D builder component acts as a synthesis chamber to synthesise simulation items with associated 3D elements. It will contain text-based task items that will record work breakdown structure (WBS) items and their associated product – based structure (PBS) elements.

The 4D builder module will aim to support project managers and planners by relating building components from a 3D CAD system to construction activities from a project schedule or a construction project system, via a graphical interface. By executing the planning, this will lead to the simulation of the construction process via the VR Simulator, and finally output planning results visually and by text-based/information reporting.

The Product & Resource Library (Database 1)

Building a database is an efficient and important approach towards storing and capturing all types of information regarding construction elements and resources like construction plant and equipment sub-models and having access to their productivity data in the process [53].

The product and resource library will contain resources and productivity data from past and similar construction projects and this feeds into the VR Simulator which further simulates the operations of the resources (plant and equipment) and tests for resource allocations and possible resource conflicts/collisions.

The Case Library (Database 2)

The proposed model would have an information modelling component based on case-based reasoning (CBR) techniques. The basic approach to CBR has two phases; the construction of the case base (case database), and the resolution of new problems using the case base [42], [20].

The construction and use of the case library is beyond the scope of this work, but it is worthwhile to state that in the development of the case library, the following processes are adopted;

- The problem domain must be understood;
- The indexing mechanism of the case library must be operationalised; and
- Historic or past cases must be stored for further problem-solving retrievals.

The VR Simulator

The VR Simulator component would be based on the creation of realistic 3D images of the structures of construction projects and site conditions, and subsequent visual simulation of the construction process [62]. The component would be designed to use knowledge-based simulation of the construction work progress and to have integration and visualisation capabilities.

By using knowledge-based simulation of construction progress and visualisation capabilities, the PR-VIRIS system will aim at addressing the problems identified in current practices and also help planners to tackle the limitations of current computer-based systems.

The Output Chamber

2D visual tools and modules have in the past been effectively used to visually share and communicate modelled construction processes [35], [56]. Although effective in communicating the logic of past simulation models, 2D visualisation lacks the real-world capabilities of 3D required for accurate client-convincing visualisation or many complex construction operations [39].

The output chamber would be designed with visual-supporting requirements that aid the ability to see and output 3D, 4D and 5D (5th dimension) animations of processes that have been simulated by the VR simulator. This ability allows for proper verification and effective validation of planning and construction processes. [61] describes the 5D as the complex of three parts interconnected for the design and execution of construction projects; the first part is 3D and is described as the project data, the second part (which creates the 4D) is time-related data and mostly represented by a project schedule. The third and final part is cost-related data (the 5th dimension), which makes the proposed system a very important tool as regards cost simulation and output.

Visual Output Component

It is assumed that the visual output component will perform functions like;

- presenting visualisation of simulation results,
- visual display of work progress at any specified point of time,
- visual display of resource usage,
- visual display of site-space requirements and conflicts
- display accumulation of costs [74] by an extension to 5D, etc.,

When the proposed system reads a DXF (Drawing Exchange Format) file off construction data, coordinates are fetched for each part and constructed in mesh forms with the display model of the visual output system dependent on the display mechanism of the hardware. The visualised output shows the situation of work progress at every given time and can be saved to a memory and retrieved for further evaluation.

The Text-based Output Component

With the growing importance of text-based applications in the architecture-engineering-construction (AEC) industry, it is necessary to prepare domain-specific reference collections in support of these applications [52] but text extraction, conversion and output from simulation models is a relatively new area and requires high level mathematical simulations. Studies by [13] addressed the issue of segmentation and recognition of text embedded in video sequences by proposing a probabilistic algorithm based on Bayesian adaptive thresholding and Monte-Carlo sampling.

The above methods are beyond the scope of this work, and a limitation of this research is the lack of literature on the availability of models addressing the concerns of extracting, converting and presenting test-based information and reports from a VR simulator.

PR-VIRIS Enterprise (Collaborator)

The authors posit that this proposed system presents a state-of-the-art solution to the problems experienced by construction firms in the execution of project, programme and portfolio responsibilities. It is expected that with the successful implementation of this system, albeit with further development and improvements, an enterprise version, which would utilise internet and intranet facilities between several project-led and project-based organisations, or between the functional units of a construction project-based organisation, would be required to bridge the divide.

The PR-VIRIS Enterprise would represent Enterprise Project Management (EPM) for project-based organisations in the sense that it will support integral management and enable organisations adapt to the dynamics, changes and transformation of the built industry. It is expected that deliberately organised Communities-of-Practice (CoP) as analysed by [49] can be effectively developed through the effective deployment of the PR-VIRIS Enterprise capabilities.

Justification of the Proposed System

Considering the great need for implementing computer-aided systems in the planning of construction projects, this study briefly stated the impact of CAD on areas of construction like construction process visualisation, resource analysis and allocation, site-space layout and information modelling, all of whose capabilities have been built into the proposed system.

The proposed system has been analysed and presented, with room for constructive critique of its structure and/or components, leading to further improvements. However, the components of the system have been carefully proposed with the assumptions that the areas presented by the authors above would be effectively and positively impacted to enable construction project managers and planners tackle the problems of increasing costs, low quality of delivery and unplanned elongation of project durations.

It is expected that this proposed system will require future improvements particularly by experienced computer and software designers, working together with experienced project managers/planners, and this is an area for further research.

FINDINGS FROM EXPERT VALIDATION WORKSHOPS AND POSSIBLE IMPLICATIONS FOR CONSTRUCTION PLANNING THEORY AND PRACTICE

To validate the findings and apply the proposed system architecture to current and future construction planning and management systems, two (2) workshop sessions brought together Nine (9) experienced construction management practitioners, academics and experts to appraise and critique the proposal.

Workshop findings: Components of system architecture

While the participants found the system reflective of their construction planning practices, they agreed that the capabilities required to design such a model system is currently lacking, and where available, was expensive to put together, as this would require massive improvements in both software and hardware capabilities of existing project management programs and computer-based systems.

The reactions by workshop participants to the Eight (8) system components were very positive. They agreed that while current computer-aided systems such as Revit © and Navisworks ©, had the capability to model or simulate aspects of the construction process after being fed information and data from a case library as well as a product/ resource library, the capability of delivering quality output reports in the form of real-time visual displays as well as formatted text-based reports was still either lacking or limited, and where available, might require a third party system add-on. Workshop participants pointed to the collaborator being of massive importance in the era of collaboration between construction projects across an organisation or even across countries.

Workshop participants unanimously agreed that a stand-alone system with the capabilities of PR-VIRIS was timely for the construction industry to boost efficiency and productivity, giving the global construction industry the ability to try-before-build.

Implications for theory and future research

Considering the limitations of the study, the authors only reviewed and presented the application and impact of the proposed system in the areas of construction process visualisation, resource analysis and allocation, site-space layout modelling and information modelling. Regardless of this limited focus, the study has shown that the construction planning process can be automated by the use of simulation models, hence it is recommended that other areas across the construction project life-cycle should be analysed for logical and systematic sequencing which can aid future development of models and systems to tackle the problems associated with all stages of the project life-cycle.

A final recommendation would be for researchers to seek more collaboration with computer hardware and software designers towards developing stand-alone packages that will lead to the development of more adaptive and creative simulation models for use in construction project planning and management.

SUMMARY AND CONCLUSION

This paper reviewed the application and impact of virtual reality/prototyping and computer-aided design (CAD) technologies on the current construction planning practices of the architecture-engineering-construction industry. The review shows that developing the plans for a construction project involves processes such as the gathering of project information, the definition of the activities for construction, the selection of suitable construction methods which leads to the methods of sequencing and allocating resources to the activities. The last stage of the planning process involves the optimisation of the plans. The findings from this study have revealed that the whole construction planning process can be automated by the use of simulation models which enable construction managers and planners to visualise chosen construction methods and watch how the construction process proceeds via computer screens, revealing conflicts and areas needing proper management and control.

Findings from this study have also revealed that computer simulation models can be effectively utilised in the areas of resource analysis and allocation, by the use of genetic algorithms and in combination with flowchart-based simulation tools, towards tackling time-cost optimisation problems. Studies show that resources such as plant, equipment, space and human resources can be analysed in the visualisation process. In the reviewed literature, construction planners realised errors such as the limited storage areas for storing façade elements, steel formworks, reinforcements and temporary supports. Also revealing from the literature was the limited working area for workers and access road for material transportation. The literature further showed that through equipment-based and activity-based resource modelling, issues regarding resource allocation can be tackled and simulation models can enable project managers and planners improve space management aspects of construction projects.

A further insight into the findings of this review reveals that simulation models can help tackle the problem of information modelling and management. Several models proposed by previous researchers have shown significant limitations in this area but this paper proposes that current models should be designed to apply the case-based reasoning (CBR) technique as an effective way to dealing with project information archived and retrieved when in demand.

Having critically expressed the concerns of practitioners and researchers, the authors proposed an all-inclusive PRototyping and VIRtual Information modeling System (PR-VIRIS). It is expected that the PR-VIRIS system would 'smoothen' the way construction project planning practices are carried out. The study reveals that the efficiency of the proposed system would depend on its adaptive, integrative and stochastic capabilities, as these features aid and reveal the simplicity and ease of simulating the construction planning process, which has been a major problem in past and recent times.

With the system's proposed ability to simulate and output visual and text-based construction project information, the decision-making process would be greatly optimised and in its enterprise form, the collaboration between project participants, virtual teams, corporate functional units, and the AEC industry at large, would be highly efficient, leading to massive improvements in the planning processes of construction projects, which is the core aim of this study.

Conflict of Interest

The authors are not aware of any conflict of interest regarding our submission for publication.

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