Article

Digitisation of Existing Water Facilities: A Framework for Realising the Value of Scan-to-BIM

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Abstract: Building information modelling (BIM) has been implemented in many utility-based organisations worldwide, and it has proved to provide substantial cost- and time-saving benefits and improved performance and asset management especially during the operations and maintenance (O&M) phase. BIM adoption and implementation success rely on the accurate asset information stored in BIM models, mainly for existing assets. However, the asset information stored in asset management systems is often inaccurate, incomplete, out of date, duplicated or missing. Capturing the accurate as-is conditions of existing buildings has become feasible with the recent advancement of point cloud from 3D laser-scanning, resulting in a shift from ‘as-designed’ BIM to ‘as-constructed’ BIM. The potential benefits of using as-constructed BIM models for facility operations are compelling. This paper identifies the cost and benefit elements of the scan-to-BIM process as part of a case study research project at a water treatment plant (WTP) in South East Queensland, Australia. The paper develops association mapping between the cost and benefit elements for relevant stakeholders and identifies the critical asset information for effectively managing the WTP case selected. Furthermore, the paper investigates the impact of various levels of detail (LOD) and levels of information (LOI) on BIM applications depending on the project and asset requirements. Finally, this paper presents a framework that water asset owners and stakeholders can utilise to obtain value from investing in scan-to-BIM for existing facilities.

Keywords: building information modelling (BIM); 3D laser scanning; scan-to-BIM; as-constructed assets; BIM adoption in the water sector

1. Introduction

The level of building information modelling (BIM) adoption has been increasing within the architecture, engineering and construction (AEC) industry over the past decade [1–3]. BIM encourages the efficient management of assets by changing the traditional way in which they are designed, constructed and then managed post-construction [4]. BIM itself is not a technology but a data-rich, model-centric business process with the power to transform project delivery. Within the digital world, BIM can be defined as ‘a digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition’ [5]. In contrast to the traditional method of file-based information organisation, the BIM process represents an object-based organisation of knowledge that enables the production of a model as an assembly of digital information and facilitates collaboration and information exchange among AEC professionals and other stakeholders such as contractors and suppliers [6,7]. BIM delivers...
value, efficiency and safety while recognising the whole life of asset knowledge and better business information management [8,9].

Individuals and organisations such as business and government agencies currently utilise BIM for planning, designing, constructing, operating and maintaining various physical infrastructure assets [9]. However, some sectors have been slow to embrace BIM with the latest technological opportunities and to implement a fully digital strategy; the water sector is one of them. According to Kamunda et al. [10], BIM has not fully matured in the water sector despite making some progress. Dodge Data & Analytics [11] carried out a study assessing the value of BIM for water projects observed by engineers, contractors and owners who had implemented BIM. According to the study, those who had previously used BIM plan to use it more going forward. This suggests that BIM will become more common in the water sector in the future. Furthermore, governments around the world become active and take steps towards implementation of policies that push the industry to adopt BIM and related digital engineering technologies on government projects with both new and existing assets [12]. For example, since 1 July 2019, all Queensland Government construction projects with a value of AUD 50 million or more are required to use BIM from the early planning phase. All major government infrastructure projects including water utility projects will transition to implement BIM by 2023. One of the objectives set by the Queensland Government for the development of BIM practices is “to promote consistency and interoperability in the information requirements for state infrastructure projects to facilitate a harmonized approach for industry” [13]. The real gains of BIM implementation by water utilities should come from digitising existing infrastructure, given that 90% of the infrastructure that will be in operation 25 years from now has already been built [11]. For digitisation to be efficient, asset owners must have access to accurate and complete as-constructed information. However, developing accurate as-constructed BIM models for existing buildings is challenging because as-designed information is often non-representative of site conditions [14,15]. Using 3D as-constructed data acquisition technologies such as laser scanners to feed data into BIM modelling software provides opportunities to accurately generate integrated BIM models [16]. As an outcome of laser scanning, developed 3D point cloud data contain a high level of detail (LOD) and provide better visualisation of as-constructed conditions. Nevertheless, subsequent processing is required to enrich the semantic asset information necessary for converting point clouds to objects recognised in BIM models. The typical scan-to-BIM process consists of three stages, namely, (i) laser scanning, (ii) the registration of scans into a unified global coordinate system and (iii) 3D modelling [15–18].

Even though the scan-to-BIM has been widely adopted for enhancing asset owners’ and project teams’ capabilities to obtain accurate as-constructed information, depending on the specific practical BIM application, the accuracy of generated 3D models varies along with the level of modelling details and level of information (LOI) assigned. Ultimately, the research presented in this paper aims to improve stakeholders’ understanding of the broad range of BIM adoption options and different modelling scenarios that are employed to generate laser-scan integrated 3D models for existing facilities. To achieve this aim, five objectives were developed:

1. To demonstrate and evaluate various modelling scenarios concerning the different applications of back-built digital models for an existing water treatment plant (WTP);
2. To map out the cost–benefit elements of the scan-to-BIM process for relevant stakeholders;
3. To investigate the impact of various LOD and LOI levels on practical BIM application for the effective management of the WTP;
4. To recommend various modelling scenarios to the industry for better planning and execution of the scan-to-BIM processes;
5. To propose a framework for realising the value of scan-to-BIM for existing facilities.

Following this introduction, Section 2 reviews BIM applications in the water sector and developments in 3D laser scanning for creating as-constructed BIM models for managing existing facilities. Thereafter, Section 3 describes the cost–benefit analysis methodology of
experimental laser-scan integrated 3D modelling for a case study research project of a WTP in South East Queensland (SEQ), Australia. Section 4 presents the results of the experimental modelling under different BIM integration scenarios, describes the costs and benefits of data mapping and discusses the potential implications of various models developed by considering fit-for-purpose LOD-LOI combinations for use in asset management in the water sector. Section 5 then presents a framework for obtaining value from an investment in scan-to-BIM for existing WTPs. Finally, Section 6 concludes the research findings, discusses the study limitations and provides future research directions.

2. Background

2.1. Applications of Building Information Modelling (BIM) in the Water Sector

Within the water sector, a typical asset such as water or wastewater treatment plant or a pumping station is a complex system of engineering structures required to manage multiple processes concerning fluid mechanics, microbiology and chemistry [6,10]. Conventional water treatment processes include coagulation, flocculation and clarification, sedimentation, filtration and disinfection. They are managed and operated by facility personnel, including operators, maintenance planners, process engineers and asset managers. Therefore, planning, design, and operations and maintenance (O&M) of such facilities require many skills from different industry specialists across several disciplines. In other words, water utilities and their supply chains must be integrated and collaborative. Effective and reliable information management, including the acquisition, storage and digital exchange of data and information, is essential for enhancing the capacity for operating, maintaining and monitoring water infrastructure, plants and expansive natural assets over their entire life cycle. Traditional design approaches can no longer meet the demands of complex treatment works, and BIM offers a solution to this complexity [10].

In Australia, the water industry recognises the community benefits of water infrastructure. It takes a ‘business-like’ approach, with several commercialised and some corporatised water service providers [19]. The elements of this recommended ‘business-like’ approach include the following:

- Establishing a more rigorous infrastructure investment decision-making process, with non-asset solutions, full-cycle costs, risks and existing alternatives being considered before a decision is made to construct infrastructure;
- Making the best use of existing infrastructure;
- Ensuring that infrastructure can sustain agreed customer service standards;
- Recognising asset management as a core business function to support service delivery.

For this purpose, the Queensland (QLD) Government created and recommended QLD water total management plans (TMPs) to promote best-practice planning and least-cost outcomes for water supply and sewerage planning [19]. A TMP quantifies and assesses the condition of assets, prioritises expenditure and identifies options for cost saving and improvement in environmentally and financially sustainable ways. This research adopts the TMPs’ four identified critical elements for managing a water treatment facility: asset, risk, data and communication management.

A BIM used for utility infrastructure projects has a different desired outcome than other BIM applications [8]. In the water services industry, the level of effectiveness of the BIM approach would play a significant role in the maintenance and operational needs of an infrastructure project. In other words, the primary driver in such projects is the advanced ‘smart’ asset management capabilities that require the integration of a large amount of information and data accumulated at earlier stages of the asset life cycle, with information that appears during asset maintenance. There is a need to align BIM with data, information, digital strategies and security across factors to fully realise the potential benefits and savings in operation [8]. Whereas design and construction benefits are evident from the detailed geometry data allowing for coordination and clash avoidance, water infrastructure benefits and created value opportunities are more long-term from the non-graphical data collected within the model [20,21].
2.2. Scan-to-BIM

BIM models are initially designed to record drawings and documentation during the design and construction phase and are referred to as ‘as-designed’ BIM [22]. However, the O&M of a facility takes up most of its life cycle and equates to more than half of a project’s overall costs and time [23]. Hence, the potential benefits of using BIM for facility operations are compelling, with the recent advancement of BIM technologies resulting in a shift from ‘as-designed’ BIM to ‘as-constructed’ BIM [24,25]. While BIM has been studied and applied to many new projects, developing an as-constructed BIM model for existing buildings and their built environment in the O&M phase is often a challenge due to the lack of an as-designed 3D model and difficulties with the data set that characterises the facility [14,15]. One of the tools that resolves the problems arising from inaccurate, out-of-date, or missing asset information is the reality-capture point cloud technology created through the utilisation of a light detection and ranging (LiDAR) laser scanning process [26–28]. The 3D point cloud data obtained as geometrical and spatial information through a LiDAR laser scan represent the as-is geometries of existing facilities. These data can later be exported to a digital BIM model and further enable the success of an existing building O&M strategy [15]. The process of transferring laser-scan data into BIM models is known as scan-to-BIM and has been widely adopted in the AEC and heritage management sectors [16–18,29].

The point cloud data collected from the laser scanning process do not contain any semantic information or geometrical context. The common practice in the industry is to feed laser-scan data into BIM authoring tools by manually drawing lines, ‘joining the dots’ in point cloud data and associating 3D models with the information on material and dimensions. However, the manual process is tedious, time-consuming and error-prone, allowing for high user errors and incorrect information, especially for complex projects with numerous building elements. Hence, it is crucial to use scan-to-BIM to fulfil the practical BIM application requirements. Some researchers have developed semi-automated or automated scan-to-BIM techniques to replace the manual approach [30,31]. These developed techniques focus on the automation of converting raw 3D point data from a laser scanner, including the object recognition and geometric modelling of building components.

Even though the scan-to-BIM process must be a robust, automated method that avoids the problems that the manual modelling of information can cause, for BIM to be a successful asset management tool, the gathered data must consider not only the object’s immediate attributes but also its function within the complete asset set. At the same time, collecting too much information may become a case of ‘information for information sake’, rendering a useless BIM model for the intended application [32]. Moreover, before embarking on a BIM process, asset owners and stakeholders should consider what information will be of value to them to support their long-term project and organisational requirements, along with how this information should interact with their current enterprise management systems [33–35]. Therefore, since BIM involves a high investment in terms of both time and money, it is critical to prioritise the key elements, systems and components for which BIM can offer the greatest benefits [36]. Moreover, the required information must be identified for each specific BIM application before asset data and LiDAR scan data are collected for existing assets [15]. According to Suprun et al. [37] and Mostafa et al. [6], different BIM applications require additional information sets to be accumulated. It is unnecessary to model all data for all assets to the highest degree. Identifying the information requirements usually involves establishing the required LOD and LOI.

2.3. Level of Detail (LOD) and Level of Information (LOI)

In this paper, LOD refers to ‘level of detail’ rather than ‘level of development’, although the two terms are often used synonymously in the AEC industry [38–40]. On the one hand, ‘level of development’, also known as ‘level of definition’, is a collective term used to describe the extent to which an object category is modelled for a certain purpose, customarily related to project stages from the conceptual design stage until the completion
of construction. On the other hand, ‘level of detail’ represents the degree to which an element’s geometry has been thought through [41,42]. It relates to the amount of specific detail included within the model space, system or component, and it may differ in content depending on the contract, the discipline and the type of asset being described. In essence, the LOD can be considered an input to the element, while the level of development is an output. Since this research focuses on creating BIM models for existing WTPs, it is more appropriate to adopt the terms LOD and LOI than to use a collective term describing both graphical data and non-geometric attributes.

While the model LOD focuses on the required geometric attributes of an element, the LOI refers to the quality of the non-graphical content that fulfils the intended BIM application’s needs [41,43]. It relates to the information included within the model’s elements and attributes. LOI examples include the performance specifications (e.g., valve mechanism, size, material, flow coefficient, measured flow rate) and asset maintenance information (e.g., serial number, acquisition date, warranty period, warranty content). It must be noted that the scan-to-BIM process can collect only a minimum number of non-geometric attributes, such as the spatial relationships between building elements and the surface properties of building elements [15]. Hence, the success of BIM implementation for existing buildings relies on accurate asset information stored in asset management systems. BIMForum [44] and National Building Specification [41] provide detailed descriptions of the five typical levels of model LOD and LOI specification.

According to Delavar et al. [45], selecting the proper model development level to match asset management requirements is challenging in BIM. Generally, a BIM model with high LOD-LOI supports more BIM uses and applications, mainly where the accuracy of the geometry, such as 3D coordination for clash detection, is essential. However, developing and managing high LOD-LOI 3D models for existing facilities is time-consuming. The total time spent in modelling increases vastly when going from one LOD-LOI to another. Hence, it is crucial to identify the LOD and LOI that are sufficient for BIM applications for existing assets and to develop different models accordingly while analysing the time, costs and benefits of such a development.

3. Research Methods

This research aims to develop an integrated framework for the value of scan-to-BIM in managing water utility assets. Therefore, the study scope includes scan-to-BIM applications (e.g., 3D modelling using point cloud, which is extracted from laser-scan images), water asset input and validation, and investigation of the specific WTP’s stakeholders, for a cost and benefit analysis of BIM integration and the creation of a data map for the WTP stakeholders. This research adopted a mixed method to achieve the research aim. The data collection methods comprised case study reviews and other 3D modelling process evaluations, the utilisation of existing WTP data, a structured interview and an equipment survey from a WTP site visit and group meetings, and experimental 3D modelling processes.

Table 1 presents a summary of eight case studies of water sector BIM projects. This research documented the project-related BIM activities that occurred frequently in each of the case studies. These activities included the creation of bid or construction drawings, clash detection and avoidance, quantities and cost estimation integration, the automated tracking of equipment lists using ‘smart’ piping and instrumentation diagrams (P&IDs) and the leveraging model for maintenance activities. The research also identified the BIM adoption stage, the BIM objective as well as the underlying cost and benefits.

The cost and benefit mappings were validated through a case study of a WTP in SEQ, Australia. The research team conducted site visits and attended team meetings with the WTP process engineers, operators as well as maintenance and asset managers to inform asset creation and inputs in the 3D model and validation by WTP stakeholders. The research team utilised the WTP’s existing data (e.g., WTP manuals, P&IDs, asset records and reports), current meeting reports and other shared files for asset validation during 3D modelling and WTP stakeholder validation.
Table 1. Summary of case study projects.

| Project                                      | Location                        | Case Study                                      |
|----------------------------------------------|---------------------------------|-------------------------------------------------|
| Kawana Sewage Treatment Plant upgrade [46]    | Sunshine Coast, Queensland, Australia | Using BIM for design, construction and operation |
| Minworth Thermal Hydrolysis Plant [47]       | Minworth, West, Midlands, UK    | Using BIM for design, construction and operation |
| Smart asset management:                      |                                 |                                                 |
| Pukete Wastewater Treatment Plant [48]       | Hamilton, New Zealand           | Advancing the asset management practice         |
| EchoWater project: Biological nutrient removal facility [49] | Elk Grove, California, USA      | Pioneering BIM for life cycle operations         |
| Liverpool Wastewater Treatment Works [50]    | Liverpool, UK                   | Demonstrating the benefits of BIM on first try  |
| Tomahawk Creek Wastewater Treatment Facility expansion [51] | Leawood, Kansas, USA            | Improving coordination through visualisation and data sharing |
| Southeast Water Treatment Plant construction [52] | Huntsville, Alabama, USA        | Transitioning to BIM                            |
| Bonnybrook Wastewater Treatment Plant upgrade and expansion [53] | Calgary, Canada                | Expanding BIM use through design and operations |

4. Results and Discussion

4.1. Different BIM Integration Scenarios

As part of the research methodology, three back-built digital models of the existing WTP were developed to investigate the designer costs of creating those models, followed by exploring the potential costs and benefits of BIM adoption for various WTP asset stakeholders. The developed models required different levels of model building effort using multiple software as outlined below. Moreover, additional asset information input was embedded into each model.

The WebShare model was built to aid the asset management approach. This model is user-friendly and allows for a common data environment (CDE) where project, asset and facility managers have access to the same data at the same time, through the usage of FARO’s Scene WebShare cloud-based 3D viewing platform [54]. The primary model’s characteristics are as follows:

- The asset information can be included; however, from an operational point of view, this model offers less functionality than the model options described below.
- The absence of data printouts, simulations and clash detections is a significant disadvantage of such a model.
- Basic LOI is provided, including only the critical asset information.
- Overall, the model is applicable for remote visualisation of the WTP to understand what assets are available and in what configuration.

The Revit model was built using the Revit BIM 3D software [55]. The primary model’s characteristics are as follows:

- The point cloud data are included in the model.
- The model can create a P&ID or drawing’s library.
- Most asset information could be included. However, due to the software’s constructional approach, the benefits would primarily accrue during the design and construction phases of a project to deliver further benefits during the O&M phase.
- The model would be helpful for designers seeking to refurbish an existing WTP.
- For users without a design background, the unfriendly interface of the model makes it less appealing for general use by O&M professionals.

The Plant 3D model was built using the AutoCAD Plant 3D utility software [56]. The primary model’s characteristics are as follows:
The model can simulate plant processes, convert P&IDs to smart P&IDs and link them to the model, thereby updating the asset data at both ends.

The model is beneficial from a WTP operational point of view, where most of the asset information can be uploaded to the model.

The Plant 3D + Revit model is a joint model that includes the point cloud data first uploaded to Revit and then transferred to Plant 3D. The primary model’s characteristics are as follows:

- The model can be constructed on top of the point cloud images, which have a precise layout of the case study area.
- Most asset information can be included, and simulation within the model is also possible.
- Due to the model’s complex interaction and the need for a constant exchange of data between Revit, point cloud data and Plant 3D, the interaction for the user is difficult and time-consuming.

Table 2 provides a qualitative comparison of the different digital models.

### Table 2. Comparison of BIM integration models.

| Capability                     | WebShare | Scan-to-BIM  |
|-------------------------------|----------|--------------|
|                               | Revit    | Plant 3D     | Plant 3D + Revit |
| Live interaction              | ✓        | ✓            | ✓                |
| All asset data and information| ✓        | ✓            | ✓                |
| Manufacturer and supply data  | ✓        | ✓            | ✓                |
| AEC design                    | ✓        | ✓            | ✓                |
| External link attachment      | ✓        | ✓            | ✓                |
| Pipe and plant creation       | ✓        | ✓            | ✓                |
| Simulation                    | ✓        | ✓            | ✓                |
| ‘Smart’ P&ID                  | ✓        | ✓            | ✓                |
| Clash detection               | ✓        | ✓            | ✓                |
| GIS data                      | ✓        | ✓            | ✓                |
| Single mode assembly          | ✓        | ✓            | ✓                |
| Phone access                  | ✓        | ✓            | ✓                |
| O&M manuals and other data    | ✓        | ✓            | ✓                |
| Reduction in construction costs and duration | ✓         | ✓            | ✓                |
| Life cycle and maintenance data | ✓     | ✓            | ✓                |
| QA/QC reports                 | ✓        | ✓            | ✓                |
| Bill of materials             | ✓        | ✓            | ✓                |
| Level of detail               | Low (LOD 100) | High (LOD 400) | High (LOD 500)  |
| Level of information          | Low (LOI 100) | Medium (LOI 300) | High (LOI 500)  |

#### 4.2. Identified Costs of the Scan-to-BIM Integration

The cost and benefit data mapping involved the creation of matrices for the costs and benefits for WTP stakeholders. Through the experimental 3D modelling and case study review, the costs and benefits of scan-to-BIM were observed and recorded in the BIM life cycle phases, such as the BIM design, O&M and the potential WTP upgrade phases.

The research revealed that the costs of BIM adoption can be described based on their respective elements (Table 3). First, the costs of point cloud-based BIM or the WebShare model from the laser-scan images include software costs, such as scan processor software (e.g., FARO Scene and Autodesk Recap), BIM software (e.g., Autodesk Revit and Navisworks) and 3D utility software (e.g., Autodesk AutoCAD Plant 3D). Second, hardware ranges from mobile devices to different specs of personal computers (i.e., 8G RAM to 16G RAM above) to enable fit-for-purpose 3D modelling and model use. Other utilities, such as an internet connection, are required for most phases, from access to WebShare and data input to data collaboration. The intensities were assessed based on a scale (high, medium and low) to quantify the labour and training costs, as illustrated in Table 4.
As mentioned above, the cost elements from Table 3 were identified during the experimental 3D modelling and case study review of various BIM life cycle phases. Each phase consists of multiple activities. Thus, BIM design and redesign for WTP upgrade activities include laser scanning, the transfer of laser-scan images to point cloud, WebShare uploading and laser-scanned integrated BIM activities. The O&M and construction for WTP upgrade activities include data access, input and output, and surveying. Table 5 presents the WTP cost-activity matrix of laser-scan processes during the experimental BIM design and the O&M as well as potential upgrades found in the literature. Each activity is associated with a code and represented by a combination of processes or functions and cost elements from those listed in Table 3. The codes are used as reference codes for further data mapping. The research revealed that utility software and BIM software have cost impacts when used in conjunction with each other and could potentially reduce the cost of the processes.

Table 3. Cost elements and resource references.

| Code | Software | Hardware | Labour | Training | Utility | Source |
|------|----------|----------|--------|----------|---------|--------|
| 1    | Scan processor | PC—8G RAM | High | High | Internet CXN | Literature review |
| 2    | FARO Scene | PC—16G RAM | Medium | Medium | Online tutorials |
| 3    | Autodesk Recap | PC—16G RAM above | Low | Low | 3D modelling |
| 4    | Autodesk Revit | Web-browsing device | | | Site survey |
| 5    | Autodesk AutoCAD | Plant 3D | | | Site interview |
| 6    | Autodesk Navisworks | | | | Laser-scan company |

Table 4. Labour and training intensity scale.

| Element | Low | Medium | High |
|---------|-----|--------|------|
| Labour  | 0 to 20 h | 20 to 40 h | 40 to 80 h |
| Training | Online tutorials | Scale Low + manual consultations | Scale Medium + expert consultations (e.g., diagnostic blogs, company inquiry request, expert advice) |

Table 5. Costs investigated for the different BIM life cycle phases.

| Activity | Code | Process/Function | Cost Element (Refer to Table 3) | Source (Refer to Table 3) |
|----------|------|------------------|---------------------------------|--------------------------|
| LiDAR scan | C1 | Scan survey | AUD 3,500 (provided) | R6 |
| Point cloud | C2 | Scanning processes | | |
| WebShare | C3 | Uploading processes | | |
| Laser-scanned integrated BIM | C4 | Smart P&ID drafting | | |
| C5 | Asset input | | |
| Validation | C8 | Uploading processes, clash detection, revalidation, etc. | | |
| Access | C9 | WebShare viewing | | |
| Input | C10 | 3D view (Navisworks) | | |
| C11 | WebShare data relay | | |
| C12 | Plant 3D data update/relay | | |
| Output | C13 | WebShare print out | | |
| C14 | Revi data print out | | |
| Survey | C15 | WebShare measuring | | |
| C16 | Plant 3D data print out | | |
| C17 | | | |
| C18 | | | |
4.3. Identified Benefits of the Scan-to-BIM Integration

The research reviewed eight case studies elaborating BIM utilisation in the water sector (Table 1) and the associated benefits of using BIM. Each of the eight case studies was investigated by interpreting the asset life cycle phase. BIM was implemented for objectives, cost considerations and benefits.

The Kawana Sewage Treatment Plant project [46] was carried out using BIM for design, construction and O&M. The project yielded significant improvements in business processes, yielding delivery time and cost savings. Additionally, there was a noticeable improvement in plant operability and maintainability, allowing the asset data generated by the design and construction team to be readily integrated into the utility’s asset management system. Some cost considerations included designing, validating and documenting the upgraded design plan in a multi-discipline 3D environment incorporating the pathology and survey information, design model, subcontractor models and vendor equipment models. Furthermore, The Minworth Thermal Hydrolysis Plant project [47] used 3D modelling aligned with laser scanning to provide accurate baseline data; 4D programming to enable the simulation of site activities for more effective planning; and virtual reviews of safety, ergonomics and general accessibility. As a result of BIM implementation, a collaborative team approach led to practical project delivery and commissioning as well as significant improvements in operator training processes.

The Pukete Wastewater Treatment Plant project [48] is a successful example of developing BIM models integrated with the council’s asset management database and financial system and creating a single source of truth for O&M activities. Similarly, the EchoWater project [49] case study has proven the efficiency of BIM use for precise information exchange, automated data migration and improved communication with stakeholders outside the design team. While BIM was relatively new in the Liverpool Wastewater Treatment project [50], the project pioneered BIM by developing a 3D model of the new facility as a construction and operational model. Design input into the 3D model was undertaken by all the sub-contract design teams and equipment manufacturers, resulting in a truly accurate model that has been used to carry out operator training, clash detection, real-time O&M manuals and maintenance management. Additionally, the Tomahawk Creek Wastewater Treatment Facility expansion project [51] has proven the success of adopting BIM for improved visualisation, quantity take-offs, cost estimation and the potential uses of virtual reality for water projects. The use of a CDE ensured access to complex data more simplistically than without BIM and allowed the project team to collaborate better with other stakeholders.

BIM-improved recollection and recognition during construction of the Southeast WTP [52] helped to reduce errors. Moreover, BIM provided contractors with a pre-built visualisation that allowed the project team to examine overhead structural and mechanical components and walk through the entire project before opening a set of 2D prints. As a result, the Southeast WTP’s BIM model significantly accelerated the construction team’s initial uptake of the design. One of the most notable developments during the Bonnybrook Wastewater Treatment Plant upgrades and expansion project [53] was the engagement of the client in the process and their interest in pursuing further uses of BIM in the future. Thus, the client began exploring the capabilities of a detailed model for operations and primary purposes even before receiving an exact as-constructed model of the plant. The project led the city council to establish a committee to explore how BIM could be implemented into its facilities management system.

Four of the reviewed case studies [46–48,51] developed as-constructed BIM models by adopting a scan-to-BIM process [15]. To do so, early in the project, the project teams laser-scanned existing operational facilities and asset geometry to provide an accurate baseline data set and to generate photo-realistic 3D point clouds of hard surfaces, including building shells and ground features, building interiors and assets. Combining point clouds with 3D modelling software led to accurate as-constructed models.
Potential design, client and overall project benefits of BIM were identified following a thorough review of the case studies. The benefits included reduced time and costs during asset life cycle stages, clients’ serviceability and improved communication. Validation of the benefits of BIM was conducted through meetings with multiple teams in the SEQ case study. The teams were distributed across different business disciplines and were primarily involved in planning, operating and maintaining the WTP. Table 6 lists the 18 identified benefits of the BIM application for water and wastewater treatment plants.

Table 6. BIM benefits.

| Code | Benefit                                                                 | References               |
|------|-------------------------------------------------------------------------|--------------------------|
| B1   | Improved design solutions                                                | [46–53]                  |
| B2   | Reduced errors and omissions in project documents                       | [46–53]                  |
| B3   | Enhanced ability to maintain quality                                    | [46,47,49–53]           |
| B4   | Reduced rework during construction                                       | [46–53]                  |
| B5   | Better control and predictability                                       | [46,49–52]              |
| B6   | Reduced cycle time of workflows among multiple parties                 | [46–53]                  |
| B7   | Reduced construction cost                                               | [46,49–51,53]           |
| B8   | Improved safety and faster approval cycles                              | [46–53]                  |
| B9   | Better safety performance for all parties involved                      | [46–50,52,53]           |
| B10  | Reduced project duration                                                | [46,49,51–53]           |
| B11  | Ability to work collaboratively with other project team members          | [46–53]                  |
| B12  | Increased client satisfaction                                           | [47–51,53]              |
| B13  | Overall enhancement of the organisation’s reputation as an industry leader | [48–50,52,53]           |
| B14  | Ability to offer new services                                           | [46,49–52]              |
| B15  | Marketing of new business to new clients                                | [49,50,52,53]           |
| B16  | Ability to attract or retain talented staff                              | [47–53]                  |
| B17  | Maintenance of repeat business with past clients                        | [49,52,53]              |
| B18  | Increased profits on projects using BIM                                  | [49–52]                  |

As Table 6 indicates, in addition to the optimised design performance, reduced errors and reduced project durations, BIM’s real benefits are enjoyed by the asset owner, as BIM can reduce the complete life cycle costs of the asset during the O&M phase.

The identified benefits were further validated during the experimental 3D modelling process and categorised based on the asset, data, risk and communication management elements found in the TMPs’ interpretations [19]—that is, the QLD government’s recommendation of asset management as a business-like approach, as discussed in Section 2.1. Figure 1 depicts a conceptual analysis of the BIM adoption benefits (B1–B18) of the above-mentioned four elements. As illustrated in the figure, most of the outlined benefits are associated with improved communication and risk management practices.

Table 7 lists the potential benefits of some of the elements presented in Table 3, the TMP [19] elements and the different BIM life cycle stages.

Table 7 shows that the BIM benefits are relatively evenly distributed during BIM design, O&M, upgrade plan and upgrade construction phases.

An accurate design of BIM models is essential since it will become the CDE, a single source of truth to all stakeholders. During the benefits investigation, the activities of the stakeholders relevant in the BIM lifecycle phases were observed and recorded. The following WTP stakeholders were considered for further analysis:

- BIM technical team;
- Facility personnel;
- Managers;
- Contractors;
- Clients;
- Owner/s;
- AEC professionals.
As Table 6 indicates, in addition to the optimised design performance, reduced errors and reduced project durations, BIM's real benefits are enjoyed by the asset owner, as BIM can reduce the complete life cycle costs of the asset during the O&M phase.

The identified benefits were further validated during the experimental 3D modelling process and categorised based on the asset, data, risk and communication management elements found in the TMPs' interpretations [19]—that is, the QLD government's recommendation of asset management as a business-like approach, as discussed in Section 2.1.

Figure 1 depicts a conceptual analysis of the BIM adoption benefits (B1–B18) of the above-mentioned four elements. As illustrated in the figure, most of the outlined benefits are associated with improved communication and risk management practices.

Figure 1. Observed relevance of the outlined benefits (B1–B18, Table 6) of the total management plan (TMP) [19] elements (Developed by the authors).

Table 7. BIM validated benefits.

| Code (Refer to Table 6) | BIM Lifecycle Phase | Element | Source (Refer to Table 3) |
|-------------------------|---------------------|---------|--------------------------|
|                         | BIM Design | O&M | Upgrade Design | Upgrade Construction | |
| B1                      | √         |     |               |                       | Data/Asset | R1, R3, R4 |
| B2                      | √         |     |               |                       | Data/Asset | R1, R3, R4 |
| B3                      | √         |     |               |                       | Asset/Risk | R1, R3, R4 |
| B4                      | √         |     |               |                       | Communication/Risk | R1 |
| B5                      | √         |     |               |                       | Communication/Risk | R1 |
| B6                      | √         | √   |               |                       | Data/Communication | R1 |
| B7                      | √         |     |               |                       | Asset/Risk | R1 |
| B8                      | √         | √   |               |                       | Communication/Risk | R1, R3, R4 |
| B9                      | √         |     |               |                       | Communication/Risk | R1 |
| B10                     | √         |     |               |                       | Asset/Risk | R1 |
| B11                     | √         | √   |               |                       | Data/Communication | R1, R4 |
| B12                     | √         |     |               |                       | Communication/Risk | R1, R4 |
| B13                     | √         |     |               |                       | Data/Communication | R1, R4 |
| B14                     | √         |     |               |                       | Communication/Risk | R1, R4 |
| B15                     | √         |     |               |                       | Communication/Risk | R1 |
| B16                     | √         | √   |               |                       | Data/Asset | R1 |
| B17                     | √         |     |               |                       | Communication/Risk | R1, R4 |
| B18                     | √         |     |               |                       | Asset/Risk | R1 |
These specific WTP stakeholders and respective BIM costs and benefits were identified during the literature review and were validated by the other data collection methods. Further analysis involved the development of a data map demonstrating the potential costs and benefits to the identified WTP stakeholders (Table 8). It shows the overall costs and helps from the developed coding system for costs and benefits (Tables 5 and 6, accordingly).

Table 8. WTP cost and benefit data map.

| Stakeholders                          | WebShare | Scan-to-BIM | BIM Lifecycle Phase | Potential Costs (Refer to Table 5) | Potential Benefits (Refer to Table 6) |
|---------------------------------------|----------|-------------|---------------------|-------------------------------------|---------------------------------------|
| **BIM technical team**                |          |             |                     |                                     |                                       |
| BIM coordinator                       | ✓        | ✓           | ✓                   | C1–C14                              | B1–B5, B8, B9                         |
| 3D BIM designers                      | ✓        |             |                     |                                     |                                       |
| Facility personnel                    |          |             |                     |                                     |                                       |
| Operators                             | ✓        | ✓           | ✓                   | C10–C18                             | B2–B9                                 |
| Maintenance planners                  | ✓        |             |                     |                                     |                                       |
| Schedulers                            | ✓        |             |                     |                                     |                                       |
| Process engineers                     | ✓        |             |                     |                                     |                                       |
| Facility managers                     | ✓        | ✓           | ✓                   | C10–C18                             | B2–B9                                 |
| Managers                              |          |             |                     |                                     |                                       |
| Asset managers                        | ✓        | ✓           | ✓                   | C10, C11, C15–C17                   | B2, B3, B5–B9, B11–B18               |
| Project managers                      | ✓        |             |                     |                                     |                                       |
| Main contractors                      | ✓        | ✓           | ✓                   | C10, C11, C15–C17                   | B2, B3, B5–B9, B11–B18               |
| Sub-contractors                       | ✓        |             |                     |                                     |                                       |
| Suppliers                             | ✓        |             |                     |                                     |                                       |
| Managers                              |          |             |                     |                                     |                                       |
| Local residents                       | ✓        |             | ✓                   | C10                                 | B12, B14, B15                         |
| Local businesses                      | ✓        |             | ✓                   | C10                                 | B12, B14, B15                         |
| Others                                | ✓        |             | ✓                   | C10                                 | B12, B14, B15                         |
| Investor                              | ✓        | ✓           | ✓                   | C10                                 | B1–B18                               |
| Owner/s                               |          |             |                     |                                     |                                       |
| Local government                      | ✓        |             | ✓                   | C10                                 | B1–B18                               |
| State government                      | ✓        |             | ✓                   | C10                                 | B1–B18                               |
| Federal government                    | ✓        |             | ✓                   | C10                                 | B1–B18                               |
| Architects                            | ✓        |             | ✓                   | C4–C18                              | B1–B11, B16–B18                       |
| Engineers                             | ✓        |             | ✓                   | C4–C18                              | B1–B11, B16–B18                       |
| Construction personnel                | ✓        |             | ✓                   | C9–C18                              | B1–B11, B16–B18                       |

Table 8 presents the observed relevance of the WebShare and scan-to-BIM approaches and the BIM life cycle phase activities. Based on this relevance, WebShare can benefit all involved stakeholders, while the overall relevance of BIM is distributed throughout different phases. The data map aids in consolidating the constant repetition of costs and benefits related to each stakeholder. Ultimately, this method aims to mitigate repeated expenses and hence reduce overall project costs.

4.4. Fit-for-Purpose LOD-LOI Combination Scenarios

As part of the research on BIM adoption for managing existing water treatment facilities, the impact of various LOD and LOI levels on BIM applications was investigated (Figure 2).

Following the experimental 3D modelling and the exploration of the potential costs and benefits of BIM adoption for various WTP stakeholders, Figure 2 was developed to present multiple combinations of LOD and LOI to demonstrate that no combination can be considered the most optimal per-industry application, as different 3D models have their advantages and disadvantages depending on the project’s or asset’s requirements.
Nevertheless, the most efficient model is the one that best balances the costs of creating a model at a certain LOD-LOI combination and the benefits of using the model. In other words, an appropriate LOD-LOI selection for models must encompass most of the information requirements of an asset management’s goals while avoiding imposing unnecessary modelling time and costs from overdevelopment.

4.4. Fit-for-Purpose LOD-LOI Combination Scenarios

As part of the research on BIM adoption for managing existing water treatment facilities, the impact of various LOD and LOI levels on BIM applications was investigated (Figure 2).

Figure 2. Level of detail (LOD) and level of information (LOI) combination scenarios explored for existing water treatment facilities (Developed by the authors).

4.4.1. Functional Asset Management

According to the research, in situations where several changes to the WTP process or equipment are expected, a high LOD and medium LOI option such as the Plant 3D model is recommended, as it can provide most benefits considering the time and cost invested. The research determined that exceeding LOD 400 for the back-building of digital twins for existing facilities may not be worthwhile. The considerable extra time to build a LOD 500 BIM model from the point cloud data does not provide commensurate benefits in terms of design, construction and O&M functions. The Plant 3D model includes valuable features, such as simulations, automated piping isometric and orthographic production, spec-driven intelligent P&IDs and a bill of materials. The model not only has sufficient asset information to successfully improve the degree of possible interaction and management of the assets within the case study area but also provides the capability of simulation and clash detection within the same software. When refurbishing or upgrading a particular water treatment process, this functionality would reduce design time and errors in the design and construction phase.

4.4.2. Visualisation of As-Constructed Conditions

In contrast, following the experimental 3D modelling, it can be concluded that point clouds of a poor resolution may not be sufficient to produce highly detailed models of piping or membrane elements, for example, since the density of the points may not be high enough to interpret the form of the component. Nevertheless, the developed WebShare
model is an example of a low LOD and low LOI model, and it is recommended to be implemented as a temporary solution for maintenance and operational purposes. The model enables an efficient asset classification and interaction, allowing for the introduction of relevant asset information that could benefit operations within the WTP. The classification system will allow for the immediate identification of an asset that requires maintenance or replacement as well as the identification of an asset that has just been replaced, thereby preventing double-ups and mistakes. Furthermore, 3D visualisation can be used for training purposes, ‘walking’ through a WTP, carrying out inductions or safety training and identifying the different sections and assets within the scanned area. This is a low-cost way of visually capturing the assets of a water utility at a particular point in time and assigning only critical asset information. Hence, even though such a model could be used as a 3D as-constructed model for O&M purposes alongside higher LOD BIM models, it may not offer a suitable, comprehensive asset management solution.

4.4.3. Back-Built Digital Twins

The research findings suggest that the higher the LOD-LOI of the model used in BIM collaboration is, the more accountability is required for the accuracy of the model and its contained information. Developing a higher LOD-LOI has been proven to be a time-consuming process, and, beyond a certain level of LOD, the requirement for computer processing and graphic capabilities increases significantly. For example, the usage of the Plant 3D + Revit model (i.e., the high LOD and high LOI option) is recommended only when a significant upgrade is proposed for a WTP. Architectural and construction data can be included after successfully simulating the created model in Plant 3D. The different teams within the project would interact, making the most of the software’s tools. Moreover, the bill of materials for both software would be provided for the process plant services and the civil and structural aspects of the construction project. Nevertheless, managing such models is challenging due to associated risks and the issue of interoperability and data exchange constraints. Moreover, much of the capacity to model a higher LOD-LOI in existing buildings depends on how it has been documented rather than the capacity of the modelling software to create complex geometries. First, the database must be well organised to ensure the successful application of a high LOI. Second, while higher LOD-LOI models can convey more detailed information, they can also raise some related intellectual property issues, leading to questions about the ownership of the data. Industry best practices address these issues by relying on thoroughly developed BIM execution plans and exchange information requirements, including specified LOD-LOI transfer expectations and agreements, to mitigate potential risks associated with the ownership of the models [57–60].

5. Scan-to-BIM LOD-LOI Combination Value Realisation Framework

To make the best use of existing infrastructure, water asset owners must recognise the benefits of BIM and digital asset management as a core business function to support service delivery [8,11,21]. At the same time, the process of integrating BIM into an organisation’s existing information and management systems should stage the transition sensibly and target best value opportunities first to eliminate cost overruns or issues during implementation [9]. According to Thorp [61], organisations should avoid hastily adopting new technology without undertaking a rigorous review and questioning process. When creating and delivering value through BIM, the critical resource is not the advanced technology alone. Still, a strategic approach is used to develop information that will provide asset management and business outcomes [36]. To ensure understanding of the extent to which BIM adoption options will add value for managing as-constructed assets, a conceptual framework for obtaining value from an investment in scan-to-BIM is proposed (Figure 3).
organisation’s existing information and management systems should stage the transition sensibly and target best value opportunities first to eliminate cost overruns or issues during implementation [9]. According to Thorp [61], organisations should avoid hastily adopting new technology without undertaking a rigorous review and questioning process. When creating and delivering value through BIM, the critical resource is not the advanced technology alone. Still, a strategic approach is used to develop information that will provide asset management and business outcomes [36]. To ensure understanding of the extent to which BIM adoption options will add value for managing as-constructed assets, a conceptual framework for obtaining value from an investment in scan-to-BIM is proposed (Figure 3).

Figure 3. Framework for realising the value of scan-to-BIM LOD-LOI combination for managing existing assets (Adapted from [9,36,61]).

The cornerstones of the proposed framework are risk management, data management, asset management and communication management [19]. Each cornerstone plays a critical role in enabling efficient management of water treatment facilities and improving the following aspects of operating and maintaining existing assets [8,62]:

• Monitoring of costs;
• Optimising operational efficiency;
• Assessing asset condition;
• Evaluating asset performance;
• Optimising asset maintenance;
• Replacing or upgrading assets.

According to Love et al. [36] and Thorp [61], an asset owner should ask four key questions when developing either a business case for the use of new technology or a management approach, to assess its relative value. Each of the questions is discussed in Section 5.1, Section 5.2, Section 5.3, Section 5.4 respectively.

5.1. Are We Doing the Right Things?

While scan-to-BIM enhances owner operators’ capabilities to obtain accurate as-constructed information, modelling all data for all assets to the highest degree is unnecessary. Due to BIM being an increased investment of both time and money, asset owners together with the help of stakeholders must first identify critical assets and critical projects where BIM can offer additional benefits [9]. In other words, before embarking on a BIM process, asset owners should ask themselves what assets they must prioritise to ensure that material risk and critical control requirements are addressed.
The information required for each specific BIM application must be identified before asset data and LiDAR scan data are gathered for existing assets. Otherwise, collecting too much data may become a case of ‘information for information sake’, which may not be valuable to asset owners [32]. A detailed asset information management strategy that specifies these owners’ data needs for the O&M of the facility must be devised before BIM models are developed, to determine and reconcile the fit-for-purpose LOD modelled and asset information incorporated. Moreover, stakeholders must understand each LOD and LOI that could be used as a point of reference for value realisation to determine whether to continue to build the intended BIM model (Figure 2). This clear understanding would further allow asset management’s goals while avoiding imposing unnecessary modelling overdevelopment.

5.2. Are We Doing Them the Right Way?

This question raises organisational and technological issues that must be addressed to enable effective asset management. There is a need to align BIM with data, information, digital strategies and security across the water sector to fully realise the potential benefits of such modelling in operation [8]. First, reliable data management, including acquisition, storage and digital exchange of data and information, is essential for enhancing the operating, maintaining and monitoring water assets [63]. Moreover, the ability to back-build digital models of existing facilities relies not only on accurate asset information stored in BIM models but also on the enterprise systems and processes and their integration with BIM models [36].

Depending on the specific practical BIM application, such as visualisation of as-constructed conditions; analysis of the facility and equipment condition assessments; tracking of the use, performance and maintenance of assets; or a significant facility upgrade or refurbishment, various modelling scenarios can be implemented (Table 2). Clearly defined information requirements must consider all the organisation’s information systems to support the modelling process. BIM models must ultimately be integrated into enterprise applications to ensure seamless transfer between them and to facilitate semantic interoperability [36,37]. The accuracy of data transmission among different departments must also be guaranteed to simplify associated data flows and avoid failure to update models.

5.3. Are We Getting Them Done Well?

This question addresses the ability of business units within the asset owner’s organisation to deliver BIM adopted for particular asset management purposes. Efforts should be made to strategically model the existing facilities for effective long-term use by all stakeholders, including facility and asset managers. According to Love et al. [36] and Sanchez et al. [9], benefits materialisation from a BIM investment can be conceptualised as an asset owner’s capability to ensure that the adopted processes and technological solutions can consistently generate value. Specifically, value creation is initiated by an organisation’s ability to mobilise, assemble and utilise the resources required to develop BIM models and integrate them into the information, data, asset and other enterprise management systems.

The development and integration of BIM models require careful consideration of the skills and knowledge of asset owner’s employees and managers to ensure effective coordination of implementation activities. The modelling process also requires different model building efforts, resources and supporting infrastructure such as software, hardware and utilities (Table 3). Investments should be made in resources that would best assist asset owners to successfully acquire a sustainable O&M of the facilities when they adopt BIM. Accurately designed as-constructed BIM models are essential, since they will become the CDE, a single source of truth for all stakeholders and improve organisational communication.

5.4. Are We Getting the Benefits?

Each of the previous questions should be used to consistently interrogate the usefulness of a scan-to-BIM process in generating value and contributing to better maintenance
of or improvement in performance against risk. As mentioned previously, it is crucial to identify the fit-for-purpose LOD and LOI that are sufficient for most BIM applications for existing assets and to develop different models accordingly while analysing the costs and benefits associated with such a development. This cost and benefit assessment must be conducted to determine what benefits of scan-to-BIM can be achieved when each stakeholder’s investment objectives are realised. It is necessary to determine whether operational, managerial, infrastructural, organisational and strategic benefits are achieved [36].

With suitable capabilities in place, asset managers and other relevant stakeholders should be encouraged to continually review and modify the scan-to-BIM process to develop as-constructed BIM models to manage risk better and improve business value through the remediation of controls and the implementation of BIM.

6. Conclusions

While BIM processes are well established for new buildings and assets, there is a need to leverage BIM technologies to operate, maintain and refurbish existing assets. This would ensure the improvement of asset management practices in the industry and enable the development of a necessary strategic direction to transition towards a comprehensive digital asset management plan. With the gradual digitalisation of the water sector, scan-to-BIM has become a feasible approach for collecting updated and complete as-constructed information, dealing with uncertain accuracy of existing data and centralising asset information in a CDE for new works and maintenance. Nevertheless, it is evident from current literature that developing BIM models for existing built assets as a part of the scan-to-BIM process might be complex, tedious, time-consuming and costly [15,64]. This paper evaluated the costs and benefits of scan-to-BIM by experimental 3D modelling processes under different modelling scenarios and created a data map for various WTP stakeholders. Aside from this contribution, the paper discussed the potential implications of various laser-scan integrated models for asset management in the water sector based on the multiple combinations of graphical data and non-geometric attributes included in the model. Finally, the paper proposed a conceptual framework for developing a strategy for asset owners to consider how scan-to-BIM could create value and lead to improved asset management and sustainable business outcomes.

To summarise, the following conclusions are drawn from this work. As BIM models acquire more 3D components, managing these components becomes increasingly difficult for computer and human operators. Hence, in all cases of 3D modelling, an understanding of what the organisational objectives are and what the information will be used for is essential. In other words, efforts associated with developing a BIM model from point clouds should be proportionate to the asset owner’s needs. In the case of asset O&M, a WebShare model with a lower level of graphical detail and only critical asset information included may, in fact, be more desirable. When a new water or wastewater treatment plant or a new section of an existing plant is to be constructed, the highest possible levels of graphical data and non-geometric attributes included in the model may be more appropriate. Based on the research results, it is imperative that existing facilities are strategically modelled for effective long-term use by all stakeholders. In other words, a detailed asset information management strategy must be created before BIM models are developed for managing existing assets to determine and reconcile the fit-for-purpose LOD modelled and asset information incorporated.

This research entailed a cost–benefit mapping of the scan-to-BIM applications under different modelling scenarios for relatively simple BIM objects (e.g., walls, water reservoirs, pipes). The primary purpose of the cost-benefit mapping was to provide a comparative assessment of LOI-LOD combinations and underpin the development of the Scan-to-BIM LOI-LOD value realisation framework and associated guidance for water utility asset owners seeking to determine the value proposition for different levels of investment in a Scan-to-BIM project. Further research is needed to standardise factors that affect the detail and accuracy of complex modelling elements (e.g., membranes). The research utilised
Autodesk products (Revit, Navisworks, Plant 3D and Autodesk Recap) for generating the 3D usable model from the point cloud or the water treatment facility. The selection of these products was based on the academic subscription given to Autodesk software, the nature of the assets of the water treatment facility, and considering compatibility among these products. Hence, future research could use other software for the scan-to-BIM integration in the water sector or across other industrial sectors, leading to improved cost and benefits. Furthermore, there is a need to assess factors such as the accuracy, precision, time and training required for modelling when automating the process of developing various laser-scan integrated BIM models.

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