ANNEX D

CLOSEUP ON BIM PRINCIPLES

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D.1. COMPLEMENTARY TABLES

D.1.1. BIM knowledge framework

BIM Fields — players, deliverables and interactions

		Policy Field	Process Field	Technology Field
Definition		Policies are "written principles or rules to guide decision-making" [13]	Process is "a specific ordering of work activities across time and place, with a beginning, an end, and clearly identified inputs and outputs: a structure for action" [18]	Technology is "the application of scientific knowledge for practical purposes" [65]
Extended Field Definition		The field of interaction generating research, talents, standards and best practices for the purpose of safeguarding benefits and minimizing contestation between AECO stakeholders	The field of interaction between design, construction and operational requirements for the purpose of generating and maintaining structures and facilities	The field of interaction between software, hardware, equipment and networking systems for the purpose of enabling or supporting the design, construction and operations of structures and facilities
Players (sub-field)		Governments, researchers, educational institutions insurance companies and regulatory bodies, …	Owners, operators, architects, engineers, estimators, surveyors, developers, contractors, sub-contractors suppliers, fabricators, facility managers, …	Software, hardware, network and equipment companies plus their development and sales channels
Deliverables (sub-field)		Regulations, guidelines, standards, best practices, bench marks, contractual agreements, educational programmes	Construction products and services including drawings, documents, virtual models/components, physical components, structures and facilities	Software, hardware, peripherals, network solutions, and office/ site equipments
Sample interactions between fields and sub-fields	Push into other fields	– Skilled graduates, standards, guidance into Process – Concepts, mathematical solutions into Technology	– Case studies into Policy – Feedback to Technology	Innovative solutions and new equipment into Policy and Process
	Pull from other fields	– Subject matter experts from Process – Interoperability from Technology	– Development of solutions from Technology – Standards, guidelines and graduates from Policy	– Standardisation efforts from Policy – Requirements and experiences from Process
	Push–pull within the same field	Interchanges between research, education and accreditation boards	Architect's Instructions (AI-push) and Request Further Information (RFI-pull)	Hardware capabilities (push) and software requirements (pull)

Table 1: *BIM fields – players, deliverables and interactions [5]*

Project Lifecycle Phases and sub-phases

Design phase		Construction phase		Operations phase	
D1	Conceptualisation, programming and cost planning	C1	Construction planning and construction detailing	O1	Occupancy and operations
D2	Architectural, structural and systems design	C2	Construction, manufacturing and procurement	O2	Asset management and facility maintenance
D3	Analysis, detailing, coordination and specification	C3	Commissioning, as-built and handover	O3	Decommissioning and major re-programming

Table 2: *Project lifecycle phases and sub-phases [5]*

D.1.2. BIM technology

Table 2–1 Built-In Base Object Families in Major BIM Architectural Design Applications

BIM DESIGN Tool / Base Objects	ArchiCAD v14	Bentley Architecture v8.i	Revit Architecture v2011	Vectorworks 2010	Digital Project V1, R4, SP 7
Site model	Mesh tool, site objects	(Contoured model)	(Topo surface) & site objects	In Landmark product	Surface model
Space definition	■ (manual)	■ (manual)	■ (automatic)	■ (manual)	■ (automatic)
Wall	■	■	■	■	■
Column	■	■	■	■	■
Roof	■	■	■	■	
Stair	■	■	■	■	■
Slab	■	■	■	■	■
Zone	Zone	Zone	Area	Area	
Beam	■	■	■	■	■
Unique Objects for Each Platform	Cast-in-place, precast concrete, steel, masonry, thermal & mois-ture, furnish-ings, equipment, conveying systems, plumbing, HVAC, electrical, site	Curtain walls, truss, plumbing, toilet accessories, handrails, shelving, shaft	Area, component, ceiling curtain system, curtain grid, mullion, truss, beam system foundation items, ramp, railing	Window wall, mech. equipment, kitchen cabinet, railing, elevator, escalator, rail, pipe fittings, duct fittings, mechani-cal equipment	Pipe, duct, mech. equipment, railings, opening, opening profile construction equipment

Table 3: *Predefined object families for main BIM architectural platforms [4]*

Table 2–2 Predefined Objects in Some Common Construction/Fabrication BIM Tools

BIM Detailing Tool Base Objects	Tekla v16.1	Design Data SDS/2	Revit MEP v9.1 (Objects)	AutoCAD MEP (Objects & Blocks)	Bentley Mechanical and Electrical v8.i
Base Objects	Part Beam Polybeam Contour plate Welds Weld Logical weld Polygonal Weld Loads Load line Load area Load point Bolts Bolt array Bolt circle Bolt list Reinforcing Rebar strand Rebar mesh Single rebar Rebar group Rebar splice Task type	Grid lines Member Material Connection Bolts Holes Welds Loads Moments	Air terminals Communication devices Cable tray Connectors Conduit Connectors Duct fittings Duct accessories Duct connectors Electrical devices Elect equipment Elect. fixtures Fire alarm dev. Flex duct Flex pipes HVAC zones Lighting devices Lighting fixtures Mech. equipment Nurse call devices Pipe accessories Pipe connectors Plumbing fixtures Space	Cable tray Cable tray fitting Conduit Conduit fitting Device Duct Duct custom fitting Duct fitting Duct flex Engr. space Hanger Multiview part Panel Pipe Pipe custom fitting Pipe fitting Plumbing line Schematic line Pipe flex Plumbing fitting Wire Space	**Mechanical:** Ducts Pipes Connectors Valves Grills & Diffusers Dampers Filters Silencers **Electrical:** Cable trays Power distribution – Lighting – Fire alarm – Emergency Lighting Telecommunications – Information technologies – Security – Public address – Lighting protection – Video – EIB Spaces Engineering zones
Knowledge Functionality	☐ Clash detection ☐ 4D simulation ☐ Work packet coordination ☐ Quantity take-offs ☐ Supports automated fabrication ☐ Interfaces to multiple structural analysis tools	☐ Automatic connection design ☐ Erectability checks ☐ Quantity take-offs ☐ Supports automated fabrication ☐ Interfaces to multiple structural analysis tools	☐ Synchronized schedules ☐ Duct and pipe sizing/pressure calculations ☐ HVAC and electrical system design ☐ Conduit and cable tray modeling ☐ (gbXML) interface for use with Autodesk® Ecotect® Analysis software and ☐ Autodesk® Green Building Studio® Web-based analysis and IES	☐ Synchronized schedules ☐ Interfaces for fabrication ☐ Automatic duct sizing based on space demands ☐ Electrical circuit manager ☐ Interference checking ☐ Radiator sizing and number ☐ Plumbing pipe sizing	☐ Exchange data with energy analysis programs such as EDSL/TAS, ECOTECT, Trace 700, Carrier HAP, Green Building Studio, etc. ☐ Feeder and branch circuiting ☐ Automated circuiting and labeling ☐ Online design checks for circuit load, length, and number of devices ☐ Automated fixture arrangement ☐ Bidirectional links to third-party lighting analysis programs: – Lumen Designer – DIALux – Relux

Table 4: Predefined object families for main construction-oriented BIM platforms [4]

D.2. BIM SOFTWARE REVIEWS

D.2.1. Introduction

This annex intends to describe major BIM software platforms and their features. A proposed framework for BIM software is described to organise these features and facilitate their comparison. A brief view on lightweight BIM model viewers is also given.

The provided framework for BIM software and the overviews on major BIM software platform and lightweight viewing applications have been extracted from *The BIM Handbook*, by Eastman et. al. [4]

Additionally, at the end of this annex two lists are provided. The first one gives external links to reviews of the latest versions of market-leading BIM software tiles. The last one intends to offer a complete enumeration of the most relevant AEC-related BIM software titles grouped by area of application, with their respective links to vendor's webpages.

D.2.2. BIM software performance framework

Building Information Modelling technology has a vast potential, and relies in parametric modelling as a fundamental approach to project design and information use.

All BIM software titles can be seen as a tool for design of building object components and their management. Most BIM software titles offer pre-defined sets of basic building object components. These objects cover the basic components that BIM users will use for design and other tasks. As these sets are fairly basic, BIM software allows their modification and extension. Various instances of object classes can be created, and their data attributes modified. This way, BIM users are able to use customized objects, with varying geometry, attributed information and behaviour. Their behaviour is understood as the automatic updates encountered when the environment changes.

To take full advantage of BIM capabilities such as analyses, schedules and quantity take-offs, BIM users have to specify and adjust to their need the attributes of building object components. Users will also have to define the level of object 3D detailing depending on the use it will serve. For instance, fabrication models will need detailed definitions of building object components.

Nevertheless, BIM goes beyond parametric modelling and further distinctions can be made between the features offered by diverse commercial software vendors. There is a wide range of BIM software titles, some are fairly general and others are destined to various specific tasks and sectors within the AEC industry. BIM users will see these software titles in different ways, depending on their use. Some may be seen as a **tool** for specific tasks, usually related to a **platform** for managing data within a model and using it for other purposes. Others will see them as BIM **environments** that allow them to manage information in diverse BIM models.

To further analyse and compare BIM software titles at their different levels, the following definitions are provided:

BIM tool: It is an application that serves a specific use. They generate stand-alone outcomes, or deliverables. Ex: Rendering, drawing generation, energy analysis, cost estimate, clash detection, etc.

BIM platform: It is an application destined for design that allows for object oriented information modelling and management. It hosts this information for re-use by industry-specific tools. It also serves as an interface for its platform-embedded applications.

BIM environment: It allows the data management of the different tools and platforms used within an organization. This organization may be a firm itself or an entire collaborating project team. Its basic purpose serves the automatic generation, sharing and management of datasets for all BIM applications used in an organization. It can also be destined to information sharing and control over these communications. BIM clouds and servers best represent BIM environment capabilities. Among information shared, the following can be found: BIM models, object libraries, external tools files, etc.

Commonly understood as both tools and platforms, BIM software titles can be described and compared amongst each other. There are basic parameters that users will perceive and distinguish when using them:

As a tool:

- Sophistication of its predefined base objects
- Ease of generation of new object families and classes
- Ease of use; User-friendly interfaces
- Complex surface generation capabilities
- Drawing generation capabilities
- Coping with a large number of objects
- Additional tool capabilities

As a platform:

- File size management; Performance with large or high-detailed models
- Interfaces with industry-specific BIM tool software
- Tool interface consistency with user's discipline
- Extensibility; Software functionality enhancement and customization[1]
- Interoperability
- Support of collaboration amongst project players

[1] Extensibility can be supported through BIM software vendor provided scripting languages or excel interfaces. New customized applications can be developed with Application Programming Interfaces (API).

- Completeness of predefined object libraries and availability of external libraries
- Effective object property set management

As an environment:

- No BIM software can effectively support the whole of a project's modelling, analysis and fabrication capabilities itself. Nevertheless, their support to BIM environments can be described.

D.2.3. BIM platform reviews

Perception of BIM software performance by users may vary depending on whether they are architects, engineers, contractors, owners or facility managers. Although BIM software titles may be generic or targeted to a certain sector of the AEC industry, the provided reviews have a generic approach to their capability analysis.

The framework of BIM software levels and capability parameters previously provided will be used in the following reviews.

Revit

We consider the Revit platform from the perspective of Revit Architecture. Revit is the best-known and current market leader for BIM in architectural design. It was introduced by Autodesk in 2002 after Autodesk acquired the Revit program from a startup company. Revit is a completely separate platform from AutoCAD, with a different code base and fi le structure. The version reviewed here is 2011. Revit is a family of integrated products that currently includes Revit Architecture, Revit Structure, and Revit MEP. It runs on Windows OS and on Macs, using the Windows BootCamp® plug-in. It runs on both 32- and 64-bit processors and versions of the OS.

As a tool: Revit provides an easy-to-use interface, with drag-over hints for each operation and smart cursor. Its menus are well organized according to workflow and its operator menus grey-out non available actions within the current system context. Its drawing generation support is very good; its drawing production is strongly associative, so that drawing releases are easily managed. It offers bidirectional editing from drawings to and from the model, and also bidirectional editing from schedules for doors, door hardware, and the like. Revit supports the development of new custom parametric objects and customization of predefined objects. Its rule set for defining objects has improved with each release and includes trigonometric functions. It can constrain distances and angles and the number objects in an array. It also supports hierarchical relations of parameters. Thus, an object can be defined by using a group of sub-objects with parametric relations. It is more difficult to set up global parameters that can constrain assemblies of objects' layout and sizes. The release of the current API provides good support for external application development.

Revit has a very large set of product libraries, particularly its own Autodesk SEEK library for specification and design objects. It carries information for about 850 different companies, and about 13,750 different product lines (including over 750 light fixtures). The products are defined in a mixture of file types: RVA, DWG, DWF, DGN, GSM, SKP, IES, and TXT. They are accessible from Masterformat, Uniformat, and Omniclass formats. There are about a half-dozen other sites with BIM products, where Revit objects dominate.

As a platform: Revit, as the BIM market leader, has the largest set of associated applications. Some are direct links through Revit's Open API and others are through IFC or other exchange formats. These are denoted (Dir) and (IFC), respectively. DWF is another interface for Revit, denoted (Dwf).

• *Structural (with Revit Structure):* Revit Structure (Dir), ROBOT (Dir), and RISA structural analyses (IFC), BIM ME S.A.R.L. ETABS Link, SismiCAD for FEA analysis, Graitec's Advance and ARCHE, Fastrak Building Designer, StruSoft FEM-Design, SOFTEK S-Frame, STAADPRO via SIXchange, SOFiSTiK

• *Mechanical (with Revit MEP):* Revit MEP (Dir), HydraCAD (fi re sprinklers), MagiCAD (mechanical design), QuantaCAD (mechanical laser scanning for as-builts), TOKMO (COBie facility operators handover— see Chapter 3)

• *Energy and environmental:* Ecotect, EnergyPlus, IES all indirect, Green Building Studio via gbXML

• *Visualization:* Mental Ray (Dir), 3D Max (Dir), Piranasi

• *Facility management:* Autodesk FMDesktop® (Dwf), Archibus (IFC)

Revit interfaces with AutoCAD Civil 3D for site analysis, Autodesk Inventor for manufacturing components, and with LANDCADD for site planning. It interfaces with US Cost, Cost OS by Nomitech, Innovaya, and Sage Timberline and also with Tocoman iLink for quantity take-off for cost estimation. Innovaya also provides 4D simulation links with Primavera and MS Project schedules. Revit also supports links to Autodesk Navisworks through DWF. VICO Office supports both scheduling and quantity take-offs. Revit has links with specifications to e-SPECS® and BSD SpecLink through the BSD Linkman mapping tool. Revit is able to import models from SketchUp, AutoDesSys form•Z®, McNeel Rhinoceros®, Google™ Earth conceptual design tools, and other systems that export DXF files. Previously, these were visible but not referencable. They are now referencable in Version 2011 ("referencable" here means that users can select points on the objects, allowing dimensionally accurate referencing, rather than visual dimensional coordination).

Revit Architecture supports the following file formats: DWG, DXF, DGN, SAT, DWF/DWFx, ADSK (for building component), html (for area report), FBX (for 3D view), gbXML, IFC, and ODBC (Open DataBase Connectivity).

Revit is a strong platform, especially because of its range of supporting applications.

As an environment: Autodesk earlier invested in Web server capabilities, such as Buzzsaw and Constructware. These existed from the 1990s using file level support, with no visible strategy to support multiple platforms.

Revit carries object IDs and seems to manage them well. However, version and change information is carried at the fi le level, not at the object level. This limits synchronization of objects with different views in different files. Revit is a platform but not a BIM environment. It needs to be able to manage objects, similar to ArchiCAD's DELTA Server capability, if it is to support large-scale BIM environments.

Revit's strengths: As a design tool, Revit 2011 is strong; it is intuitive; its drawing production tools are excellent. However, many designers wishing to go beyond the built-in objects' limitations use other tools to design in a more freeform manner, and then import the results into Revit for production modelling. Revit is easy to learn and its capabilities are organized in a well-designed and user-friendly interface. It has a very broad set of object libraries, developed both by themselves and by third parties. Because of its dominant market position, it is the preferred platform for direct link interfaces with other BIM tools. Its bidirectional drawing support allows for information updates and management from drawing and model views, including schedules. It supports concurrent operation on the same project. Revit includes an excellent object library (SEEK) that supports a multiuser interface.

Revit's weaknesses: Revit is an in-memory system that slows down significantly for projects larger than about 300 megabytes. It has a few limitations on parametric rules. It also has only limited support for complex curved surfaces. Lacking object-level timestamps, Revit does not yet provide needed support for full object management in a BIM environment.

Bentley Systems

Bentley Systems offers a wide range of related products for architecture, engineering, infrastructure, and construction. Their architectural BIM tool, Bentley Architecture, introduced in 2004, is an evolutionary descendant of Triforma, an earlier product. This review is from the perspective of Bentley Architecture. The reviewed version is V8i-08.11.07.80. It runs on top of Microstation V8.i. These run on both 32- and 64-bit processors. Bentley is a major player in the civil engineering and infrastructure marketplace.

As a tool: As a building modelling and drawing production tool, Bentley has a standard set of predefined parametric objects (see *Table 4*). These have relations between each other. The predefined parametric objects can only be extended through the MDL Application Programming Interface (API). Bentley also supports custom parametric objects, using the Parametric Cell Studio module; Global- or Assembly-level parametric modelling is supported by Generative Components. Each of these different toolsets has objects with different behaviour and cannot support relations with objects generated by a different toolset. Bentley has good freeform B-spline surface and solid modelling capabilities. Its Luxology integrated rendering engine is fast and provides high-quality renderings and animations. For drawing production, 2D detailing and annotation on a 3D model section are well supported. For drawing editing, the predefined objects are bidirectional, but the other objects must be edited in the model to be updated. Its drawing capabilities are strong, showing actual line weights and text. It is easy to add properties to object classes. Its user interface has good features: drag-over operator hints, a smart cursor, and user definable menu setups. Bentley Architecture, with its various modules, is a large system, with lots of functionality but is less easy to access and become proficient in. Bentley Architecture supports import of external objects and clash detection.

As a platform: Bentley Microstation platform applications are file-based systems, meaning that all actions are immediately written to a file and result in lower loads on memory. The system scales well. In addition to its base design modelling tools, Bentley has a large array of additional systems, many of which acquired in support of its civil engineering products. These include:

- Bentley Speedikon Architectural
- Bentley PowerCivil
- RAM Structural System
- RAM Steel
- RAM Frame
- RAM Connection
- RAM Foundation
- RAM Concrete
- RAM Elements
- RAM Concept
- GEOPAK Civil Engineering Suite
- Bentley Building Electrical Systems V8i for AutoCAD
- Facility Information Management
- ConstructSim
- Bentley PowerRebar
- Bentley Rebar
- ProConcrete
- STAAD.Foundation
- STAAD.Pro
- Bentley Building Mechanical Systems

- Bentley Tas Simulator
- Hevacomp Dynamic Simulation
- Hevacomp Mechanical Designer

Some of these products were acquired by purchasing small third-party companies and have only limited compatibility with others within the same platform. Thus a user may have to convert model formats from one Bentley application to another. User cognition sometimes must change because user interface conventions also vary.

Primavera and other scheduling systems can be imported and grouped with Bentley objects for 4D simulation. Bentley Architecture interfaces include: DWG, DXF, PDF, U3D, 3DS, Rhino 3DM, IGES, Parasolid, ACIS SAT, CGM, STEP AP203/AP214, STL, OBJ, VRML, Google Earth KML, SketchUp, Collada, and ESRI SHP. Its public standard support includes IFC certification, CIS/2 STEP, and SDNF. Bentley products are extensible. It supports user-defined Macros, Microsoft (VBA) .NET, C, C#, and Bentley MDL.

As an environment: Bentley offers a well-developed and popular multi-project server, called ProjectWise. It supports replication of files to a prearranged set of local sites, managing the consistency of all files. It is file- and not object-based. It supports links to manage relationships between DGN, DWG, PDF, and Microsoft Office documents. Bentley supports Object IDs and timestamps and their management on round-trips.

Bentley System's strengths: Bentley offers a very broad range of building modelling tools, dealing with almost all aspects of the AEC industry. It supports modelling with complex curved surfaces, including Bezier and B-splines. It includes multiple levels of support for developing custom parametric objects, including the Parametric Cell Studio and Generative Components. Its parametric modelling plug-in, Generative Components, enables definition of complex parametric geometry assemblies and has been used in many prize-winning building projects. Bentley provides scalable support for large projects with many objects. It provides multiplatform and server capabilities.

Bentley System's weaknesses: Bentley's large product offerings are partially integrated, at the data consistency and user interface levels. It thus takes more time to learn and navigate. Its heterogeneous functional modules include different object behaviours, further adding to learning challenges. The weaknesses in the integration of its various applications reduce the value and breadth of support that these systems provide individually.

ArchiCAD

ArchiCAD is the oldest continuously marketed BIM application for architectural design. Graphisoft, the parent company, began marketing ArchiCAD in the early 1980s. Headquartered in Budapest, Hungary, Graphisoft was acquired in 2007 by Nemetschek, a German CAD company popular in Europe, with strong civil engineering applications. The reviewed version of ArchiCAD is Release 14.0. ArchiCAD supports the Mac platform in addition to Windows.

ArchiCAD is a 32-bit application that runs on both 32- and 64-bit versions of the Windows or the Mac Snow Leopard OS.

As a tool: ArchiCAD's user interface is well crafted, with smart cursors, drag-over operator hints, and context-sensitive operator menus. Its model generation and ease of use is loved by its loyal user base. Drawing generation in ArchiCAD is automatically managed by the system; every edit of the model is automatically placed in document layouts; details, sections, and 3D images can be easily inserted into layouts. Drawings are treated as reports and are not bidirectional. As a parametric modelling tool, ArchiCAD incorporates a very broad range of predefined parametric objects. It includes modelling capabilities for site planning, for interiors, and provides strong space planning capabilities. In addition, there are 31 external Web sites that define both static and parametric objects for ArchiCAD (the majority are from Europe).

It supports the generation of custom parametric objects through its Geometric Description Language (GDL) scripting language, which relies on CSG-type constructs and a Visual BASIC-like syntax. It contains extensive object libraries for users, organized by systems: precast concrete, masonry, metals, wood, thermal and moisture protection, plumbing, HVAC, electrical, and so forth. Its user-defined parametric modelling has some limitations; its sketch tool and parametric rule generation do not support algebraic expressions or conditionals. Existing object classes can be extended and customized using GDL. It also has an Open Database Connectivity (OBDC) interface. Global grids or controls are possible but complex. It can depict and reference shapes made with complex curved surfaces, but these are not ArchiCAD typed objects and cannot be locally edited. When ArchiCAD was acquired by Nemetschek, it strengthened its design focus, releasing its early move into construction management with Vico.

As a platform: ArchiCAD has links to multiple tools in different domains. Some are direct links through GDL and others are through IFC. These are denoted (GDL) and (IFC), respectively:

• *Structural:* Tekla (If), Revit Structure (If), Scia Engineer (Dir) SAP & ETABS (IFC), Fem-Design (IFC), AxisVM (IFC)

• *Mechanical:* Graphisoft MEP Modeler (IFC), AutoCAD® MEP (IFC), Revit® MEP (IFC)

• *Energy and Environmental:* Graphisoft EcoDesigner (GDL), ARCHi-PHISIK (IFC), RIUSKA (IFC), Green Building Studio, Ecotect, EnergyPlus, IES

• *Visualization:* Artlantis and LightWork Design for rendering, Maxon Cinema 4D for animation and freeform modelling

• *Facility management:* OneTools and ArchiFM

ArchiCAD's home Web site provides tutorials for carrying out particular IFC exchanges, used in some of these interfaces. Other tools include Virtual Building Explorer 3D, a navigation tool. It also supports direct interfaces with several external tools, including Google SketchUp import Tocoman iLink, and Express for quantity takeoffs for costing and scheduling.

Recently, ArchiCAD has further strengthened its interactions with IFC and provides good bidirectional exchange. Its IFC exchange functions include object classification, filtering by object types, and object-level version management.

As an environment: ArchiCAD recently expanded its Teamwork/BIM Server backend repository, which comes with the ArchiCAD platform. ArchiCAD has addressed file exchange and design coordination by developing a smart update capability, called DELTA Server, that tracks reads and writes to its BIM Server repository. The checkouts are directly controlled by the user to access those objects, or regions of the project of interest. Updates to the server, however, are checked against what was exported and only modified objects (newly created, modified, or deleted) are passed back to the server on updates. This greatly reduces the size of updates and minimizes the time to make an update. These are managed using Object IDs, and timestamps are updated when changes are made, providing the opportunity to track object history throughout the lifetime of the project.

ArchiCAD's strengths: ArchiCAD version 14 has an intuitive interface and is relatively simple to use. It has large object libraries and a rich suite of supporting applications in design, building systems, and facility management. It can be used in all phases except fabrication detailing. Its server capabilities facilitate effective project collaboration and begin to support object-level design coordination, ahead of the capabilities of other systems. It is also supported on the Mac platform.

ArchiCAD's weaknesses: It has some minor limitations in its custom parametric modelling capabilities. While ArchiCAD is an in-memory system and can encounter scaling problems with large projects, it has effective ways to manage large projects, including its DELTA Server capability.

Digital Project

Developed by Gehry Technologies, Digital Project (DP) is an architectural and building customization of Dassault's CATIA, the world's premier parametric modelling platform for large systems in aerospace and automotive industries. DP requires a powerful workstation to run well, but it is able to handle even the largest projects. It runs on 32- and 64-bit hardware and Windows XP, Vista and Windows7 OS. Like most BIM tools, it relies heavily on an OpenGL Graphics board. The reviewed version is V1, R4, SP 7.

As a tool: DP is a complex tool which is learned in small steps. Its smart cursor presents selection options. Online documentation is readily available. Menus are customizable. As a parametric modeller, DP supports both global parameters to define object classes and assemblies and local rules and relations to be maintained between objects. Its rules for defining objects are complete and general. It is excellent in developing complex parametric assemblies, such as for dealing with fabrication issues. Subtypes of an object class can be generated and their structure or rules elaborated. Curved surface modelling is excellent, as befits a tool whose major users include automobile designers. Until the third release, DP did not include built-in base objects for buildings. Users could reuse objects developed by others, but these were not supported by DP itself. The currently provided objects shown in *Table 3* are also available for modification. DP is complex and has a steep learning curve. It has good interfaces for importing and exporting object data to spreadsheets and XML. It continues to expand its IFC capabilities. Like most applications, annotations in DP are associative with a drawing view and are not bidirectional with the model. Drawings are treated as annotated reports. DP supports clash detection. DP's Knowledge Expert provides rule-based checking that can augment the rules used in defining shapes, but can apply between objects in different parametric trees.

As a platform: Digital Project is file based and very scalable. The logical structure of CATIA involves tool modules called Workbenches. DP comes with several workbenches in addition to the Architectural and Structures Workbench: Imagine & Shape is a fully integrated freeform sketch design tool, based on CATIA, Knowledgeware supports rule-based checking of design; the Project Engineering Optimizer allows for easy optimization of parametric designs based on any well-defined objective function; and Project Manager for tracking parts of a model and managing their release. These are sophisticated tools with major potential benefits, but which require significant technical knowledge for effective use. It also includes capabilities for mechanical, electrical, and plumbing layout in its MEP Systems Routing. Other products organized as CATIA Workbenches can also be easily integrated. Of note is Delmia, a Monte Carlo simulation system allowing assembly and fabrication modelling and assessment. Its user interface is consistent across Workbenches. In addition to the integrated workbenches, DP has interfaces with Ecotect for energy studies, 3DVia Composer for documentation production, and 3DXML for lightweight viewing. It has links to Microsoft Project and Primavera Project Planner for scheduling, and ENOVIA for project lifecycle management. DP is built to define new object and family classes. It supports Visual BASIC scripting and has a strong API which uses .NET for developing add-ons. It has the Uniformat© and Masterformat© classifications embedded, which facilitates integration of specifications and cost estimating. It supports the following exchange formats: CIS/2. IFC Version 2x3, SDNF, STEP AP203 and AP214, DWG, DXF™, VRML, TP, STL, CGR, 3DMAP, SAT, 3DXML, IGES, STL and HCG.

As an environment: DP was designed as a platform, with a suite of tools tailored to integrate manufactured product design and engineering. It supports concurrent users, with the open source SVN version control manager. It has additional related features that provide integration at the environment level. Enovia is the major Dassault PLM (Product Lifecycle Management) product. DP carries multiple timestamps and a GUID at the object level for supporting object-level version management.

Digital Project's strengths: It offers very powerful and complete parametric modelling capabilities. It is able to directly model large, complex assemblies for controlling surfaces, features, and assemblies. It can support fabrication. Digital Project relies on 3D parametric modelling for most kinds of detailing. It is a complete solution, at the platform level. It has a powerful set of integrated Workbench tools.

Digital Project's weaknesses: DP requires a steep learning curve, has a complex user interface, and high initial cost. Its predefined object libraries for buildings are limited, as are external third-party object libraries. Drawing capabilities for architectural use are not fully developed.

Vectorworks

Vectorworks began as MiniCad, developed by Diehl Graphsoft in 1985. Mini-Cad supports users in a diverse set of design markets, in stage lighting theatre and set design, and in exhibit design. Vectorworks has a marine division that is a player in CNC machining forms for shipbuilding. It began as an Apple Computer Mac CAD system, adapting to Windows in 1996. Diehl Graphsoft was acquired by Graphisoft in 2000 and its product name soon was changed (to eliminate the similar naming) to Vectorworks. It has always stressed strong customer support and a strong worldwide user base, targeting smaller firms. In 2009, it adopted Parasolid geometry engine for its core geometric modelling platform; Vectorworks previously had parametric capabilities similar to Architectural Desktop. Now its parametric modelling is similar to others, but with the ease of use and fine-grained user-friendliness for which it has long been noted.

As a tool: Vectorworks provides a very wide variety of tools, organized as separate products but packaged together. These include:

Architect—for architectural and BIM applications

Designer—for product design, also has an interiors module

Landmark—a landscaping tool, with access to both 2D and 3D plant libraries

Spotlight—lighting simulation for venues and event simulation

Machine design—provides machine design, with parametric classes of machine parts, gears, cams, pulleys, and so forth, and also numerical control machining capabilities

Renderworks—Vectorworks' rendering tool

These different products provide a wide range of functionality, all with an integrated user interface and style, with drag-over operator hints, smart cursor, content-sensitive operator display, and customizable menus. The functionality of some of these products is overlapping. Vectorworks' drawing capabilities associate drawn section annotations with model projections. Annotations and dimensions are not yet associated with the 3D object projections, requiring extra care in checking the drawing view's consistency with the model. Vectorworks has a reasonable set of object libraries to import and use. Its NURBS surface modeling is very good. It supports customizing its predefined object classes and also supports new object definition, mostly using its API or Vectorscript scripting language. It has incorporated a Design Constraint Manager from Siemens PLM that facilitates the management of dynamic dimension-shape interaction. Currently, the Constraint Manager is limited to 2D applications, but can address extrusion profiles and many other such uses. Attributes are carried in a project database and associated with objects, for use when needed.

As a platform: Vectorworks is an in-memory system. It comes in both 32- and 64-bit versions, for both the Mac and PC. Like many other systems, it uses Workgroups to partition models into practical model subsets, to deal with scale problems and to allow concurrent access to different parts of a project. Its user interface across its products is well integrated.

Some interfaces to other applications are direct links but most are through IFC. These are denoted (IFC).

- *Structural:* Revit Structure (IFC), Scia Engineer (IFC), Tekla (IFC), Nemetschek Allplan

- *Mechanical:* Vectorworks includes many of the objects needed for parametric MEP layouts, such as ductwork, piping, and cable trays. It also supports interfaces with MagiCad (IFC).

- *Energy and environmental:* Vectorworks has a link to IES and its wide suite of tools; other mechanical applications are communicated through IFC

- *Visualization:* Uses Renderworks (IFC) as its internal rendering engine and Artlantis as its external high-end one; provides ESP-vision link for venue and event lighting simulation; also supports interface to Maxon Cinema 4D

As stated, Vectorworks' Marine Division is a major player in CNC cutting forms for shipbuilding. The Mac version of Vectorworks can interact with TouchCad, an unfolding and skinning tool. Other tools include Virtual Building Explorer 3D, a navigation tool. Vectorworks relies on exporting to spreadsheets for quantity take-offs and cost estimation. It also supports direct interfaces with several external tools, including Google SketchUp import. Vectorworks has a Visual Basic–like scripting language and an open API. Its exchange formats include DXF/DWG, IGS, SAT, STL, X_T, 3DS. Vectorworks has strengthened its interactions with IFC and provides good bidirectional exchange. Its IFC functions include object classification, assignment of Property sets and owner/history data. Its IFC (2x3) exchange capabilities have been tested with ArchiCAD, Bentley Microstation, AutoCAD Architecture, Revit, Solibri Model Checker™, and Navisworks®.

As an environment: Vectorworks has focused on its support for certain design tasks in different markets. It has a limited association with Siemens PLM, but it makes no claims as a BIM environment. Objects do not carry or manage GUID or version information.

Tekla Structures

Tekla Structures is offered by Tekla Corp., a Finnish company founded in 1966 with offices worldwide. Tekla has multiple divisions: Building and Construction, Infrastructure, and Energy. Its initial construction product was Xsteel, which was introduced in the mid-1990s and grew to be the most widely used steel detailing application throughout the world. It is largely file-based and scales well. It supports multiple users working on the same project model on a server. It does not currently support B-spline or NURBS surfaces.

As a tool: In the early 2000s, Tekla added precast concrete design and fabrication-level detailing for structural and architectural precast. In 2004 the expanded software product was renamed Tekla Structures to reflect its expanded support, including for steel, precast concrete, timber, reinforced concrete, and for structural engineering. Recently, it has added Construction Management capabilities. It is a platform supporting a growing range of products. In addition to full detail editing stations, it also offers Engineering, Project Manager, and

Viewing stations. All of these tools provide the functionality needed for fabrication and automated fabrication. It supports a Windows 7–like user interface, with drag-over operator hints, smart cursor, and user-configurable menus. It has good functionality to customize existing or create new parametric objects. Nevertheless, it is a complex system with rich functionality that takes time to learn and keep abreast of.

As a platform: Tekla offers interface support for a wide range of other applications:

Application	Company	Capabilities
AxisVM	Inter-VCAD Kft	CNC fabrication
CYPECAD	Cype	Structural design and analysis of reinforced concrete
Diamonds	Buildsoft	Structural design and analysis
Fastrak	CSC	Structural design and analysis
FEM Design	StruSoft	Structural design and analysis
MidasGen	MIDAS	Structural design and analysis
ModeSt	Tecnisoft	Structural design and analysis
NISA	Cranes Software International Ltd.	Structural analysis
PowerFrame	Buildsoft	Structural analysis
RFEM	Dlubal	Structural analysis
Robot Millenium	Autodesk	Structural analysis
RSTAB	Dlubal	Structural design and analysis
SAP2000	Computers & Structures, Inc	Structural analysis
SCIA	Nemetschek	Structural design and analysis
S-Frame	CSC/Softek	Structural analysis
STAAD	Bentley	Structural design and analysis
STRUDS	SoftTech	Structural design and analysis
Trimble LM80	Trimble	Jobsite layout, survey equipment
BuildSite	BuildSite	Product and technical information for manufacturers and distributors
Meridian Prolog Converge	Meridian	Project management

Table 5: *Tekla applications [4]*

Tekla has an open application programming interface. It also supports a very broad range of exchange formats, some those native to other applications, as shown in the next table:

Format	Import	Export
AUTOCAD (.dwg)	X	X
AUTOCAD (.dxf)	X	X
BVBs (.abs)		X
Cadmatic models (.3dd)	X	
Calma plant design system (.calma)	X	X
CIS/2 lpM5/lpM6 analytical, design, manufacturing (.stp,.p21, .step)	X	X
DsTV (.nc, .stp, .mis)	X	X
Elematic Eliplan, Elipos (.eli)	X	X
EpC		X
Fabtrol Kiss file (.kss)		X
Fabtrol Mis Xml (.xml)	X	X
GTsdata priamos		X
High level interface file (.hli)	X	X
HMs (.sot)		X
IFC2x/IFC2x2/IFC2x3 (.IFC)	X	X
IFCXMl2X3 (.xml)	X	X
IGES (.iges, .igs)	X	X
Intergraph parametric modeling language (.pml)		X
Microsoft project (.xml)	X	X
Microstation (.dgn)	X	X
Oracle Primavera p6 (.xml)	X	X
Plant Design Management system (.pdms)		X
SAP, Oracle, oDBC, etc.	X	X
STAAD ASCII file (.std) in out	X	X
Steel Detailing Neutral Format (.sdf, .sdnf)	X	X
Steel12000		X
STEP ap203 (.stp, .step)	X	
STEP ap214 (.stp, .step)	X	X
Trimble IM80 (.txt, .cnx)		X
Unitechnik (.uni)	X	X

Table 6: *Tekla exchange formats [4]*

As an environment: Tekla supports concurrent user access to the same project, allowing reservations at the object or higher aggregation of objects level. It carries object IDs and timestamps, supporting object-level management.

Tekla Structures' strengths: Its versatile ability to model structures that incorporate a wide range of structural materials and detailing; its ability to support very large models and concurrent operations on the same project and with multiple simultaneous users. It supports user-defined parametric custom component libraries, including customization of its provided objects.

Tekla Structures' weaknesses: While a powerful tool, its full functionality is quite complex to learn and fully utilize. The power of its parametric components is impressive and, while a strength, requires dedicated operators who must develop high levels of skill. It is able to import objects with complex multi-curved surfaces from outside applications, and these can be referenced but not edited. It is also relatively expensive.

DProfiler

DProfiler is a product of Beck Technologies. It is based on a parametric modelling platform acquired from Parametric Technologies Corporation (PTC) in the late 1990s, after PTC decided not to enter the AEC market. DProfiler is an application and platform that has evolved from the software acquired from PTC.

DProfiler functionality is unique; it addresses conceptual design from a cost of construction, and, to a degree, an operating cost basis. It supports quick definition of the conceptual design of given building types, based on the room types, and building structural and site parameters. The high-level components of a project are: Site: soils, parking, detention ponds; Massing: cladding, features, mechanical, slabs, rooms. These are building model objects that carry links to the cost definitions. A concept-level model can be laid out in an easy 3D sketch manner, using intuitive editing operations. A building can be composed as a set of spaces, floor by floor, or alternatively as a shell that is then decomposed, into floors that are assigned spaces or some mixture of the two. The site plan can be an imported terrain model or Google Earth segment. Each of these can be defined in little or great detail, using defaults, or overriding them if desired.

Defaults are set up for different building types, using the RS Means Masterformat 16 divisions, or further down to line-item detailed categories, or alternatively to Timberline's more detailed ones. Each object, such as wall or slab is associated with an assembly cost class. Objects can be changed from one construction type to another without necessarily changing the geometry. This means that a cost estimator has almost complete control of the project costing, defining types of slabs, and details of cladding and construction. It has increasingly detailed site development definition and costing. Cost parameters are carried as fixed units for the building type or location, while others are under explicit user control (such as the type of films on glazing or number of fume hoods in a laboratory), while the building geometry defines the spatial properties. The design model is thus geometrically simple and can be simple or complex from a cost standpoint, where the design intent is defined by the associated cost categories. Thus the strength of the system is the articulation of intent in the cost-estimating side, organized hierarchically as Components, Collections, Assemblies, and Line Items. These multiple levels allow contractors or other users to map to their own cost databases, if that is desired.

The resulting cost estimates are detailed, based on quantity of materials in place, that start out being estimates, but that can be tracked downstream as the project is detailed, then constructed, to compare with the actual quantities and costs for quality assurance. In addition, it provides a full economic cash-flow development proforma for the project, optionally including occupancy and operation. The cost estimating database accessed by DProfiler is centralized and maintained by the Dallas office.

DProfiler supports a range of graphical inputs for defining a project, for example, DGN, DXF, PDF, DWF. It also supports output to eQuest for energy analysis, used to estimate operating costs, and output to XLS spreadsheets and various image formats. At the time of this review (Fall 2010), Beck also has a beta version for importing into Revit, allowing a full mapping of DProfiler entities and composition into Revit object families and instances. DProfiler can also fully map its cost estimate data for a Revit project to Timberline. Informally teaming with Innovaya, DProfiler supports a user link between the imported Revit project model with the matching Timberline cost model, allowing tracking downstream as the project is further developed.

DProfiler strengths: DProfiler functionality allows it to be easily adapted to almost any building type, based on costing of assemblies and line items. With its interface to Revit, it will have strong transfer capabilities downstream. Its strength is in the value analysis of various concept designs based on a wide range of construction specifi cations and their associated cost estimates. Some case studies show that a well-developed DProfiler project is reliable to within 5 percent of construction costs, and it has supported project models that have come within 1 percent of project costs. Its ability to generate detailed economic assessments on a conceptual-level project is powerful and unique.

DProfiler weaknesses: DProfiler is not a general purpose BIM tool. Its major purpose is financial evaluation of a construction project, with financial exploration of alternative finishes and system choices, usually without modelling them geometrically. Once a model is complete, its interface to support full development is limited currently to Revit.

D.2.4. Lightweight modelling applications

Each of the above platforms consists of a building model and one or more applications that can create, edit, and translate the model data for different uses. In addition, we report here on two widely available lightweight building models and applications which have their own uses. They are 3D PDF (Portable Document Format), developed by Adobe®, and DWF (Design Web Format), developed by Autodesk®. These two building model formats are not for creating building model information, but rather for "publishing" information to support various workflows. That is, these Web formats provide design and engineering professionals with a way to package, distribute, and review the building model information, with mark-up and query capabilities; but not to enable modification of the model information. The widespread availability of these building model formats is likely to lead to their playing a useful role in the exchange and viewing of project information. Following is a brief overview of some of the features of these formats:

- **Generic, nondomain specific and extensible schema:** These formats do not have domain-specific schemes, rather they have schemas with general classes of entities, from geometric polygonal entities and sol-id entities to mark-up objects and sheet objects. They are designed to meet the broad needs of engineering and design disciplines including manufacturing and the AEC industry. PDF was originally designed for exchange of text- and image-based documents and has been extended to include support for U3D (Universal 3D) elements. The DWF schema was designed specifically for exchange of intelligent design data and is based upon Microsoft's XML-based XPS (XML paper specification) format and extensions, allowing anyone to add objects, classes, views, and behaviours. Although PDF is an ISO standard, neither DWF nor the 3D PDF extensions are ISO standards.

• **Embedded views of the project information:** Both formats represent the model data and views of that data. Data views include 2D plot views, 3D model views, or raster image views; each is separate and not interlinked. The 2D and 3D model representations are separately fully navigable, selectable, and support queries. They include object meta-data, but object parameters cannot be edited.

• **Widely available viewing tools:** Both formats are distributed with free, publicly available viewers.

• **High fidelity, accuracy, and precision:** Both formats were designed for plot-capable printing with a high level of accuracy and precision.

• **Highly compressible:** Both formats are optimized for portability and are highly compressed.

The three primary applications using these two formats are:

Adobe Acrobat 9 Pro Extended is a free 3D PDF viewer; It supports a dynamic and viewable 3D object or animation to be embedded in a document. Supports model comparison.

Autodesk Design Review is a free downloadable viewer to support review, checking, and other forms of collaboration. It supports 2D drawings and 3D models converted to DWF. Models can be spatially reviewed by fixed, walking or flying through them; views may be fixed orthogonal to various surfaces or by cutting sections through the project. Distances and angles may be derived between object surfaces. Queries by object names are also supported, with the object names returned, which when selected are highlighted in the view. Two-dimensional documents may be rotated, and mark-ups may be applied to any point on surface, for recording review comments. Reports with mark-ups are easily generated. A digital signature is provided, allowing the signature to check if changes have been made to the file since the signature was applied.

Streamline is a Web-based reviewer developed to support the manufacturing market for single parts or assemblies. It provides lightweight geometrical modelling and some data generated through DWF publisher. It incorporates a secure socket layer with client. DWF files are uploaded to a server, and can be reviewed by any approved (password protected) user. Autodesk manages the server farm.

D.2.5. Latest reviewed BIM software titles

Reviewed BIM software titles are listed below, each provided with an external link to online CAD journal reviews. The articles are sourced from the AECbytes, AEC Magazine, CAD digest CAD journal websites[2], and issue the latest reviewed versions of relevant software titles. The most remarkable changes in major vendor's products are the integration of their different disciplinary products under a main BIM software title.

- Revit 2014 –
  http://aecbytes.com/review/2013/Revit2014.html
- Bentley AECOsim Building Designer V8i -
  http://aecbytes.com/review/2012/AECOsimBuildingDesigner.html
- ArchiCAD 17 –
  http://aecbytes.com/review/2013/ArchiCAD17.html
- Vectorworks Architect 2011 –
  http://aecbytes.com/review/2011/VectorworksArchitect2011.html
  Vectorworks Architect 2014 –
  http://www.caddigest.com/exclusive/vectorworks/121213_my_weekend_with_vectorworks_2014.htm
- Tekla Structures 16 –
  http://aecbytes.com/review/2010/TeklaStructures16.html
  Tekla Structures 19 –
  http://www.aecmag.com/software-mainmenu-32/563-tekla-structures-19-
- DProfiler –
  http://www.aecbytes.com/review/2008/DProfiler.html
- Allplan 2013 –
  http://aecbytes.com/review/2013/Allplan2013.html
- Scia Engineer –
  http://aecbytes.com/review/2010/SciaEngineer.html
  Scia Engineer 2012 –
  http://www.caddigest.com/exclusive/AEC/050613_scia_engineer_review.htm
- Eco Designer –
  http://aecbytes.com/review/2010/EcoDesigner.html

[2] http://aecbytes.com/ , http://www.aecmag.com/ , http://www.caddigest.com/ Consulted January 2014.

D.2.6. Listed BIM software titles

The following BIM software titles have been listed and grouped by their targeted functionality [2]. Hyperlinks to their respective vendor's websites have been included.

Architectural

- Autodesk Revit Architecture
- Graphisoft ArchiCAD
- Nemetschek Allplan Architecture
- Gehry Technologies - Digital Project Designer
- Nemetschek Vectorworks Architect
- Bentley Architecture
- 4MSA IDEA Architectural Design (IntelliCAD)
- CADSoft Envisioneer
- Softtech Spirit
- RhinoBIM (BETA)

Sustainability

- Autodesk Ecotect Analysis
- Autodesk Green Building Studio
- Graphisoft EcoDesigner
- IES Solutions Virtual Environment VE-Pro
- Bentley Tas Simulator
- Bentley Hevacomp
- DesignBuilder

Structural

- Autodesk Revit Structure
- Bentley Structural Modeler
- Bentley RAM, STAAD and ProSteel
- Tekla Structures
- CypeCAD
- Graytec Advance Design
- StructureSoft Metal Wood Framer
- Nemetschek Scia
- 4MSA Strad and Steel
- Autodesk Robot Structural Analysis

Mechanical, Electrical, Plumbing (MEP)

- Autodesk Revit MEP
- Bentley Hevacomp Mechanical Designer
- 4MSA FineHVAC + FineLIFT + FineELEC + FineSANI
- Gehry Technologies - Digital Project MEP Systems Routing
- CADMEP (CADduct / CADmech)

Construction (Simulation, Estimating and Construction Analysis)

- Autodesk Navisworks
- Solibri Model Checker
- Vico Office Suite
- Vela Field BIM
- Bentley ConstrucSim
- Tekla BIMSight
- Glue (by Horizontal Systems)
- Synchro Professional
- Innovaya
- DProfiler

Facility Managment

- Bentley Facilities
- FM:Systems FM:Interact
- Vintocon ArchiFM (For ArchiCAD)
- Onuma System
- EcoDomus

D.3. INDUSTRY FOUNDATION CLASSES SCHEMA OVERVIEW

D.3.1. IFC Schema

The system architecture of the IFC schema used to define all its content can be very complex. Based on the latest IFC version's (IFC4) specification files [3], a brief overview of its schema is given as shown in *Figure 1*.

From top to bottom, physical objects (ex: beam), process objects (ex: analytical beam) and all other information entities (ex: data sets, project players' sets, etc.) are hierarchically defined through the schema's layers:

- **Resource layer:** This is the lowest layer. It contains the most basic information attributes gathered in the so called 'resources'. For example, steel texture, density, and Young modulus would go into the Material Resource. Information is semantically grouped in these elementary data entities, and do not have meaning by themselves until they are used in higher-level constructs.

- **Core layer**: The elementary data entities of the Resource Layer are combined to generate the most general entity definitions in the Core Layer. These are basic building elements such as walls, slabs, structural elements, process elements, service elements and operation and management elements. All entities defined at the core layer or above, carry a globally unique identification and optionally owner and history information. In other words, they have meaning by themselves and can be inserted in a model.

- **Interoperability layer**: This layer includes schemas containing entity definitions that are specific to a general product, process or resource specialization used across several disciplines. These definitions allow interchange and sharing of construction information within all those players involved in a designated project category. For example, in the shared building services element category, relevant information regarding facility's systems can be defined and shared within MEP designers, contractors and facility managers.
- **Domain layer**: The top layer includes schemas containing entity definitions that are specializations of products, processes or resources specific to a certain discipline. Entities created at domain level can be gathered in different ways to form information sets used in specific workflows.

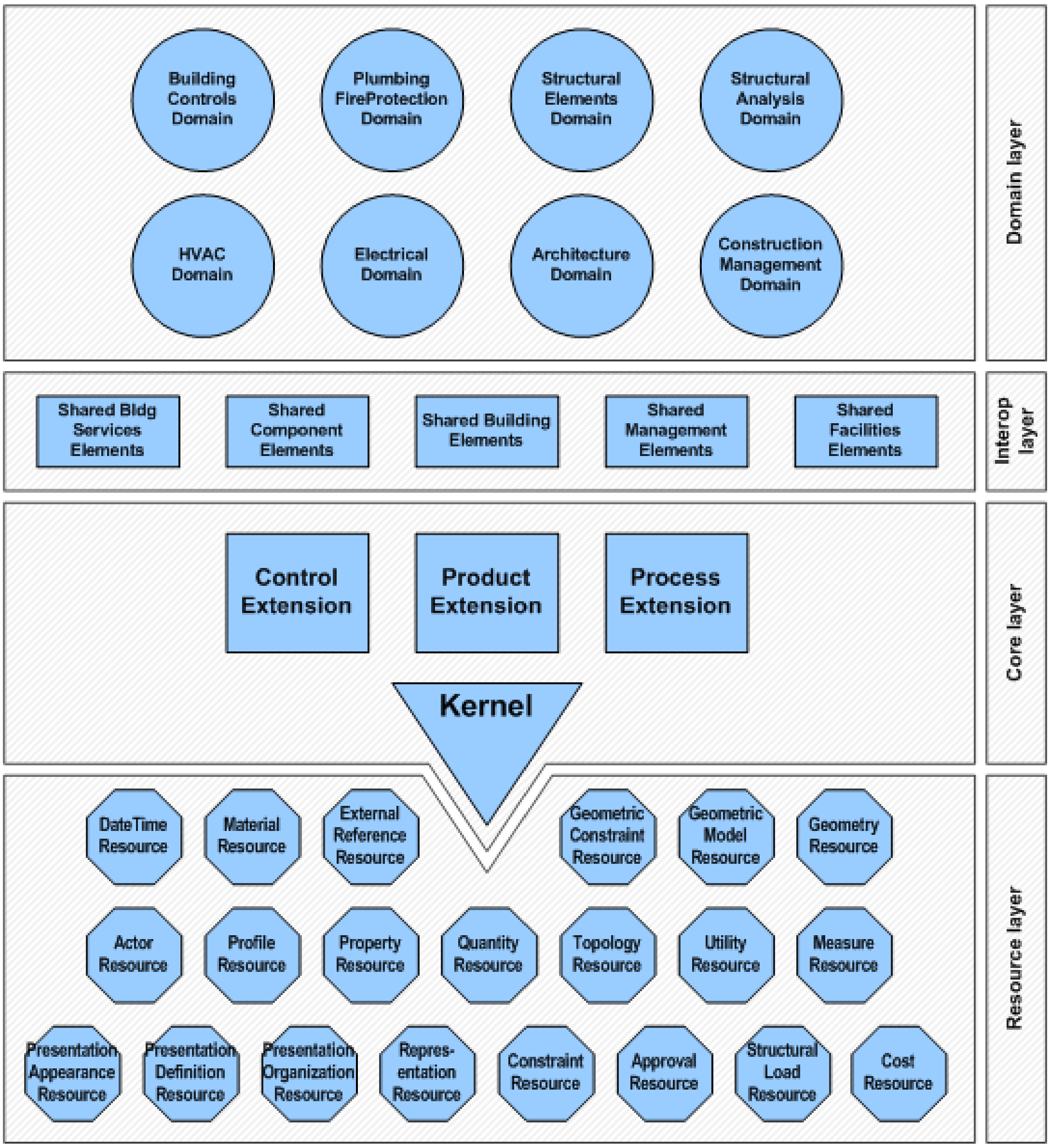

Figure 1: *System architecture of IFC.4 Schema [3]*

D.3.2. IFC limitations

When using IFC for data interchange a wide range of geometry can be represented. As mentioned, object behaviour does not always have a direct translation between different BIM platforms. Therefore, parametric relations between objects have to be carefully defined when using the IFC format.

Regarding property sets destined for diverse applications, IFC lacks some of the required information. For instance, in structural analysis property sets, welding typologies, specifications, buckling assumptions or restrain conditions are missing [4]. Although missing properties can be defined in the structural analysis tools, the reverse process cannot take place in order to update the model. Representation of the information needed for highly-detailed design of building component fabrication is scarce as well.

When it comes to handling information, IFC offers great support in data management, providing reliable information ownership and tracking of changes, evaluation and approvals. Nevertheless, users don’t seem to take advantage of these features.

D.4. INFORMATION MANAGEMENT AND BIM SERVER REPOSITORIES

The information created during a project’s lifecycle has to be effectively managed so it can be easily shared, stored and accessed by all applications that request it. Traditionally, updating and synchronization of project documentation has been quite a complex task. Once the technical and conceptual challenges for information interchange have been overcome, the basic technological support for its management is crucial for effective interoperability. If interoperability is understood as a common language for BIM software titles, data management technology is the ‘telephone system’ that makes data interchange possible amongst project players.

The technology developed to manage project information is known as **building model repository**. Inspired in traditional project data management systems, BIM model repositories are databases or server solutions that gather all of the project information for its coordination and management. Instead of holding CAD files, BIM repositories hold BIM model files but allow the selective access of information within those files. Information can be independently grouped in various ways and focuses at an object level rather than at a file level.

The process of creating, changing or updating database information is called **transaction**. BIM databases have certain differences in comparison to traditional ones. As mentioned, transactions can take place at different hierarchical information levels other than files, such as building or object level. Usually various users work on a same model in collaboration and spend long periods of time accessing and modifying them. These concurrent long transactions have to be handled carefully to maintain consistency across data related to a building model.

How transactions are managed to keep data consistency will determine the ways users collaborate on a same model. There are many approaches. For instance, users may be allowed to access a model or parts of a model one at a time, or they may be able to collaborate concurrently in a same file with automatic notifications of recent changes made by others. As concurrent access to a model focuses at the object level, transaction policies become more important.

Once transactions take place, all files and data that keep relationship with that modification must be updated. Consistency between all information contained in a BIM model repository is achieved through **synchronization**. Traditionally these updates are propagated manually based on user's criteria of which files have been affected by a certain change. Although the parametric nature of BIM models ensures consistency within all deliverables generated from a same model, models of different disciplines or distinct BIM platforms are not parametrically synchronized. Even if all data could be technically synchronized, the process could never be fully automated, as it implies heavy design decisions. For example, a change in a slab depth in an architectural model could clash with ventilation systems and produce changes in loads. Once transactions were propagated, MEP engineers would then have to arrange possible solutions for the ventilation system and structural engineers re-analyse their model before the disciplinary models can be considered synchronized and consistent with each other.

Nevertheless, a high grade of synchronization can be achieved when transaction is managed at an object level. With the use of **metadata**, objects can be tracked down, identified and updated regardless of the BIM platform or BIM model they pertain to. **Global Unique ID's** (GUIDS) are used to track and identify objects, and timestamps are used to correctly update objects by keeping record of their latest versions. All BIM applications have to be able to create, import, modify and export object metadata for correct transaction management at object level. Consistency is then kept by identifying objects and updating them to the most recent timestamp. This procedure, effective as it is, contributes to reduce server traffic as only created, modified and deleted objects are updated, rather than synchronizing entire model files.

BIM model repositories, or BIM servers, also have to manage user access to information and privileges over it. In design stages, where collaboration is more intense, each player needs access to certain information sets. These worksets are usually limited model views and only have to be coordinated with certain disciplines. Control over changes can also be carried out by keeping record of changes at object level based on user's ID.

D.5. BIM MODEL REPOSITORIES REVIEWS

D.5.1. Introduction

BIM model repositories are the technological base that support information sharing, storage and re-use for task specific applications. Server solutions are essential for collaboration and for establishing effective interoperability.

In this annex the basic capability requirements of BIM model repositories are summarised. Following, metadata management of major BIM platforms are compiled. And last but not least, commercial BIM server solutions are reviewed. All information exposed in this annex has been directly extracted from *The BIM handbook*, by Eastman et. al. [4]

D.5.2. Functional requirements of BIM model repositories

Base Requirements for a BIM Repository

The base requirements for a BIM repository are fairly straightforward. Some are common to most database management systems. Others are basic needs articulated within the AEC industries and can be summarized as follows:

- *User access control* provides access and read/write/create capability for different levels of model granularity. Granularity of model access is important, since it identifies how much model data must be impounded for a user to revise it.
- *Represent users associated with a project*, so their involvement, access, and actions can be tracked and coordinated with workflows.
- *Read, store, and write* both all-native data models of platforms and also the derived data models used by other various BIM tools.
- *Read, store, and write open standard model data models* for some interoperability workflows and for project management.
- *Manage object instances* and read, write, and delete them based on update transaction protocols.
- *Support product libraries* for incorporating product entities into BIM models during design or fabrication detailing.
- *Support storing product specifications* and other product maintenance and service information, for linking to as-built models for owner handover.
- *Store e-business data, for costs, suppliers, orders shipment lists, and invoices* for linking into applications.
- *Provide model exchange capabilities for remote users,* for example, Web access, FTP file exchange, PDF, and XML.
- *Manage unstructured forms of communication*: email, phone records, notes from meetings, schedules, photographs, faxes, and videos.

These provide basic content capabilities of a BIM server. However, these capabilities do not address how complex object models and all their ancillary data should be managed.

D.5.3. Metadata management capabilities of BIM Platforms

Table 3–3 Synchronization of Object Metadata for a Selected Set of BIM Platforms

BIM Platform	Manage Unique IDs	Manage Timestamp
Revit, Release 2011	Has a tag object that can carry ID at the object instance level	At the file level
Bentley	At the object instance level	Modification marks carried in object
ArchiCad	At the object instance level	At the object instance level
Vectorworks	No support	No support
Digital Project, V1, R4, SP 7	At the object instance level	At the object instance level
Tekla	At the object instance level	At the object instance level

Table 7: *Metadata management capabilities of main BIM platforms*

D.5.4. BIM server solutions review

BIM server solutions have not yet been fully developed to handle object level transaction management and synchronization. Some of them are being adapted from other domains to the AEC industry. With each release, BIM server capabilities are improved. Following, the major BIM server solutions are reviewed:

Autodesk Collaborative Project Management incorporates Buzzsaw and ConstructWare, both Web-based accessible on-demand project management systems, developed in 2000. Together they support document management with project-related document and contract tracking; version control and search capabilities; design management with automatic notifications of design changes; reference file management; cost management with budget and expenditure tracking and forecasting; data exchange with accounting systems to enable tracking of individual projects; construction management with notification of RFIs, transmittals, meeting minutes, change orders, and reporting; and project management dashboards. Data is managed at the file level and does not support object-level management.

Bentley ProjectWise Integration Server is a well-developed and popular base server platform that provides central capabilities for a single office or distributed services for an enterprise or team project. For distributed services, it relies on cached servers providing fast local services for project files. The ProjectWise Server provides version control of reference files so that any XREF files are flagged if not up to date. Web versions are also available. Unit of management is a file, not an object. Integration Server can be augmented with additional services defined below.

i–Model is an extensible XML format with its own schema for publishing DGN and other Bentley data. A plug-in for generating i-Model data from Revit is also available. i-Model data can be derived from STEP models including CIS/2, IFC, and ISO 15926, as well as DWG and DGN file formats. This provides a platform for mark-up and review, and for integrating applications within Bentley and with their System Development Kit (SDK) and for third-party applications. It also includes generation of 3D PDF format.

ProjectWise Navigator provides an overlay display capability for dealing with heterogeneous project files. Handles DGN, i-Model, PDF, DWG, and DGN overlays; uses indices to key files for access and viewing. Incorporates internal applications for multiproduct clash detection, allows grouping for managing product data, for purchases, review, and so forth. It supports 4D simulation, rendering, and mark-ups for review but only limited editing. The ProjectWise products do not yet provide object-level management of data, although Bentley has had earlier products with this capability.

BIM Server (an open source server), from TNO Netherlands and TU of Eindoven, (www.bimserver.org/) supports import/export of IFC which is the basis of the BIMserver open standards. This includes incremental updates and change management. It provides an easy-to-use (Web) user interface with an IFC viewer client (www.ifcbrowser.com/). It provides IFC versioning, and can go back in time and see who made what changes and when. It supports Filter & Query such as “get only the windows from a model,” or “get one specific wall” using direct Objectlinks. It has a Web service client for exploration of the BIMserver. It has SOAP (Simple Object Access Protocol) and REST (which supports URL-based object access) for the Web service interface. Mostly written in java, it currently runs on Oracle, using BerkeleyUnix. RSS feeds are provided for real-time change alerts. It includes some support for IFD. It is developing a clash detection embedded application. It supports CityGML export of IFC Models to CityGML (www.citygml.org/), including the BIM/IFC-Extension (www .citygmlwiki.org/index.php/CityGML_BIM_ADE). Several client applications are based on BIM Server: clash detection, rendering, gbXML energy interface, KML, and SketchUp export to Google Earth, XML export, and COBie export for construction operations handover. This is a true shareware system with a user development team and source code access.

Drofus is a Web-accessible SQL database that addresses the spaces within any building and the equipment within the spaces. It is thus not a complete building model server addressing all aspects of a project, but rather a model view dealing with spaces, their furnishings and finishes. It can start with the programming phase to define the requirements for equipment and furniture, then the design and layout, in quantitative terms. It supports spatial program review by two-way exchanges with BIM authoring tools through IFC. Equipment, finishes, and material definitions can be linked to automatic ordering and tracking, including procurement. At the end, the system can be used for operations and facility management. Drofus carries object IDs and supports synchronization between itself and the building model (www.drofus.no/). Drofus has been used in production for several years and is quite mature and is especially relevant for building types where equipment support is a fundamental part of the design program, such as hospitals and laboratories.

EuroSTEP Share-A-Space Model Server is a model server initially developed for aerospace, being adapted to AEC; uses Oracle (soon also Windows SQL Server) as its host database. It is an object model server that relies on IFC as internal representation but also supports native models at the file level; it applies ISO10303-239 STEP and the OGC Product Life Cycle Support (PLCS) schema for change management, versioning, consolidation, requirements, status, and so forth. It uses MS Biztalk for XML-based communication and incorporates a Web client portal. It supports strong business process capabilities, for part and product entities, testing, and requirements, status, and people-tracking. It includes email services and has interesting workflow capabilities; it includes a Mapper function that translates one object view to another, implemented in XML and C#; its imports can have associated rules that apply to change updates that can be automatic, partial, or manual. It incorporates Solibri Model Checker, for applications and requirements checking; also uses VRML for visualization. This PLM-type system is being adapted to AEC applications.

Graphisoft ArchiCad BIM Server: ArchiCad Version 13 and 14 provides Web server project management with simple project access control, version and change management for ArchiCad and IFC-based projects. It is the first major BIM design platform with a backend database whose unit of management is objects rather than files. This allows selecting objects to work on, while the BIM server manages those accesses and access locks. In most cases, object reading and use of reference objects for context greatly reduces the scope of each transaction. Updates then are limited to those objects actually modified, reducing file transfer size and the time it takes to make the updates. All users can graphically see what other users have reserved. Updates are trimmed of unchanged objects and called Delta updates. Synchronization is an important issue—when are the changes to one object propagated to others that may not be reserved? ArchiCad provides three options: real-time and automatic when objects are selected and worked on without checking them out; semi-automatic synchronization for the objects checked out and modified, only for those objects requested; or on-demand. It supports the use of 2D DXF files for coordination.

Horizontal Glue™ is a Web-based server with its own lightweight geometry viewer that can automatically translate and view objects from multiple BIM platforms (currently Revit, and IFC; Bentley is coming). This greatly facilitates collaboration. It supports management of IFC and native files. It supports both its own and Navisworks' clash detection; its particular strength is providing open communication links and change record tracking; it incorporates cost estimation and project tracking through Prologue, and Proliance® for lifecycle management. This is a young start-up, with much ambition.

Jotne EDM Model Server supports any Express language schema, with a full implementation of Express and any EXPRESS schema, such as IFC and CIS/2. It includes multi-language support (spoken language) with IFD. It supports Express-X, an ISO model mapping language that allows mapping between EXPRESS schemas. This could be used to map between model views or ISO-15926, for example. Express-X also supports rule checking and interfaces to applications on the server. It uses MVDs as one of multiple query/access modes. It supports both TCP and HTTP, for direct and Web interfaces. It has limited version control, allows object level access and updates; updates always overwrite the stored version. Selection for checkout is limited.

***Oracle Primavera* and *AutoView*:** Primavera on Oracle enables organizations running Primavera P6 project cost, schedule, and resource requirements with Oracle's project and portfolio system and plant maintenance information. It supports storage of native platform files for check-out and check-in. It is not an object-level BIM manager. It addresses multiple markets including production plant management for engineered-to-order products (steel and precast fabrication, curtain wall systems). It supports 3D PDF and AutoView, a lightweight 2D drawing and 3D model viewer for review and walkthroughs. It supports accurate spatial measurements and 3D identification of clashes. (www.oracle.com/us/products/applications/autovue/index.htm).

D.6. MULTI PARTY AGREEMENTS (MPA)

MPA are a single contract specifying the roles, liabilities, obligations and rights of all players. These contracts require the will of all players to collaborate as a team and are based on trust, as benefits depend on the overall success of the project and individual achievements are tied to the other players' performances. In the development of a project approached through IPD, liability, information ownership and many other concerns arise. As every project is unique, agreements have to be tailored to each and every one. Before a project is commenced, considerable effort has to be put on MPA planning, negotiation between parts and team designation.

Although flexible solutions of MPA are needed for each case, there are three major MPA typologies[3]:

- **Project Alliances**

  Project Alliances were developed to support oil exploration in the North Sea. To meet these challenges, the parties created a project structure where the owner guaranteed the direct costs of non-owner parties, but payment of profit, overhead and bonus depended on project outcome. This compensation scheme bound the parties to succeed or fail together. To reinforce Alliance teamwork, all significant decisions were made by facilitated consensus and the parties waived any claim between them, except for wilful default. Since their development by the North Sea oil industry, Project Alliances have been extensively used in Australia for large civil works and vertical construction, have seen continued use in the United Kingdom, and are beginning to be adopted in the United States.

- **Single Purpose Entities**

  A Single Purpose Entity (SPE) is a temporary, but formal, legal structure created to realize a specific project. The SPE can be a corporation, limited liability company, limited liability partnership, or other legal form. In an integrated SPE, key participants have an equity interest in the SPE based on their individual skill, creativity, experience, services, access to capital or financial contribution. Typically, equity owners are paid for any services they provide to the SPE. However, an additional element of

[3] Extracted from the AIA California Council's Guide to IPD [1]

compensation is tied to overall project success. The creation of a new, independent legal entity raises additional issues regarding taxation, corporate formalities, and management. Because the SPE is a separate entity, it must also be adequately insured.

- **Relational Contracts**

  Relational Contracts are similar to Project Alliances in that a virtual organization is created from individual entities. However, it differs in its approach to compensation, risk sharing and decision making. In a relational contract, the parties may agree to limit their liability to each other, but it is not completely waived. If errors are made, conventional insurance is expected to respond. Thus, there is a measure of traditional accountability. Compensation structures have project-based incentives, but there may or may not be any collective responsibility for project overruns. Decisions are developed on a team basis, but unlike the Project Alliance, the owner usually retains final decision rights in the absence of team consensus.

The implication of the exposed MPAs is seen in further detail in the AIA's Guide to IPD (4). Despite existing diversity, most MPAs share some common attributes: Agreements are unified in a single contract; Temporary organizations are created; Decisions are consensually made to the project's benefit; Earnings are partially based on overall project success; Teams are assigned based on the best capabilities of players.

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