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4D BIM for Environmental Planning and Management

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Abstract

For more than a decade research has shown that 4D Building Information Modelling (BIM) can improve construction planning, scheduling and production control as well as the onsite management of safety, workspaces and waste. The increasing use of 4D BIM in construction highlights opportunities for utilising these capabilities in new digital management systems replete with role reorganization, new practices and workflows, and not solely as a tool for constructability analysis and onsite monitoring of construction progress. Continued focus on construction-based environmental impacts provides an impetus to leverage 4D BIM to improve communication and information flow throughout environmental planning and management tasks. This paper explores how environmental planning and management can be supported by 4D capabilities. 4D modelling and analysis technologies combined with structured workflows are presented as the basis for developing a tailored framework for environmental planning and management. Five functional prerequisites necessary to the collaborative development and onsite monitoring of environmental management systems are identified before laying out the directions for future research.

Keywords: 4D Modelling; Virtual Models; Construction Environment Management Plans

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1. Introduction

With the increasing application of asset and performance based rating schemes in Australia, including Green Star and Nabers, a concomitant rise in low-energy and net-zero energy buildings is being reported [1]. In realizing higher levels of environmental performance in building design during operations, the building’s ongoing impact is decreased and the importance of reducing the impacts of construction is brought into focus [2]. Onsite construction activities are a major source of environmental degradation. When considered at the national scale, the aggregation of new construction projects and their collective environmental impacts are significant [3]. In Australia, ‘construction environment management plans’, are used to coordinate and document the numerous and sometimes interdependent environmental management controls, mitigation measures and monitoring systems specified for any given project.

Construction environment management plans typically refer to the AS/NZS ISO 14001:2004 standard [4], which provides structure and guidance to environmental planning and management processes. Throughout project delivery phases, a range of environmental plans and management activities are developed, which are aimed at avoiding or reducing the impacts of construction. These activities typically commence during the early briefing phase and continue as a collaborative endeavor between project team members until handover. Sound economic objectives underpin these environmental processes; for example, loss of topsoil means importation of replacement topsoil at substantial cost; excessive sedimentation of onsite or nearby waterways can require expensive dredging, result in flooding, or destroy valuable wetlands; and costs to the community through loss of amenity can also be a potential side effect of construction activities that have negatively impacted on the environment. Therefore, effective planning and management is not only aimed at improving a project's environmental performance but also at reducing risk and paying returns on an economic level [5].

Effective environmental planning and management presents a range of process and informational challenges to project participants. These challenges surround gaps in communication and information flows, difficulties in identifying and monitoring interdependencies between environmental management plans, reliance on 2D paper based representations of environmental management systems, and inconsistencies in assessments of the significance of impacts. Process and informational difficulties are compounded by a lack of research on the effectiveness of construction environment management plans during the construction phase and the extent of onsite monitoring of environmental impacts is limited. As a result, a dearth of environmental data on construction activities and their impacts relative to project type and environmental context means that it is difficult to benchmark improvements in the environmental performance of the construction phase. Further, in the absence of reliable environmental models, it is difficult to track the accrual of environmental impacts over the construction phase [6].

In the past decade, the use of 4D modelling for conducting constructability analysis during the pre-construction phase and for monitoring onsite activities during construction has increased. The use of 4D modelling in conjunction with onsite production control methods to track actual progress and analyse the effects of delays on the overall project schedule has led to higher levels of onsite construction performance. Using 4D BIM for construction planning, scheduling and production control, research has shown that 4D modelling can improve the management of construction safety, workspaces and waste. The increasing use of 4D BIM in construction highlights opportunities for utilising these capabilities in new digital management systems replete with role reorganization, new practices and workflows, and not solely as a tool for constructability analysis and onsite monitoring. By leveraging 4D tools, methods and visual simulations, improvements to the communication, information flows and outcomes of environmental planning and management activities can be made possible. This paper explores how a new digital management system for environmental planning and management can be supported via 4D BIM technologies and workflows. It is proposed that 4D scheduling, simulation and visualization can improve the collaborative development of construction environment management plans and their onsite monitoring. A project's environmental performance can be improved by linking construction schedules with building information models so as to dynamically describe the: (1) virtual building model (including environmental data about supplier products), (2) site, logistics and materials handling, (3) temporary and site production structures, and (4) environmental management controls and associated equipment. In a BIM-enabled project environment, a model-driven approach to developing and implementing environmental management plans would provide additional impetus in 4D modelling processes, while not adding significantly to the data collection overhead. The article explores the concepts of 4D modelling in light of current applications and identifies the challenges to existing approaches to environmental planning and management. A structured workflow is identified as the basis for developing a tailored 4D framework for environmental planning and management and five functional prerequisites that would enable the collaborative development and onsite monitoring of environmental management systems are identified. The paper closes with a discussion of the potential benefits for collaborative planning and management supported by dynamic 4D modeling.

2. Background

Construction-based environmental planning and management processes rely on the collaborative efforts of a range of professional AEC (architecture, engineering and construction) disciplines. An underlying challenge to these processes relates to the quality of information flows, reflecting a common problem in the construction sector. The use of 4D BIM has been shown to be key to improve integration and continuity in information flow [7]. Developments in the application of 4D scheduling and simulation for managing construction safety, work space planning, and waste has shown that it can improve communications in the pre-construction phase, support shared understandings of the construction process, and enable more accurate, on-time and appropriate exchange of information to onsite construction workers. These capabilities reflect many of those that are lacking in environmental planning and management processes.

2.1. 4D BIM for Construction and Site Planning: Capabilities and Applications

4D BIM has become an accepted acronym to convey a variety of terms that have come before, including 4D CAD [8], 4D Modelling [9], 4D Planning and Scheduling [10] and 4D Simulation [11]. Common to all terms, is the definition of the 4D concept which is defined as the "linking a schedule to a 3D-model to improve construction planning techniques" [12]. To generate a 4D model, Koo & Fischer [8] specify three requirements, including the: (i) 3D geometric model with building components; (ii) construction programme (with activity data, durations, logical relationships); and (iii) 4D simulation tool that allows linking of 3D model elements with those of the programme. Thus, 4D BIM can only be achieved via the integration of three core capabilities, namely the: (i) visualization of the time and space relationships of construction activities [9, 11], (ii) analysis of the construction schedule to assess implementation [8], and (iii) reduction of errors through construction plan interrogation/validation, and improving communication between the project team [13]. Since the earliest proposals of the 4D concept, dedicated 4D tools now enable the integration of multiple discipline-specific models and schedule data to link intelligent objects to individual resource-loaded and logic-linked activities [12]. 4D BIM capabilities can now be divided into two categories: (i) construction planning, and (ii) site planning. Applications and benefits within these two categories are many and varied. For example applications of 4D BIM for construction planning include: winning work at tender stage, construction method planning, timescale communication, design interrogation, resource management, workspace planning, ID hazards and safety planning. For site planning, 4D applications include its use for the management of: site logistics, pedestrian and traffic flows, material delivery and storage, major plant activities, temporary works, welfare facilities, and site security. The implementation of range of 4D model functions have therefore evolved, extending 4D construction planning and site planning capabilities to include a number of management activities; thereby adding value to core 4D modelling processes. Four applications of 4D BIM have received increasing attention in research and industry include 4D for: work-space planning [14-21], safety planning [7, 22-28], waste management [29-31], and most recently life cycle assessment [32].

The development of 4D BIM for work-space planning is a well-established research domain, with early work pioneered over a decade ago at Stanford's Centre for Integrated Facilities Engineering (CIFE) by Akinci *et al.*, [14-16]. 4D BIM for work-space planning methods aim to address ineffective traditional work-space planning practices, which fail to account for the spatial features of each construction activity [20]. Recent work by Choi *et al.*, [21] has formalized a work-space planning process based on a categorization of characteristics describing function and movability. The work-space planning process defines five phases, including the generation of the 4D BIM model, work-space requirement identification, work-space occupation representation, work-space problem identification, and work-space problem resolution. It is claimed that the framework improves the accuracy of work-space status representation and work-space problem identification by considering activities, work-spaces, and construction plan. The process is demonstrated using a case study, showing its ability to improve the work-space planning process.

Another area that has attracted much researched attention is 4D BIM for safety planning. Whilst much of this research remains at the conceptual level a few recent implementations have demonstrated its value in practice. Benjaoran & Bhokha [23] propose an integrated system for safety and construction management using a 4D model and a rule-based system capable of detecting work-at-height related hazards. Kiviniemi *et al.*, [24] and researchers at the VTT Technical Research Center of Finland developed and implemented a framework for fall protection modelling that utilizes 4D visualization and the modelling of temporary safety structures and equipment required to carry out safe construction work. The approach also models the permanent installation of safety equipment used in construction, operation, and maintenance phases. Guo *et al.*, [25] developed a conceptual framework, adopting virtual prototyping technology to aid in construction safety management. In an applied example, Zhou *et al.*, [26] have explored the implementation of 4D visualization technology for safety management and risk assessment in metro construction. Collins *et al.,* [27] present a study of the level of safety risk at each phase of a scaffolding's project lifecycle for the construction of masonry walls. The research examines how risks and related mitigation measures can be supported by 4D BIM. Safety is integrated with the 4D model by linking the scaffoldings safety risks and mitigations with the project schedule. The 4D BIM is then used as a tool for the safety management and monitoring, thereby diminishing associated safety hazards. In addressing the limited level of automation in 4D modelling and planning safety processes, Zhang *et al.,* [7] investigate how potential fall hazards that are unknowingly built into the construction schedule can be identified and eliminated early in the planning phase. The proposed method automates the safety checking process. The method's implementation demonstrates its effectiveness and efficiency in detecting and preventing fall-related hazards.

4D BIM for construction and demolition waste management [28-30] is a growing field of research. Whilst only focused on one aspect of the environment, 4D waste management shares similar objectives with the topic of this paper – environmental planning and management. The work of Cheng *et al.,* [35] exemplifies some of the common end points in leveraging 4D capabilities to improve the planning, management and monitoring of waste. The approach explores a variety of BIM technologies currently available and how they can support construction and demolition waste management. These technologies include 3D functionalities (design validation, quantity take-off, and digital prefabrication) as well as 4D capabilities (phase planning and site utilization planning). Cheng *et al.,* [35] proposes the integration of these digital design and construction approaches as part of a waste management work flow which seeks to support collaborative approach to construction and demolition waste management.

A related and emerging research area looks to a model-driven approach to manage the carbon footprint of a construction project. Chhatwani & Golparvar-Fard [31] examine existing inefficiencies in life cycle assessment (LCA) methods and leverage 4D models by coupling them with LCA tools to benchmark the project's carbon footprint during pre-construction phases and monitor the carbon footprint during the construction phase. The research focuses on a management framework that focuses on 4D simulations as visualization tools to communicate the results of LCA. The method is based on earned value management concepts and metrics to assess deviations between benchmarked and actual carbon footprint.

2.2. Environmental Planning and Management in Construction

Managing the environmental performance of construction relies on the documentation of numerous aspects of the environment so as to plan and specify management controls. There are different ways to conceptualize the different aspects of the environment relative to impact. The literature does not reflect a clear consensus regarding a classification schema. However, a widely recognized classification is the 'Eco-management and audit scheme' (EMAS) [32], which identifies nine environmental aspects, including: (1) emissions to air; (2) releases to water; (3) avoidance, recycling, reuse, transportation and disposal of solid and other wastes; (4) use and contamination of land; (5) use of natural resources and raw materials; (6) local issues including noise, vibration, odour, dust visual appearance; (7) transport issues; (8) risk of environmental accidents and impact arising as a consequence of incidents, accidents and potential emergency situations; and (9) effects on biodiversity. The Australian and New Zealand Standard for Environmental Management Systems, AS/NZS ISO 14001:2004 [4], provides structure and guidance to construction-based environmental planning and management processes across these nine areas of the environment. The standard is generally referred to in construction environment management plan documentation and the individual management controls that address each aspect of the environment.

As a process, environmental planning and management starts during the early briefing phase and continues as a collaborative endeavour until the end of construction. The process therefore depends on the input of a range of AEC disciplines across all project phases. Environmental planning and management tasks are heterogeneous in nature and link the disciplines of the basic sciences (biology, chemistry, earth sciences) with those from applied sciences (engineering and management) [33]. 12 broad categories of environmental planning and management tasks are identified by Tam *et al.,* [33] in Table 1, which relate to research, analysis, documentation, specification of mitigate measures, and on-site risk management methods.

Table 1. Tasks underpinning Construction Environmental Planning & Management, adapted from Tam *et al.,* [33]

#	Task Type	Description
1)	Environmental Mgmt. Plan Orientation	Identification of aims, objectives, resources and pattern of management
2)	Environmental Impact Assessment (EIA)	Conduct EIA across all relevant areas of management planning, including assessment of risk relative to significance and probability
3)	Environmental Planning & Mgmt. Consultation	Mapping of procurement route and environmental orientation issues
4)	Budgeting	Arranging budget for environmental management within outlined cost target
5)	Coordinate Environmental Information for Design Process	Integrate all environmental information for inclusion with design processes and other detailing aspects of the project
6)	Review Legislative Requirements	Review of requirements to confirm all legislations are met
7)	Specify Environmental Mitigation Measures	Identify environmental impact and risk mitigation measures to be incorporated into EIA requirements
8)	Documentation	Translation of EIA requirements into technical specifications & contract docs.
9)	Environmental Permits	Obtain required environmental permits (EP)
10)	Specify On-site Environmental Management Systems (EMS)	Specification of all aspects of environmental management related to site processes in pre-contract meetings
11)	Environmental Monitoring and Audit (EM&A)	Implementation of EM&A programs
12)	Monitor EMS On-site	Implementation of plans and associated EMS/ risk mitigation strategies onsite

Tam *et al.,* [33] classify environmental planning and management activities according to project phases and participant involvement, see Table 2. Whilst some activities are independent, others are linked across project phases, relying on the consistent involvement of project participants. Understanding each environmental aspect, its potential impact and significance relative to construction activities is a complex process, which presents numerous challenges.

Table 2. Principal environmental management tasks in project process, Source: Tam *et al.,* [33].

Phase	Activity	Environmental planning and management tasks	Participants
Briefing	1. Project Inception 2. Feasibility study 3. Outline proposals	• Identify environmental orientation of project relative to aims, objectives, resources and management patterns • Conduct EIA • Mapping of procurement route and environmental orientation objectives • Budget for environmental management • Information integration for inclusion in design process	1. Clients 2. Lead consultants 3. Environmental consultants 4. Quantity surveyors 5. EPD officers
Design	4. Schematic design 5. Detail design 6. Production info. 7. Bill of quantities 8. Tender action	• Review legislation needs and expectations are met while satisfying overall project requirements • Incorporate mitigation measures in accordance with EIA • Translate brief of environmental requirements into technical specification and contract documents	1. Clients 2. Lead consultants 3. Environmental consultants 4. Quantity surveyors
Construction	9. Project planning 10. Construction	• Obtain environmental permit • Attend pre-contract meetings and address all aspects of environmental management relating to site processes • Implement environmental monitoring and audit programmes • Implement waste management plans	1. Clients 2. Lead consultants 3. Consultant reps. 4. Environmental consultants 5. Independent checkers 6. Main contractors 7. Sub-contractors & suppliers
Hand over	11. Feedback 12. Completion	• Undertake environmental testing	

3. Challenges to Environmental Planning and Management in Construction

In Australia, investigations of the challenges or effectiveness of environmental planning and management related to construction has received limited attention. The survey of the literature has therefore included studies that are not specific to the Australian construction industry or environmental context. Broadly, the challenges relate to six areas, including: (1) Gaps in communication and poor information flow, (2) Traditional approaches to project delivery and responsibilities, (3) Scope of environmental management tasks, (4) Reliance on traditional 2D paper-based approach, (5) Interdependencies between environmental management controls, and (6) Methods for assessing the significance of environmental impacts.

3.1. Gaps in communication and poor quality information flow

Gaps in communication and poor information flow between project participants is cited by Tam *et al.,* [33] as two of the main challenges to construction-based environmental planning and management. The identification of environmental impacts, assessment of significance, and the specification of mitigation controls all depend on a range of expertise across multiple disciplines. Interdisciplinary collaboration is therefore essential and environmental performance depends on robust communication and consistent information flow. Gaps in communication have been shown to exist at both the upper and lower levels of the project management hierarchy [33], and a lack of information flowing to on-site construction workers is also highlighted by Tam *et al.,* [33] as a significant challenge. Environmental planning and management activities are typically a difficult management priority for project participants to appreciate [34], and poor information flows may therefore result in the failure of ongoing monitoring activities. Inappropriate work planning and supervision, insufficient communication between different partners as well as a lack of environmental data surrounding on-site practices are also identified as significant factors to successful development and implementation of environmental management systems [34]. Communication at the level of individual construction workers is therefore challenging given the dynamic nature of on-site construction. It is well-established that more effective design and construction processes can be achieved via the improvement of information flows between project participants [35]. Poor information flows stem from fragmentation between project participants and inconsistencies in information transfer, storage, accessibility, and redundancy.

3.2. Traditional approaches to project delivery and responsibilities

In traditional approaches to project delivery there are often clear disconnects between participant involvement across project stages. Relative to environmental planning and management activities this can mean that lead consultants and contractors are only responsible for particular project phases and outside of these there exists a lack of connections and communications between them. Responsibilities for the coordination of environmental planning and management activities largely fall to the client, lead design consultant and environmental consultants, whereas the responsibilities of the contractor and subcontractor are limited to the implementation of mitigation measures. Compounding these issues is a lack of ways to enforce quality controls around proper implementation of environmental management systems.

3.3. Scope of environmental management tasks

Construction-based environmental impacts occur over a relatively small period of time, resulting in a high density of potential impacts across numerous aspects of the environment. There is therefore a large scope surrounding the monitoring construction practices and improving them to reduce their impact [34]. Construction sites are constantly changing, and management systems need to be in place to modify control measures and maintain their effectiveness. Frequent inspection and monitoring is required to continually check the effectiveness of measures across each aspect of the environment under management. This is compounded by the complex nature of the supply chain and coordination of onsite labor [6].

3.4. Reliance on traditional 2D paper-based approach

Another obstacle to improving the environmental performance of construction activities surrounds 2D paper-based representations of environmental management plans and controls. 2D representations are inadequate when identifying environmental issues relative to the construction activities, including understanding nature of the building, construction activities, associated work-spaces, and the site. All these aspects of construction delivery processes can affect the environment. Further, the representation of mitigation measures and controls using 2D drawings can overlook and fail to reduce the risk or minimize the impact of environmental hazards. Fig. 1 presents an example of a 2D erosion and sediment control management plan. The plan shows mitigation strategies drawn on the construction plan using different colours. However there is no relation to the other environmental management controls, such as the soil and water management plan nor is there any connection with the construction schedule.

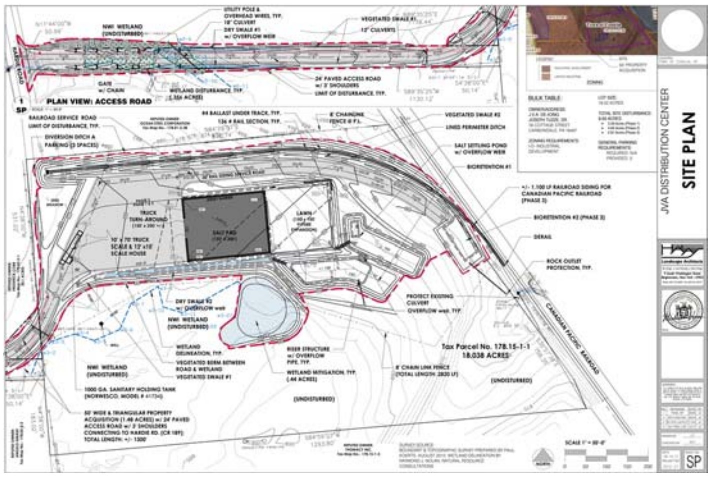

Fig. 1. 2D Paper-based storm water pollution and sediment control plan

3.5. Interdependencies between environmental management plans and controls

Each environmental aspect is addressed according to the unique environmental control plan, (e.g., Water Management Control Plan). The integration of different aspects of the environmental into coordinated control plans represents a significant coordination challenge. A number of issues underlying this issue, including: (1) reliance on prior experience and expertise of project participants; (2) environmental impacts may be implicit, being the result of partially complete construction conditions not shown on 2D plans; (3) construction schedules are subject to change due to various conditions such as weather and material delivery, which can lead to changes across environmental control plans and the significance of impacts identified; (4) dynamic nature of construction projects can result in changes in mitigation strategies, making it difficult to identify the knock-on effects of environmental impacts prior to construction; (5) it is time-consuming and labor-intensive to identify and update control plans and their interdependencies, and so it rarely occurs resulting in outdated information; (6) dependencies between some environmental impacts (e.g., those caused from land disturbance) may be easier to recognize than others (e.g., those caused from contaminated construction waste); and (7) dependencies between environmental impacts may be difficult to communicate onsite using paper-based plans and may not therefore be managed appropriately.

3.6. Methods for assessing significance of environmental impacts

In specifying environmental impact assessment methods for construction projects, criteria (e.g., scale, severity, duration of impact, type, size and frequency) must be considered together with the applicable legal requirements (e.g., emissions and discharge limits in regulations) and the concerns of internal and external interested parties (e.g., public/organizational values, image, etc.) [4]. However methods are often based on qualitative and subjective scoring, making it difficult to provide in-depth and comparable results [34]. Methods may also be used inappropriately. Lui *et al.*, [39] highlight that some impact assessment methods are designed to serve as a post-construction evaluation tool for determining acceptance of completed work, rather than as a pre-construction evaluation tool to support decision-making. Only a few quantitative methods assessment methods were therefore identified in the literature [34, 36-40]. Of these, only two do not rely on subjective judgments. Gangolells *et al.*, [34] resolve this problem by comparing the overall environmental impact associated with the erection of various projects and ranking the significance of the environmental impact; comparing the absolute importance of a particular environmental aspects. Similarly, Fuertes *et al.*, [40] propose a model based on a process-oriented causal network, which considers construction processes, environmental impacts, causal factors and their causal relationships. The model was developed to assist those responsible for investigating where and how impacts will arise onsite before then assessing their significance.

4. Towards 4D BIM-enabled Environmental Planning and Management

The literature surveyed identifies a number of areas for improvement in environmental planning and management activities as well as opportunities to support the development and implementation of environmental management systems and control plans using 4D BIM. To ensure robust and efficient approach to environmental planning and management activities, it is suggested to develop a model-based approach that utilizes 4D technologies and workflows. Two overarching processes that a 4D platform must be able to address relative to supporting and improving environmental planning and management activities are identified as:

a) *Need to support collaboration across all activities of environmental planning and management*. In order to support these interdisciplinary activities, greater levels of collaboration are required such that all environmental aspects (including their interdependencies and the significance of impacts) can be proactively identified and assessed. By utilizing the 4D model, construction and site conditions relating directly to each environmental aspect can be modeled, visualized together with the construction schedule and collectively studied by the project participants identified in Table 2.

b) *Need to support onsite monitoring of environmental impacts*. This refers to continuous review of environmental conditions and the potential for environmental impacts to arise during on-site construction despite mitigation measures that have been put in place. Currently site foremen and project managers carry out these activities intuitively. A 4D BIM-enabled method can support onsite communication and monitoring using the visualization of the construction schedule. Identification of deviations from the 4D model can increase the effectiveness of onsite environmental impact monitoring.

To meet these needs, five functional prerequisites of a 4D platform are identified as follows.

1. Scheduling and simulation: The complex and dynamic nature of construction and its on-site work patterns are widely recognized. To detect and prevent environmental impacts during the construction process, project schedules not only need to be linked to the 3D model but it is also critical to be able to track and visualize construction progress according to updates in the schedule to identify and/or communicate a potential environmental impact and update mitigation strategies relative to construction work packages.

2. Environmental equipment modelling: Environmental planning and management not only relates to the control of construction activities relative to building and site conditions; it also involves the design, installation, and removal of temporary equipment that supports a mitigation measure or control plan and eliminates/reduces impacts to the environment, e.g., temporary fencing, trench breaks, water run-off prevention systems, etc. It is essential to model these temporary objects for visualization, quantification and communication purposes.

3. Construction site layout modelling: In highlighting the importance of construction logistics and the dynamic nature of the construction site, it is important to consider site layout relative to environmental planning and management. Modeling site layout can support the detailed and accurate analysis of site logistics and materials handling in connection with the environmental mitigation measures including the placement of related equipment and visualization of ‘impact significance beacons’ (see below), increasing the effectiveness of on-site monitoring.

4. Environmental impact significance modelling and visualization: The assessment and visualization of the impact severity should be supported consistently according to project type and environmental context. As an example, a quantitative method could utilize current approaches such as the matrix model that defines assessment criteria for all environmental aspects and determines their significance based on numerical interval scales. Numerical limits for each interval scale are typically based on existing regulatory frameworks. It is crucial to be able to model and visualize the significance of environmental impacts and therefore an object such as a ‘beacon’ or ‘cone’ should be used as a marker of the location that the environmental impact relates to and a colour mapping that corresponds to the level of significance of the impact, e.g., non-existent impacts = green beacon, non-significant impacts = yellow beacon, significant impacts = amber beacon, and extremely significant impacts = red beacon.

5. Rule-checking capability: A 4D BIM platform with a rule engine provides the capability to define and configure environmental impact rules to support a rule-checking process. For example, a time-space clash detection between construction activities, temporary structures and environmental control equipment together with impact significance beacons would automatically identify environmental ‘hot-spots’ and increase monitoring efficiencies.

In addition to enabling these functional prerequisites, a method that can deal with the dynamic aspects of both construction activities and environmental impacts relies on a series of eight stages in a defined workflow. Fig. 2 presents a schematic diagram of an overall 4D environmental planning and management process. The workflow relies on the detailed specification of the following stages with defined project roles: (1) development of discipline-specific 3D models with progressive levels of development (LOD100-LOD 300) together with the identification of environmental orientation and EIA; (2) development of federated 3D construction model (LOD 400) together with budget specifications and coordination of environmental information; (3) generation of baseline 4D model, which is able to simulate changes in construction activities using linkages between objects in 3D model and corresponding activities in the project schedule plan, together with the review of EIA and environmental legislative requirements; (4) detailed 4D simulation and development of environmental planning, management and control plans in response to detailed construction methods, site logistics and materials for activity execution; (5) utilisation of automated clash detection tools and rule checking methods for path analysis so as to identify unforeseen environmental impacts and explore appropriate solutions; and onsite monitoring based on 4D visualization and dynamic feedback; (6) representation of EMS and visualisation of the status of and potential for environmental impacts (beacon system), and updates based on feedback from previous step, with outcomes to be reflected in the construction plan, (e.g., activity execution plan or material management plan); (7) development of EM&A methods together with the communication of environmental management controls across subcontractors so as to identify unforeseen impacts of construction on monitoring methods.; and (8) monitoring EMS onsite using 4D model with continual process of updates informed from schedule adjustments and actual activity progress.

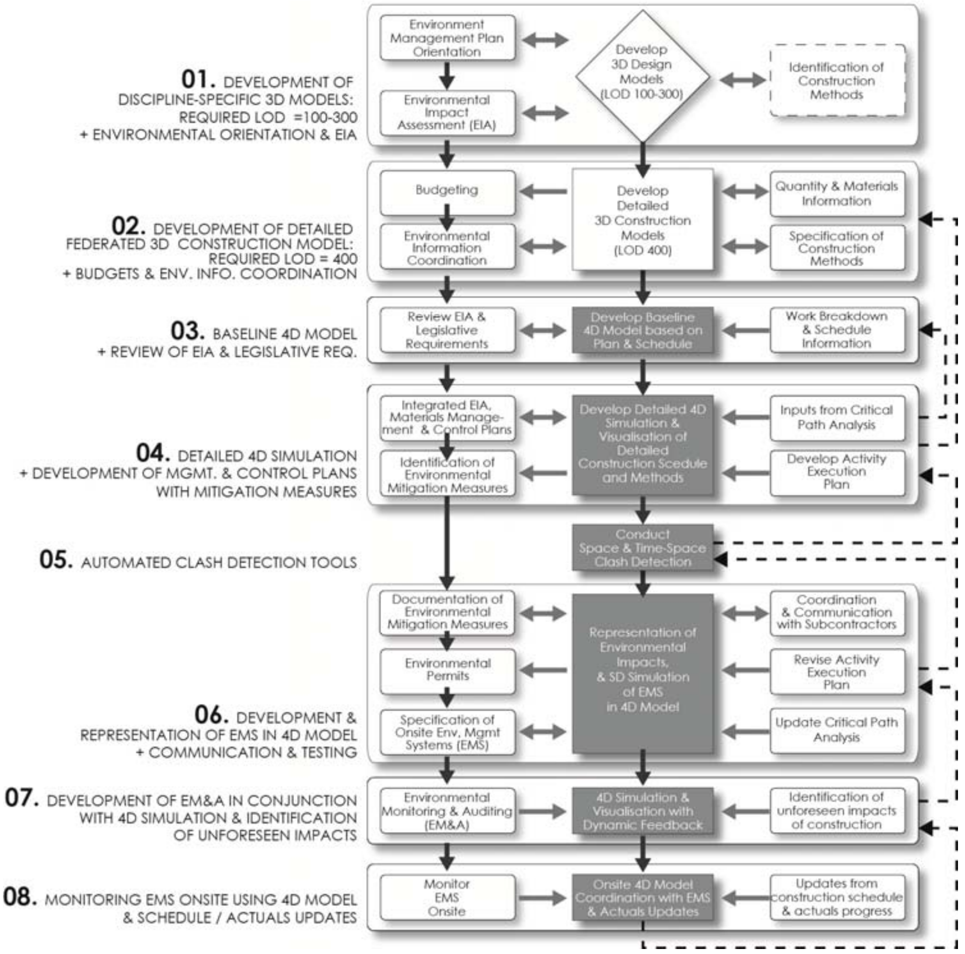

Fig. 2. 4D BIM workflow to support environmental planning and management

5. Conclusion and Future Work

Increasing sophistication in the use 4D BIM sees new opportunities for developing digital management systems that address construction-related events. This paper explored the feasibility of 4D for environmental planning and management, focusing on a literature study of 4D construction scheduling and simulation methods and an analysis of environmental planning activities. The challenges faced by participants in environmental planning and management activities throughout the design and construction phases were identified. Recent advances in the application of 4D technologies were discussed as a foundation for a digital management system to support pro-active environmental planning and management. Several related works have developed frameworks to support construction safety, work-space, waste and LCA management. These frameworks are dependent on best practices and detailed information requirements specification to ensure data quality and integrity during 3D and 4D modelling. If these works are interesting milestones, it is possible to make correspondences between their requirements and those that can support environmental planning and management activities. The definition of role reorganization and new processes and workflows are therefore also required. Essential to a digital management system for 4D environmental planning and management are early simulation and visualization capabilities, which link collaborative environmental planning deliverables to early stage virtual construction models, supporting the assessment of the significance of each environmental impact identified. By using 4D tools and methods to support communication and information flows between environmental consultants and the project team, the performance of environmental plans, controls and monitoring devices onsite can be advanced. Such a model-based approach would thus be capable of providing pro-active environmental planning and management via new capabilities to explore alternative scenarios prior to construction, provide accurate updated information to environmental plans with actuals, make alternative plans relative to the dynamics of construction work-packages (and potential onsite changes), and thereby inform and improve environment controls.

The paper identified five functional prerequisites of environmentally responsive construction process planning. Both existing and new functionalities for modelling, scheduling and visualization of various temporary environmental management systems and related equipment are required together with the development of ways to visualize the significance of environmental impacts and implement rule checking capabilities that can automate impact checking processes. Future research work is required to deliver a workable platform and workflow that can fully capitalize on 4D technologies and improve the environmental performance of construction processes.

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