REALITY CAPTURE for BIM – Application, evaluation and integration within an architectural plan of works

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ABSTRACT: *The paper explores the use of reality capture and building information modelling for collaborative retrofitting projects within an architectural SME. Through the use of a series of 'live' case studies, mixed and multiple methods of data and reality capture are tested for speed, cost, accuracy, interoperability and level of detail suitable for concept / detail designs, outline costing, options testing, energy modelling and visualisation tasks. The paper demonstrates an approach to reverse engineering from the perspectives of the different technical and non-expert stakeholders involved within a multi-disciplinary design team to ensure reality capture is appropriately specified and fit for purpose. Specific tasks / activities for (i) data / reality capture, (ii) data integration / editing and (iii) data analysis within a retrofitting architectural and construction project are described using the IDEF0 process mapping methodology and integrated within a standard RIBA architectural 'plan of works'. Examples include measured building survey, photo-matching, structured photogrammetry survey, thermal imagery and both ground level and aerial LiDar survey, combining primary and secondary data sets and utilising a mix of software packages. A comparative evaluation of these reality capture methods sets out the appropriate operational requirements and specifications for a BIM Level 2 project within an SME. The paper explains the benefits of process mapping to understand the interactions between different disciplines and the important role that BIM has in supporting collaboration between SMEs within the AEC sector. The authors also discuss the benefits of utilizing hybrid models as part of a collaborative and unpredictable design process and make recommendations for cost-effective reality capture.*

KEYWORDS: *Process Mapping, Retrofitting, Reality Capture, Drone Survey, Building Information Modelling.*

1. STANDARD ARCHITECTURAL PLAN OF WORKS

This paper is an exploration of a range of reality capture methods and techniques arising out a series of redevelopment and retrofitting projects within a small UK based architectural practice. In common with most architectural practices, this firm followed their own interpretation of a standard work plan and series of specific tasks for individual design jobs. Yet this industry standard processes or 'plan of works' has a particular emphasis on new-build construction rather than refurbishment and didn't provide any specific guidance on initial survey and recent innovations in reality capture processes. There are reasons for this omission. In part it is because within the design industry, standard 'plan of works' and business practices originally grew out of the need for legal contract documents within the construction industry. They began as standardised forms of consultancy and contractor services and have since evolved into more complex, state of the art management procedures aimed at addressing each individual stage within the design, construction and development process (Cooper 2008).

A review of BIM policy and practice within the UK house-building industry (HM Government 2012) has indicated how important such a standardised and staged method of working is and how BIM processes need to be fully integrated and embedded in this working method. This is consistent with the policy theme underlying many procedural changes within the UK planning and development professions over the last decade. This has been the idea of a 'common language' (Egan 2004) that reflects common aspects of a project brief or specification, a common set of project stages and a common understanding of measurable outcomes. For the design and development industry, this common language is most evident in the wide application and use of the architectural 'plan of works' (RIBA 2013) and an adaptation of this framework is the basis for this paper. Within this standard 'plan of works' and contract management processes, we aim to identify how project specific requirements for reality capture, as a key task within retrofitting and refurbishment projects, can be integrated with BIM protocols within such a common working process.

This area of applied-research has, in part, grown out of the increasing interest in large-scale retrofitting projects aiming at addressing energy efficiency and fuel poverty within the existing building stock, albeit it is as applicable to other non-domestic building sectors. This is aligned with the absence of any current standard approach to building survey / reality capture within the 'plan of works' or accompanying BIM overlay (Sinclair 2012). The lack of an agreed reality capture or survey process from the outset of a project gives rise to complicating issues later into the work stream and potentially negating many of the time and efficiency saving promised by the implementation of a BIM strategy. By understanding the client / employer information requirements, the best approach to reality capture can be specified and related to an overall BIM execution plan. This will avoid duplication of efforts, additional surveys being undertaken, appropriate levels of detail and information, avoid over-specification and ultimately be more efficient.

1.1 BIM overlay for an architectural 'plan of works'

> "BIM is a process that improves the efficiency of organising and distributing data ... (and) ... many working within house-building do not yet have an awareness of the potential benefits for their sector." (Nick Raynsford quoted p1 in; NHBC Trust and BSRIA, 2013).

Within the UK there are clear messages from both research and industry reviews that the current housing and retrofitting market "… is not capable of delivering sufficient housing to prevent a serious shortfall …" and that part of the solution is to "… (r)aise awareness and support the training and integration of BIM across *all segments* of the market, providing support and encouragement to the self-builder, the small to medium size house builder, the largest private house-builders, RSLs, LAs and other client organisations" (Miles and Whitehouse 2013, p33). In this context, BIM is understood, by central government at least, as the basis for economic growth in the housing and retrofitting market and the wider construction industry (Saxon 2013).

Yet, while there are an increasing number of retrofitting and refurbishment projects, the BIM 'industry stakeholders' have tended to omit the relative significance of the retrofitting market and instead concentrate on the production of execution plans suitable for new design and construction projects. This is, in part, due to the relationship of a BIM execution plan and industry standard plan of works.

1.2 Process mapping applied to an architectural 'plan of work'

In order to understand the relationship between the RIBA 'Plan of work' (2013), the requirements for project specific BIM Execution Plan(s) and retrofitting tasks or activities that currently fall outside of both of these procedural and project management tools, we based our approach on the use of a process mapping methodology that could effectively incorporate architectural, digital modelling, energy analysis and multiple survey methods in a single approach.

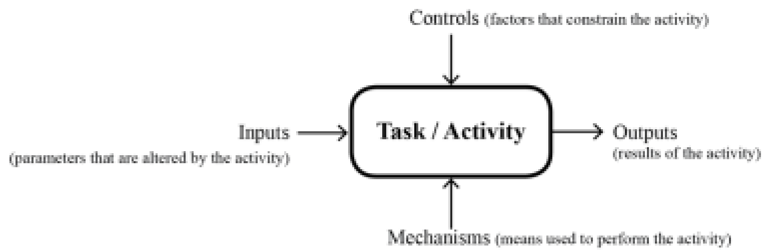

Fig. 1: Structure of IDEF0 process mapping for a specific task or activity.

Reviewing advice on choosing the most appropriate process modelling pointed us toward the Integrated Definition for Function Modeling (IDEF) as a family of hierarchical models (Aguilar-Savén 2004) that provides a comprehensive and common understanding of complex processes. IDEF0 (IDEF level zero) is a modelling technique used for developing structural graphical representations of processes or complex systems. It is used to specify function models, which are "what do I do?" models. These show the high-level activities of a process indicating major activities and the input, control, output, and mechanisms associated with each major activity. Although the methodology emerged from the operations of the US Airforce in the 1960s onwards; as the significance of ICT in the manufacturing operations and practice began to become more prominent and thus the operations correspondingly more complex and involving more stakeholders and actors; it has increasingly been utilised within the design and construction industry sectors.

There are well-documented advantages to using IDEF0 as a standardised, widely accepted and recognised process-mapping technique (Colquhoun *et al.* 1993) within both academia and industry. Firstly, is the imposition of formality for every individual user. Secondly, there is the ability to integrate individual tasks and operations into a much larger model and complex design and development process. There is the potential for ‘partitioned’ models to be generated for individual stages and / or tasks. Starting at a high level in the development of ‘parent’ process diagrams that are suitable for non-expert involvement but also the ability to examine and deconstruct any design and development process into much more specific tasks for many different technical specialists. Recognition of hierarchal nature of the processes (Zugal *et al.* 2015) (in the parent diagram) and the sub-processes (in the ‘child diagram) and recognition of common patterns (Bergener *et al* 2015) in the hierarchy. This hierarchical structure of tasks in IDEF0 closely reflects the hierarchy of stages, tasks and sub-tasks within the architectural ‘plan of works’ and the development of BIM overlay and supporting tools (NBS 2016). It is the closest thing to an industry standard that presently exists. This level of recognition is important to support external review, comparison and analysis of design and / or manufacturing practices and processes (Melao and Pidd, 2000).

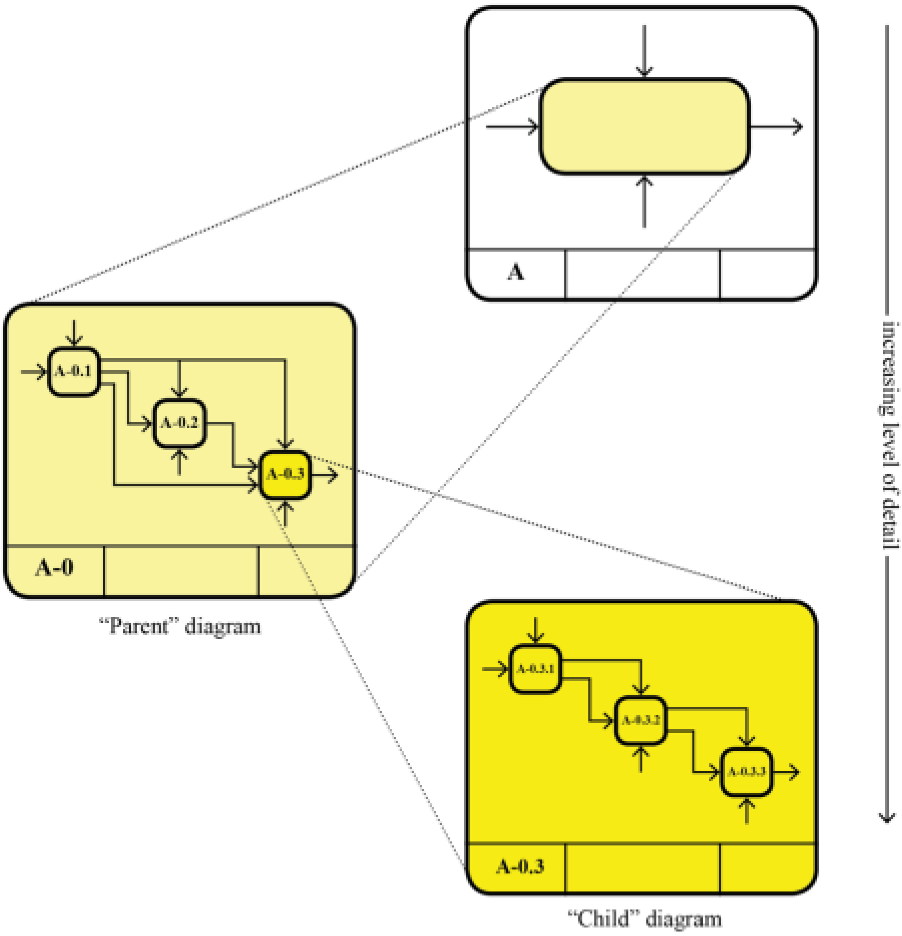

Fig. 2: Hierarchy of IDEF0 process mapping tasks.

We recognize that there are limitations around the IDEF0 model (Billo *et al.* 1994), specifically that it is a static description of any process or series of tasks, and that it is not quantitative in a manner that can provide any empirical aspects around the different weighting and relationships between the tasks that in certain engineering tasks can be limiting (Kusiak *et al.* 1994). Yet it is the core strengths of the method to create consistent multiple models that can be integrated that led to us choosing it as the most appropriate methodology for understanding the mixed and multi-disciplinary processes. As a methodology, it has proven application regarding collaboration with professional, supply-chain and construction stakeholders and partners.

There is significant published evidence to show how the IDEF0 methodology can assist in fully understanding workflows within a manufacturing process (Kim and Jang 2002), including the architecture and construction industry. It has proved useful for identifying redundancies and repetition within any design and development process (Busby and Williams 1993), highlighting missing controls or other inputs into the specified task to improve overall efficiencies. IDEF0 process mapping tools have been applied to comparative task based (and sub-task) analysis for collaboration within industry supply chain (Barratt and Oliveira 2001). One of several techniques and process mapping tools; increasingly becoming ICT based; supporting collaboration between vendors, fabricators, assemblers and distributors within any industry supply chain (Fliedner 2003). This supply chain behaviour is in part driven by the client / stakeholder pressure (Worthington *et al*. 2008) as much as the statutory legal requirements, and ultimately the realisation that these can provide a clear economic imperative to follow ethical and sustainable business practices (Walker and Brammer 2009b).

Similar architectural design processes have been previously addressed using the same methodology, albeit for a Finish construction context (Karhu *et al*. 1997). This case study analysis demonstrated IDEF0 process mapping can be an important framework for all parties / stakeholders understanding the overall process of which they play a part, and the significant aspects of exchange of information as the output from one task as the input into another task. It is structured and has graphical strengths through its strict 'standardised' rules make it suitable for implementation as computer software. Indeed, as a method for analysis its' application has brought about many process improvements suitable for both high level and sub processes (Zellner 2011).

In short, it is simple, quick and economical to use by non-experts, easily interpreted and understandable by all stakeholders, easy to add to and undertake analysis (Cantamessa and Paolucci 1998).

1.3 Aligning an architectural 'plan of work' and BIM using IDEF0 process mapping

While there has be some limited application of the RIBA 'plan of work' (2013) to wider design and construction tasks; for example, in the linking the plan of work to the tasks undertaken by structural engineers (Davies 2015); this remains a weakness for many non-standard tasks that fall outside of the remit of an architectural practice. And non-standard tasks with the use of multiple professionals are more dominant in refurbishment and retrofitting projects compared to new-build construction. In this context, it is specifically a concern in many early-stage tasks (RIBA pre-stage 0) relating to site and / or property survey for both geometry and associated performance parameters, including current energy performance. This emphasis on standard architectural tasks has been at the expense of collaboration with other built environment professionals ranging from planners, surveyors, engineers and facility managers.

Yet collaboration around a 'common language' is one of the important critical factors in the successful and efficient delivery of any design and construction project. ICT systems and BIM tools are growing in recognition as the most important 'mechanisms' in making such improvements in collaboration a reality (Xue *et al.* 2012). For example, many current examples of energy performance models increasingly see the ICT side of BIM as a means for effective integration (Schlueter and Thesseling 2009) with architectural / geometric building models as well as the means for effective integration through the requirements for environmental management systems and performance standards (Walker and Brammer 2009a) as a pre-requisite for an extended supply chain, in effect adding building specification and performance parameters to architectural / geometric building models. This support for professional collaboration is the policy intention within the current UK government, where the current requirement for compliance with BIM level 2 operations allow earlier stage collaboration with better integration between the multiple disciplines (House of Lords 2016).

This pressure for improvement in BIM standards, protocols and processes in the UK is extending to the domestic sector and the growing importance of the retrofitting industry. In this context, current British Standards (BSI 2013) establish the requirements for a suitable common data environment (CDE), interoperability standards; including file and layer naming conventions; and issues around the Levels of Detail and Definition (LoD) as they relate to geometric information and associated data. These are based on earlier attempts at developing a 'common language' or consistent set of standards (VICS 2000) within a multi-disciplinary that provided the most appropriate balance between accuracy, realism and simplicity in use. Yet, there remains a limited alignment between BIM and other design and development strategies, including sustainability, statutory planning and architects 'plan of work', and gaps that remain around the use and implementation of BIM protocols (Kassem *et al.* 2014). This is due in part to the complexity; and thus bespoke nature; of many planning, architectural and construction projects where there are multiple design decisions being made. For example, one recent study identified 35 design stages decisions / tasks from a series of over 90 design decisions made at all stages of work (Lam *et al* 2010), and this may well be an underestimation of identifiable discrete tasks within any work programme. Yet, within these complex processes there has been the development of tools to simplify the process or tasks associated with energy assessment in the early design stages (Hall and Purchase 2006) beginning to address overlay of sustainability implications on procedures within business (Kleindorfer *et al*. 2005) and construction practice. We have begun to apply IDEF0 process mapping to many of these early-stage design and project management tasks.

Table 1: Example section of a generic plan of works within the architectural and construction industry tabulated for IDEF0 process mapping as a series of hierarchical tasks and activities.

	task('parent' diagram)		sub tasks 1 ('child' diagram)		sub tasks 2
A-0	Strategic Definition	A-0.1	Identify Business Case		
		A-0.2	Project Programme	A-0.2.1	Risk Assessment
				A-0.2.2	Establish Project Team / Project Board with Management Decision-Making Responsibilities
				A-0.2.3	Pre-BEP / Draft Project or Building Execution Plan
		A-0.3	Strategic brief	A-0.3.1	Pre-application Planning Discussions
				A-0.3.2	Regional Design Review
				A-0.3.3	Precedent Project Review & Feedback
				A-0.3.4	Core Project Requirements
				A-0.3.5	Sustainability requirements
		A-0.4	EIR (Employer Information Requirements)	A-0.4.1	OIR (Organizational Information Requirements)
				A-0.4.2	AIR (Asset Information Requirements)
A-1	Initial Project Brief	A-1.1	Project Execution Plan	A-1.1.1	Technology & Communication Strategy
				A-1.1.2	Interoperability & Common Standards
				A-1.1.3	Define Common Data Environment
				A-1.1.4	(BEP) Building Execution Plan
		A-1.2	Design Roles & Responsibility Matrix / Project Roles Table	A-1.2.1	Contractual Tree / Schedule of Services
				A-1.2.2	Information Exchange Requirements
		A-1.3	Project Objectives / Success Criteria	A-1.3.1	Quality Objectives
				A-1.3.2	Sustainability Aspirations
				A-1.3.3	Project Outcomes
		A-1.4	Project Budget		
		A-1.5	Handover Strategy		
		A-1.6	Feasibility Studies		
		A-1.7	Due Diligence / Review of site Information	A-1.7.1	Ownership & restrictions
				A-1.7.2	Statutory Constraints
		A-1.8	Review Project Programme	A-1.8.1	Risk Assessment

Within the national UK context, the *Bonfield Review* (DECC 2015) has 'Terms of Reference' for retrofitting standards that are looking at elements of design stage advice, standards framework and compliance checking. There is a clear decision in emerging policy to be grounded in an agreed process that has common stages, tasks, work streams. On a similar basis, the characteristics for an effective architectural 'plan of work' is a clear and coherent programme of tasks and sub tasks and activities.

Yet, there is discrepancy between accepting the need for a common language / common process and the day-to-day practice within the industry. There is currently no statutory requirement to apply a 'plan of work' in work practices and the running of contracts, or a requirement for adoption of BIM protocols. Without such a legal mandate, the promotion of advisory standards and best practices will not be sufficient to support wide take-up within the architecture and construction sectors (Samuelson and Björk 2013). This is particularly acute within a retrofitting project where the significance of site survey and reality capture tasks are largely ignored or assumed to be within the remit of non-architectural professionals.

1.4 Aligning reality capture tasks to an architectural 'plan of works'

Our challenge was to find the appropriate means for aligning site survey and reality capture activities within a plan of works or process that could be project specific and used by a range of different professionals. These activities should include a range of possible options (Table 2) for survey methodology that allowed for the appropriate accuracy and / or format of the survey data based on the end-user applications.

Table 2: Hierarchical reality capture activities.

	task('parent' diagram)		sub tasks 1 ('child' diagram)		sub tasks 2
A-S	Reality capture	A-S.1	Measured survey		
		A-S.2	Photographic / photo matching survey		
		A-S.3	Photogrammetry survey		
		A-S.4	LiDAR survey	A-S.4.1	Ground level survey
				A-S.4.2	External conservation survey
				A-S.4.3	Combined external and internal survey
				A-S.4.4	Complex services survey
		A-S.5	Aerial survey	A-S.5.1	Photographic / Photogrammetry survey
				A-S.5.2	Thermographic survey
				A-S.5.3	LiDAR survey

In the application of the IDEF methodology, the most effective application of process mapping within practice is to tabularize the individual tasks or component processes in the form of an activity table (Damij 2007) as the starting point for understanding the overall business process. This then becomes suitable form linking and integration into a standardised flowchart. Thus, in short the simplified process we followed is as follows; (1) tabulate the high levels tasks and stages, (2) IDEF0 diagram produced for each of the 'parent' tasks, (3) breakdown high-level tasks and processes into any additional sub-processes, (4) IDEF0 diagram produced for each of the 'child' tasks, and (5) integrate and link these tasks into a flow chart.

2. REALITY CAPTURE

In undertaking a series of process mapping exercises and experiments, we have based our research on a number of 'live' architectural projects being undertaken within a small to medium sized practice in North Yorkshire. As a result of this pragmatism, these are opportunistic projects as much as selected case studies. However, they begin to illustrate how heuristic knowledge can be used to provide standardization and structure for a range of possible survey techniques. In each case study we begin by describing the input and output requirements needed for the particular application. In most cases this related to the employer information requirements (EIR) and the detail from the project execution plan when they actually existed. Added to this was a review of controlling factors; typically, these related to national regulations, professional standards and local planning conditions; and the particular mechanisms; such as equipment, materials, software, skills; needed to undertake the task / activity. This record formed the basis of the IDEF 'parent' diagram. Below this hierarchical level, details for each sub-task / activity was broken down into sequential actions as the basis for the 'child' diagram. In practice, these sub-tasks and sequencing are a set of instructions. In setting out the sequence of sub-tasks and creating a visual record, they have proven to be useful as the basis for knowledge transfer and supporting in-house / stakeholder training.

2.1 Measured survey

As part of the entrance remodeling of a Georgian theatre in Stockton-on-Tees, we tested the approach to process mapping a standard approach to undertaking a measured survey. The record is based on collaboration with the surveyor as part of the primary survey process. It describes the measurement of the building façade and significant physical features against a fixed measuring control point.

Table 3: Tabulation of IDEF0 process mapping requirements for undertaking a measured survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
Measured survey	Employer Information Requirements; Project Execution Plan	RICS Method (Code of measuring practice 6th edition)	Measuring equipment (Disto, laser measure); Total station / Theodolite (GPS logger / autolevel); Qualified professional (RICS / RIBA)	Field notes, annotated drawings

Fig. 3: Sequence of tasks for undertaking measured survey.

The output requirements were a simple set of measured drawings provided in a suitable digital format. The output itself was limited to two dimensions but became the basis for a three dimensional geometric model. Key reference points in the survey were typically the changes in materials, junction points and corners of windows and doors. The entire survey was limited to dimensions and held no parametric data, although annotations and field notes were included as part of the survey record.

2.2 Photographic / photo matching survey

A basic three-dimensional model was created for a North Yorkshire school block based on an historic set of design drawings. The intention was to undertake a simple energy assessment prior to and following refurbishment and the addition of insulation, new glazing and external cladding.

Table 4: Tabulation of IDEF0 process mapping requirements for undertaking a photographic survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
Photographic survey	Project Execution Plan; Field Notes (annotated drawings)	Employer Information Requirements (specification)	Camera (colour / lens); Open source images (*StreetView*); Photomatching software (*Sketchup*, *Photoshop*, *3D Max*)	Rectified images (matched images and / or textures)

A photo-matching survey was undertaken with the intention of checking the accuracy of the provided set of drawings and highlight differences between the design and as-built project. The requirement was for a single rectified image with a clear visible reference point against which we could align the digital model. For simplicity, we used the corner and building vertices. With the geometric digital model superimposed over the reference image within suitable software, we were able to and manipulate the simple model geometry. To this basis model we were able to add some performance parameters relating to materials and thermal characteristics. The output model became the input data for an energy assessment.

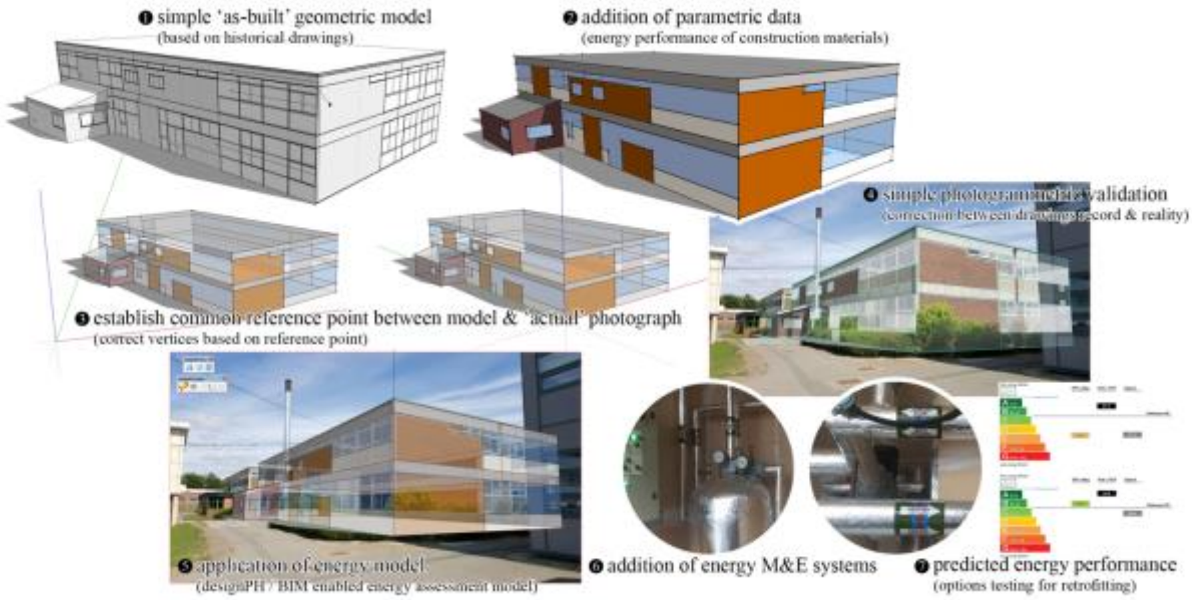

Fig. 4: Sequence of tasks for photo matching to adapt a geometric model for energy performance calculation.

2.3 Photogrammetry survey

We re-examined the Georgian theatre using a structured photographic survey with the intention of using the set of photographs to construct the building geometry in three dimensions. Photogrammetry is increasingly being used as a low-cost approach to survey and model generation in the architecture and construction sector and the practice was interested in exploiting this new technology. Like the other visual survey methods above, the use of photogrammetry uses 'line of sight' technologies and thus requires a structured approach to survey to ensure complete coverage of the site, building or object modelled.

Table 5: Tabulation of IDEF0 process mapping requirements for undertaking a photogrammetry survey.

Activity A-3.1.3	Input	Controls	Mechanisms	Outputs
Photogrammetry survey	Employer Information Requirements; Project Execution Plan	Best practice method statement (Autodesk)	Camera (specification requirements for colour / resolution / lens); GPS (in-built geo referencing system within scanning equipment); Aerial (manned and / or unmanned airborne vehicle); Qualified professionals (RICS, RIBA, RTPI)	Digital images with associated metadata

Central to this structured survey is the linking of embedded GPS data with high-resolution cameras, particularly via the growth in number and functionality of smartphones. The fact that the key 'mechanism's for the workflow have become integrated in a single technology has, in part, simplified the stage of image capture. However, we found there is still the need for semi-skilled professionals, who understand the approach needed for structured data acquisition using a photographic survey and 3D data reconstruction. Often it will be the same professional undertaking the survey who will be processing the data collected. Thus, perhaps the core control for this specific activity is the actual specification and selection of the camera and geo-referencing systems to ensure the output model is suitable for the intended process and manipulation software. In this instance, multiple view images have been used (Po-Han *et al*. 2012) in the creation of sparse point cloud models, which itself becomes the basis for the generation of a mesh and solid model object.

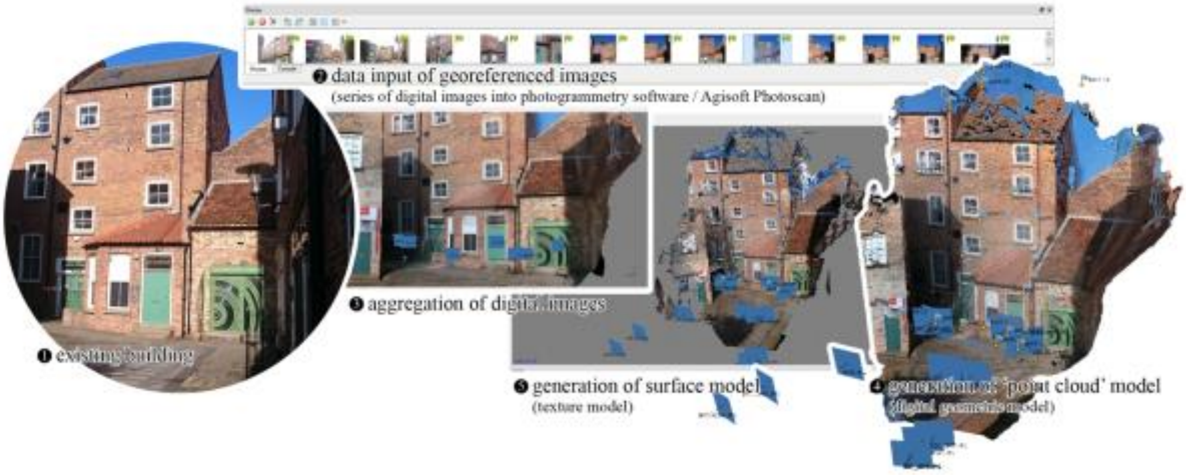

Fig. 5: Sequence of tasks for undertaking ground level photogrammetry survey.

Recent comparative workflow, software analysis and evaluation on the application of terrestrial photogrammetry (Niederheise *et al*. 2016) suggests the choices between different applications is one around the need for customisation versus the user-friendly interface. Similar comparative analysis (McCoy 2014) of the different technical (hardware and software) options have been explored for wider reality capture applications and the generation of useful 3D computer models for other stages within any construction workflow and / or 'plan of work' such as design / refurbishment / reconstruction, options modelling through to construction monitoring. Thus, in practice, it will be the availability of processing software with the supporting skills in the use of the software that will determine the accuracy of the resultant geometric model.

2.4 LiDAR survey

We then explored the process of undertaking a terrestrial LiDAR survey as part of the remodeling and extension of an industrial pharmaceutical plant in North Yorkshire. In this instance, we required external consultants to undertake the actual survey but observed and informed by staff from the architectural practice. This had much in common with a simple terrestrial measured survey in requiring reference / control points and a structured approach to covering the entirety of the property.

Table 6: Tabulation of IDEF0 process mapping requirements for undertaking a LiDAR survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
LiDAR survey	Project Execution Plan	Employer Information Requirements (specification)	Laser Scanner; Control points (checkerboard and / or prominent geometry); GPS (in-built into scanning equipment)	Digital point cloud

We found that the approach was informed by the end-use of the data and the level of accuracy needed. It thus benefited from members of the design team being more closely engaged with the survey specification, even if this was not set out explicitly within the initial EIR. Having prior knowledge of the BIM environment used for the design stages helped with data exchange and interoperability (and consequently better accuracy by avoiding unnecessary data conversion stages). It could also help with over-specification and the reduction in time and resultant costs on the project. Indeed, it was questionable if the level of detail and accuracy required actually needed a LiDAR survey whenever the data for the existing structure was external, largely contextual and of a level more appropriate for a photogrammetry survey.

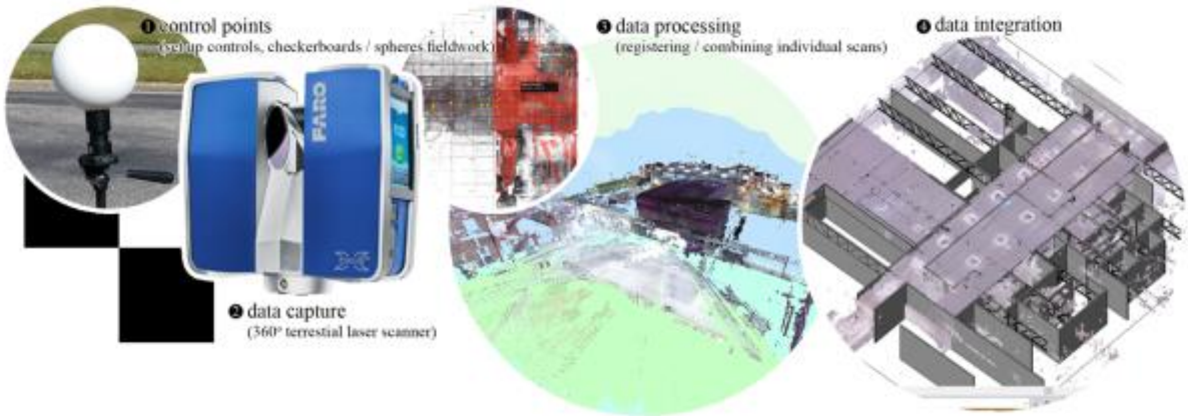

Fig. 6: Sequence of tasks for undertaking ground level LiDAR survey.

2.4.1 LiDAR External conservation survey

In comparison to a similar survey process undertaken for a conservation project on Durham Cathedral, the controls and mechanisms were constant, as were the limitations of a ground level survey. However, the inability to view the roof structures via line of sight became a restricting factor whenever there was a requirement to convert the LiDAR dense point cloud into an object orientated model. Certain assumptions had to be made in the tracing or conversion of the LiDAR point cloud to an object and resulted in potential errors and inaccuracies being introduced.

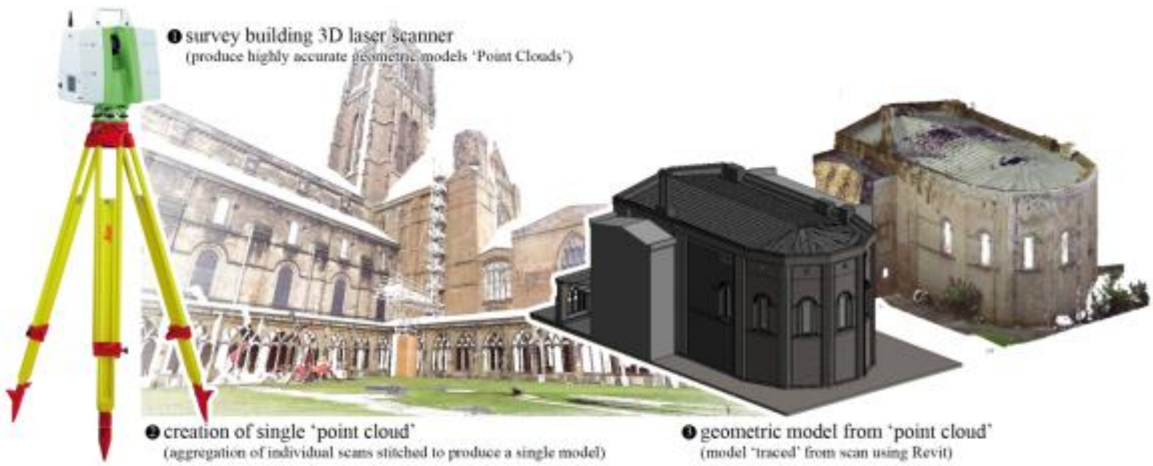

Fig. 7: Application of LiDAR survey process for external ground level building conservation survey.

2.4.2 LiDAR External and internal survey

The need for an object-orientated model to be produced from the survey was a common factor in other LiDAR data sets. We explored examples where there was a requirement for parameters to be added to the model for both internal and external applications. For example, interior architecture designs required highly accurate information to meet the EIR / statutory pharmaceutical industry requirements. Reality capture using a mix of internal and external ground level LiDAR allowed for the design team to review the accuracy of an existing object-orientated model. The LiDAR data included additional information regarding materials and textures that were valuable for several design-stage tasks including compliance checking and visualisation.

When the LiDAR survey process was based on a full appreciation of the application in the later project stages it helped with a more intelligent approach to the specification of reality capture together with a more flexible use of the data sets whenever this was appropriate. One example was in the use of variable specification and hybrid models (Figs. 8 & 9) that mixed dense point-cloud data sets with object-orientated models. This was possible for both internal and external data sets when the extension or adaptation was limited to part of the initial structure and where only the new design interventions required parametric data and higher levels of detail. In this instance, the survey process, controls and mechanisms remained constant, but the end-use applications of the data became an important input to undertaking the task. In integrating the survey process to the overall project in this way it helped to approach the survey in a more bespoke manner, avoid over specification in accuracy / detail and save time in data processing, conversion and integration.

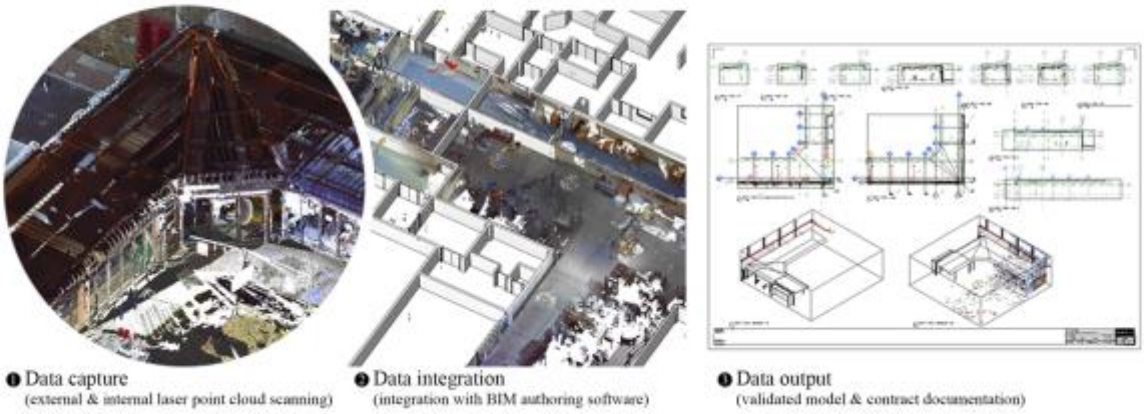

Fig. 8: Sequence of tasks for LiDAR internal / external ground level survey.

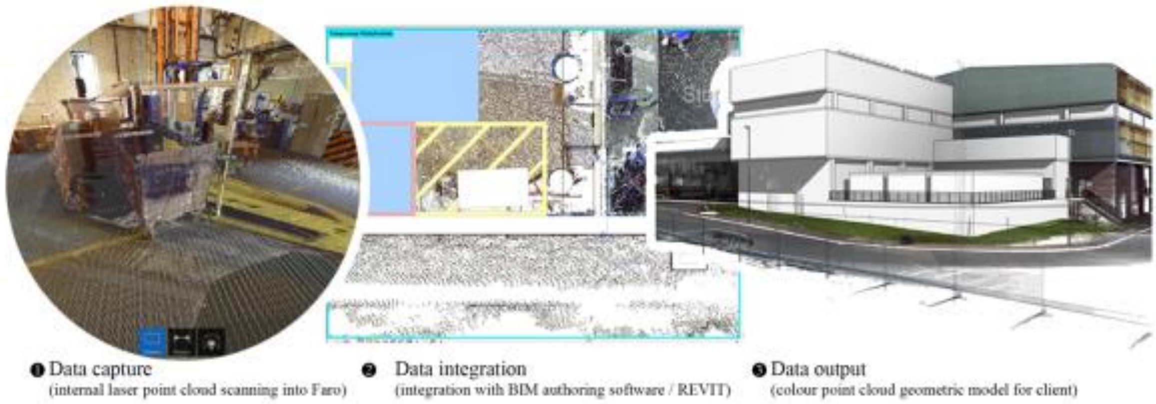

Fig. 9: Direct use of point cloud LiDAR ground level survey.

2.4.3 LiDAR complex services survey

One final application of LiDAR data was in the approach to surveying complex services and structures. Drawing examples from another pharmaceutical building, we explored complex pipework and external structures that had potential risks around clashes that had significant implications for the operation of the facility if they arose.

Fig. 10: LiDAR ground level survey of complex services.

Here the specification for the survey in level of detail, accuracy and interoperability of data ensured that clashes between external structures and M&E services were avoided. Indeed, this specific example of high quality survey data based on the appropriate specification reduced the need for on-site construction supervision, increased the speed of the project delivery and consequently reduced the direct project costs compared to similar projects undertaken by the practice for the same client.

3. AERIAL SURVEY OPTIONS

The limitations of terrestrial survey processes led us to explore the options for reality capture using aerial survey methods. In practice this was about supplementing rather than replacing ground level survey data with some form of hybrid model that could use data collected by unmanned drone. Commentators have highlighted the growing importance and application for the use of unmanned drones (Colomina and Molina 2014) to undertake aerial surveys and fill many of the procedural gaps highlighted within the preceding reality capture methods above. The use of drones is cost-effective (Fernández-Hernandez *et al*. 2015) in many instances and examples.

Table 7: Tabulation of IDEF0 process mapping requirements for undertaking an aerial survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
Aerial survey	Safety case / Risk assessment (for one-off flight) Operating manual (permanent approval)	Landowner permission Flight permission, PFAW (Permission for Aerial Work from the CAA) Pilot competence assessment process Operator insurance	Drone with attachments Operating manual NQE training (National Qualified Entities)	Survey photographic data with associated metadata LiDAR data

Fig. 11: External photogrammetry and thermal imagery survey.

The sequencing of tasks for drone-based aerial survey was significantly more concerned with the safe and efficient operation of the drone equipment. The process required the preparation of a flight plan; a pre-flight check; setting / programming of optimised survey route over the study site (in this example it comprised of a survey grid geolocation / height and size optimised for both 2D and / or 3D output model); undertaking an automated survey flight (following the pre-determined survey grid); an additional manual survey flight (providing supplementary data to ensure total coverage, particularly at lower levels for building façades – potential for additional ground level photographic survey to provided set of survey images form more than one camera).

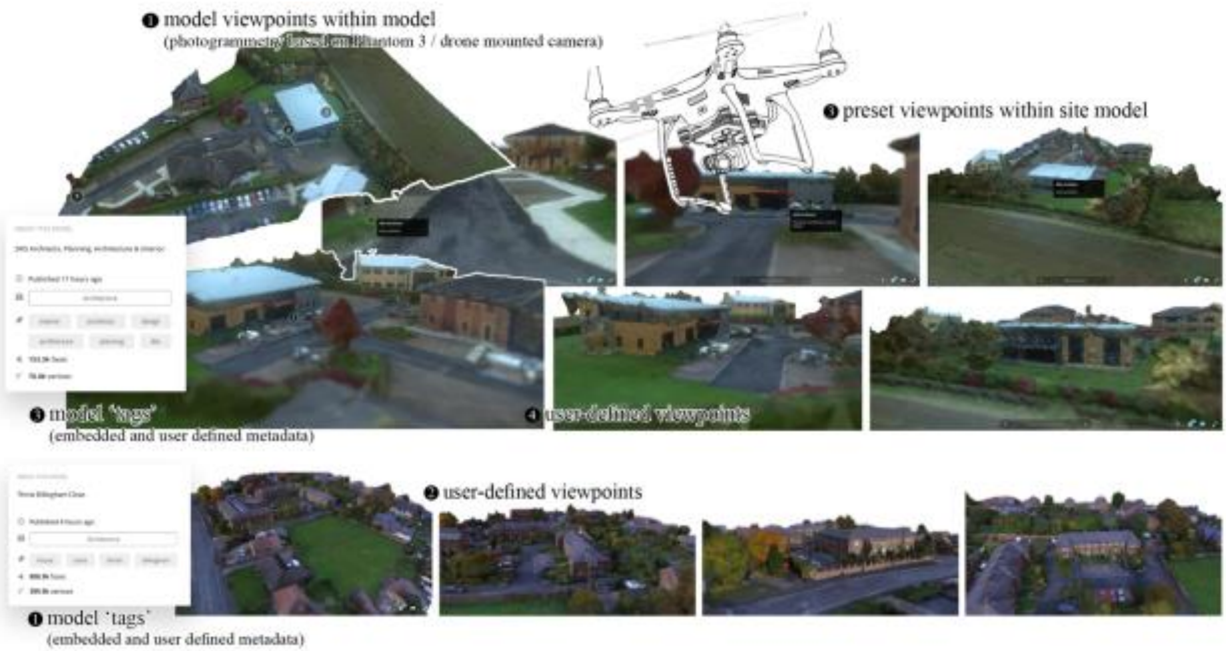

Fig. 12: Initial Drone photogrammetry site survey(s).

4. EVALUTION OF REALITY CAPTURE OPTIONS

This exploration of the different reality capture techniques currently available for a small to medium architectural practice has been undertaken in the context of the development of a practice-wide BIM execution plan. The interest and emphasis on digital survey methods and processes is commercially significant to the practice given the scale of refurbishment and retrofitting projects. Yet understanding how the reality capture processes relates to the overall design process, including many wider professional collaborators has been valuable for many different reasons.

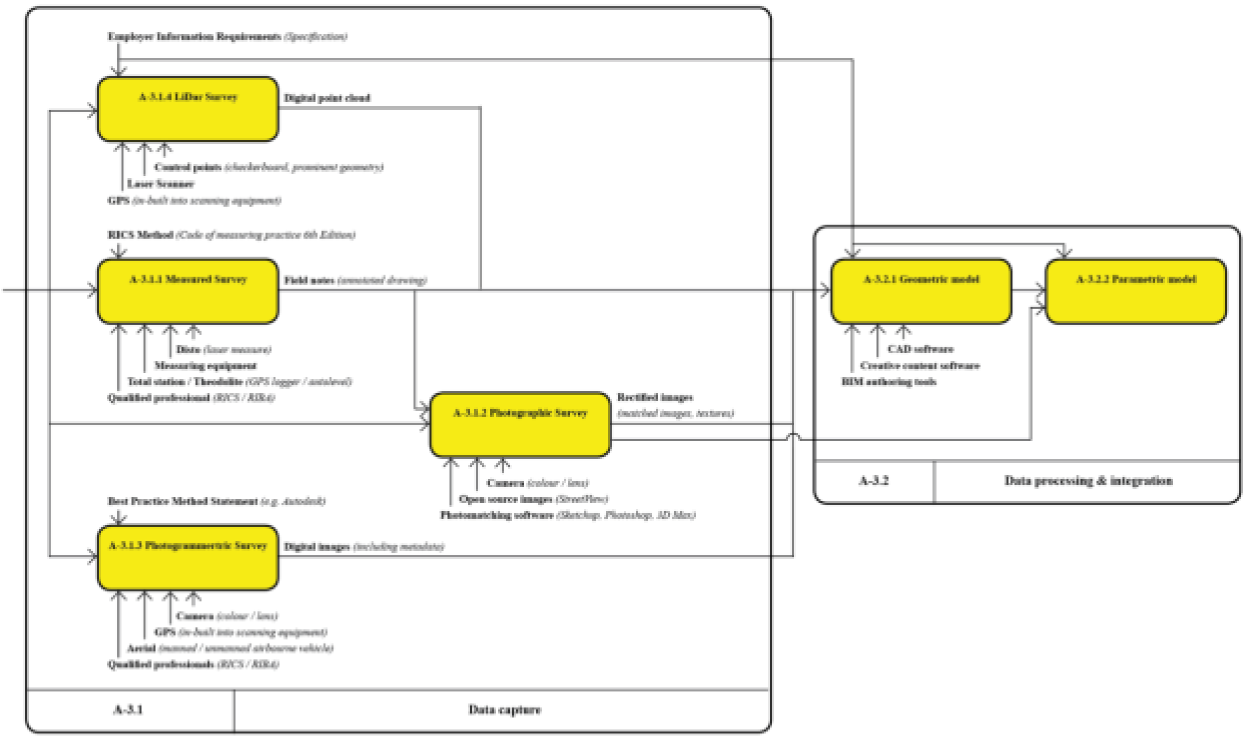

Fig. 14: Development of integrated IDEF0 process map of reality capture methods.

There is more clarity in how reality capture processes fit into current bespoke office procedures and more generic plan of works. IDEF process mapping (fig. 14) has supported the systematic consideration, visualisation and evaluation of specific tasks. Even when the detail around the task is not necessary for the design team, their involvement has allowed for more intelligent choices and technical specifications in initial survey work. Historical practices have been challenged from this learning process. Many of the procedural options are within reach of the practice and they are less reliant on other consultants to undertake survey activities. The relationship between the data management, modelling and integration is more clearly understood with regard the initial survey requirements. There is added-value for the practice in getting involved in the initial survey specification, even when they are unable to undertake it directly.

Ultimately the practice can see how reality capture fits into a wider BIM and information strategy with the resultant efficiency and cost benefits. While the work is not comprehensive, the approach to process mapping can continue to be utilised and extended as the work develops. Each of the specific processes and sequencing of tasks is adds value to in-house training and client communication as the BIM execution plan is prepared.

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