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ON THE USE OF OPEN BIM AND 4D VISUALISATION IN A PREDICTIVE LIFE CYCLE MANAGEMENT SYSTEM FOR CONSTRUCTION WORKS

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SUMMARY: *Construction works are in periodical need of performance upgrade such as maintenance, repair and rehabilitation (MR&R). Facility managers are responsible to fulfil this need during the whole life cycle of the construction works in a manner that maximises the economical profit, minimises the environmental impact and keeps the risk of failure at a low level. A prerequisite for efficient facility management (FM) is long-term planning of MR&R actions. This requires management of a large amount of information, a process that includes gathering, storing, processing and presentation of data. With the development of open Building Information Models (open BIM) and standardisation of Industry Foundation Classes (IFC) new possibilities of efficient management of FM information have emerged. Due to its parametric and object-oriented approach, the open BIM-concept rationalises the information management and makes it more cost effective. This paper discusses how open BIM, with the aid of IFC, and Product Life Cycle Support (PLCS) may facilitate the implementation of a predictive Life cycle Management System (LMS) and by that improve the feasibility for adopting long-term and dynamic maintenance strategy in the FM process. A case study on the use of a commercial BIM-based design tool as information repository and media to present life cycle information within the context of the LMS concept on a hospital building is also presented. The case study shows that the build-up of the information becomes simpler, more clear and efficient compared to a traditional database solution, as it is done with parametric objects. However, the basic BIM can not serve for all LMS functions. There is still need for development of a BIM integrated LMS solution that may support prediction of life cycle performance and maintenance needs. Such a solution needs to be communicative to any open BIM software and thus has to be built upon open standards for exchange of building information, e.g. the IFC standard, and life cycle oriented standards like PLCS. Additional focus is put on 4D simulation and visualisation. Simulation and visualisation of long-term performance of buildings is of crucial importance when improving the feasibility for adopting a long-term and dynamic maintenance strategy in the FM process.*

KEYWORDS: *Building information model, Life cycle Management System, long-term performance, 4D visualisation.*

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1. THE AEC/FM SECTOR – CHALLENGES AND POSSIBILITIES

1.1 The challenges for the AEC/FM sector

The Architecture, Engineering, Construction and Facility Management (AEC/FM) sector plays an important role in society. The construction sector is the largest industrial sector in EU-15, accounting for 7 % (~12 million) of the total employment and contributes about 10 % (~910 billion Euros) of the GNP to the economy (EC, 2008). From an environmental point of view the sector has an indisputable unique position. Besides being the largest consumer of raw materials the sector is responsible for 46 % of the total energy usage, 46 % of the CO_2 emissions and generates 40 % of all man-made waste (EC, 2008, Sjöström and Davies, 2005, Sjöström and Bakens, 1999). The fact that a majority of the energy use, and thereby the major contribution of CO_2 emissions occurs during the operational phase put special demands on life cycle design and efficient facility management. This presupposes service life planning and life cycle management, which in turn presupposes knowledge on service life performance and life cycle behaviour of buildings. The current strategy and practice in facility management is however reactive in its character (Sarja, 2004). In many cases this strategy is not justifiable, but still generally accepted. The sector has to overcome traditional thinking and put efforts on new and innovative concepts promoting sustainable development on all levels (organisational, technological, economic, social etc.) and in all phases of the building life cycle. The latter certainly requires support from Product Life Cycle Support (PLCS) information models etc.

There are several arguments for adopting a proactive approach in building design and facility management. It increases the ability to find and decide where and when to apply the most appropriate maintenance alternative in concern (i.e. spatio-temporal optimisation). It enables long-term planning of maintenance, repair and rehabilitation (MR&R), enables effective use of resources and increases the margins for better communication with tenants and others that will be affected by maintenance activities. It also increases the margins for carrying out more sophisticated inspections, which is a prerequisite for elaboration of basic data for decision model updates, high quality inquiries, procurements, long-term budgeting and cash flow statement. According to Harris (National Institute of Building Sciences [NIBS], 2007) studies have indicated that 3.8 % of improvements in productivity of the functions that occur in a building would be equal to the total cost of design, construction and operation of the facility. Therefore, designers and facility managers have to ensure that the functions provided by the facility are optimised during the whole life cycle of the building.

To generate basic data for proactive decision making, a considerable amount of information is required, even when looking at a single component. During the life cycle a large amount of information will be generated by and exchanged between the actors, a process that puts special demands on management and co-ordination skills. Unfortunately, much of the generated information is lost when being exchanged, which as a consequence causes troublesome information gaps between the different phases (Halfawy et al, 2004). The information may be missing or scattered to such an extent that it is not economically justifiable to gather it. One reason for this problem is that the sector is heterogeneous and fragmented. Many actors with various tasks and responsibilities are involved in different phases of the building life cycle (Halfawy et al, 2004). The loss of information is especially true for the exchange and sharing of information between the actors of the construction and operation phase (The National Board of Housing, Building and Planning, 2003). In many cases the lost information has to be regenerated over and over again, which is a typical example of an inefficient and non-value adding activity.

The sector is facing a number of challenges. In order to meet the demands of sustainable development the sector has to put efforts on development and implementation of business strategies, methods and tools that reduces the sector's impact on the environment. At the same time the sector has to make the business more cost-effective and competitive. By adopting a proactive approach it is argued that the sector will be able to meet the demand of sustainable development and improve the business efficiency. Implementation of proactive strategies in today's FM business requires the development of systems for service life design and optimised MR&R management, which in turn requires improved management of, and accessibility to, high quality information. By the development of Information and Communication Technology (ICT) concepts, tools and systems there will be possibilities to process and communicate large amounts of information during the building life cycle.

1.2 The opportunities

There is a rapid evolution within the ICT area, both in development of hardware and software but also in term of concepts. The ICT area has opened up new and innovative solutions in many disciplines, certainly in the area of sustainable construction. The recently developed Life cycle Management System (LMS) is one example of an ICT-dependent innovative solution and includes methods, systems and tools for life cycle design and predictive maintenance management in order to meet the demand on sustainability of construction works. Another innovative concept is the Building Information Models/Modelling/Management (BIM). With the development of BIM software applications, new possibilities of efficient computerised information management in AEC/FM have emerged. Kam et al (2003) reported from the Helsinki University of Technology Auditorium Hall 600 (HUT-600) -project that about 50 % time savings were made in the design documentation phase due to the use of BIM. This made it possible to spend more time on economic and environmental Life Cycle Assessment (LCA) as well as on planning of constructability. A BIM may include all types of building project information in design, construction and operation phases and is often presented in 3D. The “3D BIM” provides a more realistic and enriched model, beneficial to all phases in the building life cycle, compared to the conventional 2D representation. The real advantage of the BIM concept is in its parametric and object-oriented approach. Thus the BIM becomes a virtual copy of the real building and not just a stack of lines and layers. However, BIM itself cannot solve the general problem with information communication and exchange. On the initiative by the International Alliance of Interoperability (IAI) Industry Foundation Classes (IFC) has been developed as an open standard for common data structures on information capturing and exchange (IAI, 2007a). The IFC standard has made it possible to share and exchange building information between different IFC compatible BIM applications. The BIM/IFC (open BIM) concept can rationalise the whole AEC/FM process and make it more cost effective. But to what extent can open BIM promote and improve proactive and long-term planning approaches in life cycle design and maintenance management and by that contribute to more sustainable constructions?

There are a number of projects that have shown the benefits of, and provide guidance on open BIM. For example, the recently finished EU-financed Stand-INN project has, through a pan-European consortium, mapped and provided guidance on the existing standards and innovative solutions that improve the value chain in the building process and contributes to sustainable building (Lima et al, 2008). The United States Coast Guard (USCG) has shown in three projects that BIM may improve the work process efficiency in facility assessment and scenario planning by e.g. reducing work effort in data generation and data updating and by improving data quality and accuracy. The overall goal of the projects has been to implement BIM in order to support the tactical and strategic business missions (Eastman et al, 2008). A third example is the buildingSMART mission which aims at improve the productivity and efficiency within the AEC/FM sector by identifying, testing and implementing “smart” information delivery solutions (IAI, 2008). Moreover, Häkkinen (2007) discussed the need and use of building product information in building projects and building maintenance in order to meet requirements on sustainable building.

This paper discusses how open BIM, with the aid of IFC, and PLCS may facilitate the implementation of the LMS concept and by that, improve the feasibility for adopting long-term and dynamic maintenance strategy in the FM process. A case study is carried out, aimed at analysing the possibilities of using a commercial BIM-based design tool as a repository and media to present life cycle information of the exterior part of a hospital building. The case study is specifically focused on the possibilities to:

- Build-up of basic BIM - is there enough of information to build-up a basic BIM
- Add inspection data to the BIM and visualising the information in a 3D model
- Visualise performance-over-time data in a 4D model - With respect to presentation of life cycle information, the case study includes visualisation of condition assessment data and visualisation of a 4D model (3D+time) that simulates the degradation of the exterior part of the hospital building.

It is argued that visualisation and simulation of degradation in 4D will give a more understandable overview of the life cycle performance and MR&R needs of buildings than if presented in tables and graphs.

2. BIM, IFC AND BUILDING SMART

2.1 Definition of BIM

There are a number of BIM definitions among the industry, academia and authorities. Building Information Model, Building Information Modelling and sometimes Building Information Management (NIBS 2007) are all included in the abbreviation “BIM” which is a concept and methodology to describe, simulate and document a building’s physical and functional characteristic during its life cycle. According to the General Services Administration (GSA) BIM is defined as:

Building Information Modeling is the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility. The resulting Building Information Model is a data-rich, object-based, intelligent and parametric digital representation of the facility, from which views appropriate to various users’ needs can be extracted and analyzed to generate feedback and improvement of the facility design.
(GSA, 2007, p. 3)

The definition of open BIM, or Integrated BIM, is extending this definition by stating that *“Integrated BIM, when you share information, requires open standards”* (Kiviniemi et al, 2008).This definition suggests that when using BIM for internal purposes the need for standardization of interfaces is not as strong as when you are using BIM for exchange purposes. The definition aims at the information set representing a building, and not the data model structuring the information.

Due to the variety of BIM definitions there is also a variety of interpretation of the BIM term. What seems to be a common interpretation among non-BIM experts is that BIM is a 3D Computer Aided Design (CAD) model. It is correct that BIM very often is presented as a 3D model built up by a computer-aided design tool. Nevertheless, the 3D model is not a stack of lines; it is a stack of parametric objects with inherent information about themselves and their relations to other objects. Wix et al (2007) and Eastman et al (2008) have noted this confusion and described what BIM is not. Whether the BIM is represented by a 3D model or not (it could likewise be represented by a 2D model), it is the information that matters (Wix et. al. 2007). So what information and data attributes has to be included in order to be called a BIM, i.e. what is the minimum BIM?

2.2 The Minimum BIM

When looking at the definition of BIM one can interpret BIM as a virtual copy of the real building including its life cycle. BIM takes into account the design phase, the construction phase and the operation phase, including demolition. As in the real case the amount of information in the BIM will expand with time, i.e. the BIM will be updated several times during its life cycle. The most obvious information in a BIM is the geometrical attribute data. However, these are only some of many attributes that constitutes a BIM. Information such as material property data, air flow velocity in ventilation pipes and operation and maintenance instructions may be included in BIM. The National Institute of Building Science (NIBS) has developed a National Building Information Modeling Standard (NBIMS) in which they define the minimum BIM (NIBS, 2007). The definition concerns characteristics such as data richness, life cycle views, delivery method, graphical information, information accuracy and interoperability etc. The standard definition on minimum BIM has to be seen as basic requirements for AEC/FM companies who have the intention to implement BIM into their business. But still, the definition of the minimum BIM depends on the type of business the BIM is supposed to support. For example, the definition of minimum BIM is different to an engineer compared to a construction client or owner. The definition of minimum BIM will also vary in time. What is defined as minimum BIM “today” is probably way behind the scope of “tomorrow”. Hietanen and Lehtinen (2006) discussed the useful minimum of IFC implementation (i.e. implementation of interoperability or open BIM) and suggested that: rather have a small scope of implementation with high quality than a large scope with poor quality. Not before the implementation is successful it is time to expand the scope. This may also be valid for the implementation of BIM. For a facility manager it may be enough to implement BIM as an information repository of accurate data as a starter, and later on add analysis or simulation functionality.

2.3 Open BIM

Integration of open standards (e.g. IFC) into BIM (open BIM) seeks solutions to improve the productivity and efficiency of the building process by enabling interoperability between AEC/FM BIM software applications. Open BIM, is the concept of having all the relevant information for the buildings, like physical objects (walls, doors, ducts, elevators, etc.) and abstract objects (relationships, types, groups, etc.) in open formats, making them accessible and readable for anyone, and not locked into proprietary software formats. Open BIM must cover all disciplines and allow for different processes to access the information. To enable this large scope, there will be several open standards needed to support different parts of the information map. As described in section 2.4, the PLCS standard can be a framework linking together different standards.

The benefits of open BIM is demonstrated world-wide by the buildingSMART mission and industry representatives such as Senate Properties, Norwegian State Building Agency (Statsbygg) and GSA have, to various extent, mandated initiatives on supporting the use of the IFC standard (GSA, 2008). With the integration of open standards any open BIM software application will be able to communicate and exchange information with any other open standard compliant software application. The ability to communicate and exchange information is of special importance for open system concepts such as LMS. Without open standards and open BIM a major part of the benefits that follows with the use of LMS is lost as LMS essentially is built up on the prerequisite of having access to information from other system applications.

2.4 BIM and IFC at present and in the future

We now see a growing insight among AEC and FM companies, that BIM is working, but still, you can not exchange the information with other actors, if they have different BIM tools, or the same but differently configured! In the ERAbuild report “Review of the Development and Implementation of IFC compatible BIM” (Kiviniemi et al, 2008), one conclusion is that the industry is gradually starting to use the concept of BIM. Architects are the most adaptive to the new technology, possibly because of their tradition of working with objects and 3D for visualisation. The usage also increases with the size of the company, but in the case of architects in the Nordic countries it seems that small companies are possibly more dynamic and eager to use new BIM applications.

There are definitely short comings in the IFC exchange definitions and implementations of today. Work is ongoing to define exchange specifications – the Model View Definitions (MVD) and the Information Delivery Manuals (IDM) (IAI, 2007b). A more specific and detailed certification will improve the different implementations of IFC.

For a long lasting effort and collaboration among several actors, there is a need for integration and consolidation of the information in a Model Server, a common information hub, a BIM Collaboration Hub™. The standardized exchange format in its own is not enough, see Fig 1. If the standardized format is only used in point to point exchange situations, the information will not be integrated nor consolidated. The Model Server would support LMS as an information repository with all the current and historical versions of objects and characteristics.

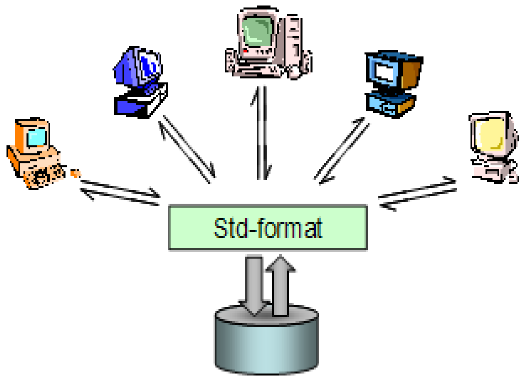

FIG. 1: The different applications are using one common interface to the Hub where the information is integrated and consolidated.

IFC can manage snap shots of the information, but to manage the whole life cycle, there is a need for a standard like PLCS, Product Life Cycle Support (ISO 10303-239) (ISO, 2008), which supports some critical business needs faced by companies as they seek to implement Product Life cycle Management (PLM) and other broad enterprise-based initiatives. The Model Servers shall secure collaboration both within an organization as well as throughout an extended enterprise and its various participants.

One implementation of open BIM is the BIM Collaboration Hub™ based on the model server Share-A-space from Eurostep (2008). At its core, Share-A-space is a standards-based data consolidation and exchange solution. It complements many existing solutions like CAD, Computer Aided Engineering (CAE), Product Data Management (PDM), Enterprise Resource Planning (ERP), and others, and provides the possibility for these solutions to deliver additional value to the enterprise and its business partners. Share-A-space is built on PLCS, a standard that promises to become a key enabler for process improvements in several service-focused industries such as aerospace and defence.

And now Share-A-space is approaching the construction industry supporting the open BIM initiative from buildingSMART International based on the IFC standard, ISO/PAS 16739. Share-A-space opens up the full industrial tool kit for the construction and facility management sector. All the functions traditionally used in the manufacturing industry are now available for the open BIM as the IFC-objects are mapped to PLCS and imported and stored in Share-A-space. The IFC standard is supporting building elements, material, properties, geometry and placements. Combining it with PLCS adds change management, versioning, consolidation, requirement, product as realized, and maintenance to the IFC model.

In Fig. 2 the 3D view of a floor with one highlighted apartment is shown with the tree structure and selected representations of the spatial element structure. The imported IFC file is from Archicad.

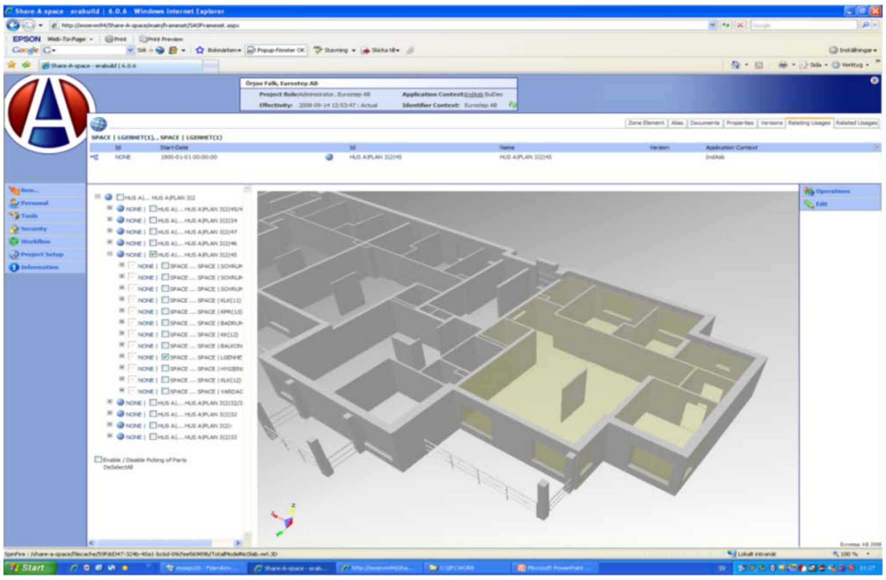

FIG. 2: 3D-view window with tree structure of the spatial break-down of the imported IFC model

A model server like Share-A-space has a number of methods for communication: the traditional Graphical User Interface (GUI), available via traditional Internet browsers, file import/export and mapping for a number of formats to PLCS, and standardized web services for OASIS PLCS PLM web services as well as OMG PLM web services.

The BIM Collaboration Hub™ is based on the results from the European VIVACE project (2004-2007) for the aerospace industry, where one result was the Virtual Enterprise Collaboration Hub. This is a collaborative platform, enabling end-users from different organizations, with different roles and tools to cooperate in all the phases of a building life cycle process. In this platform the Service Oriented Architecture (SOA) is a very important part.

One important function is the requirement break-down, linked to the functional and system break-downs. In Fig. 3, the different structures from requirements to product structure are illustrated. This shows the possibility to link a requirement to a function to a system and in this case to a space, but it could as well be a building element. If and when a requirement is changed, this can be traced to the individual room that is influenced. Notifications, depending on which objects or object classes one is subscribing to, are then sent for awareness and actions.

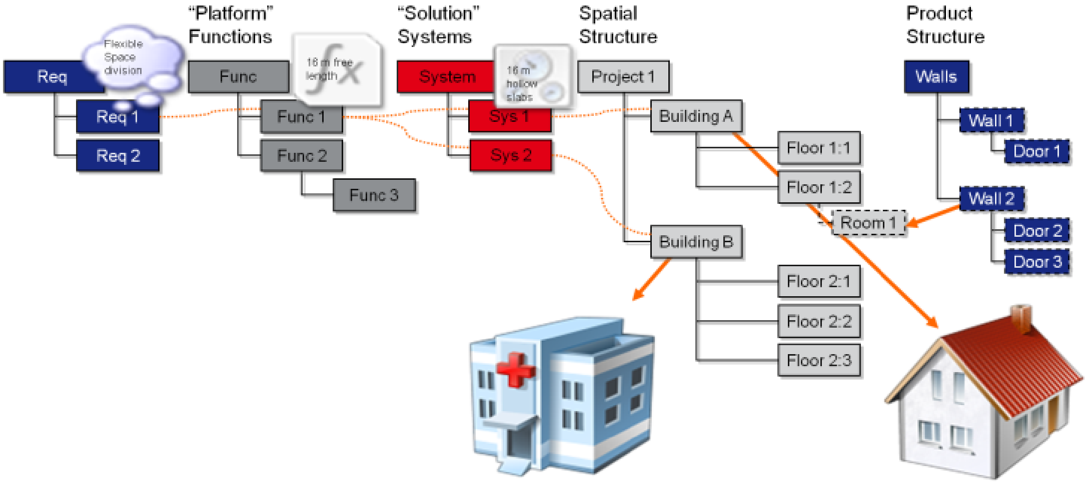

FIG. 3: Different structures are represented and linked in PLCS and Share-A-space

All the IFC objects imported into Share-A-space are represented with properties, versions, relations, and geometry. In addition to the IFC geometry, also native CAD formats, Virtual Reality Modelling Language (VRML) and specific 3D viewing formats can be added to each object depending on needs. In Figure 4, a door is shown in the Share-A-space GUI with some of the available information.

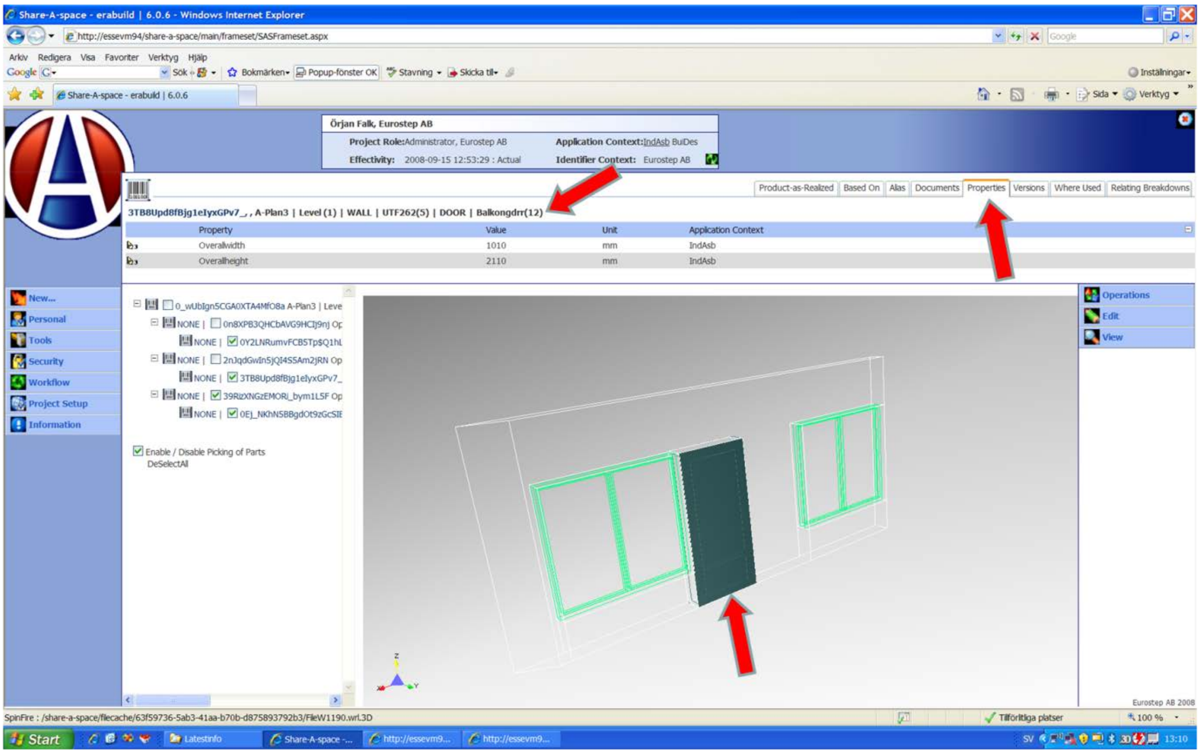

FIG. 4: The individual objects can be viewed together with their tree structures, properties, and other information types.

The PLCS standard enables product information to be linked to support information during the whole life cycle for a product, see Fig. 5, which now also is applicable for the AEC and FM industry.

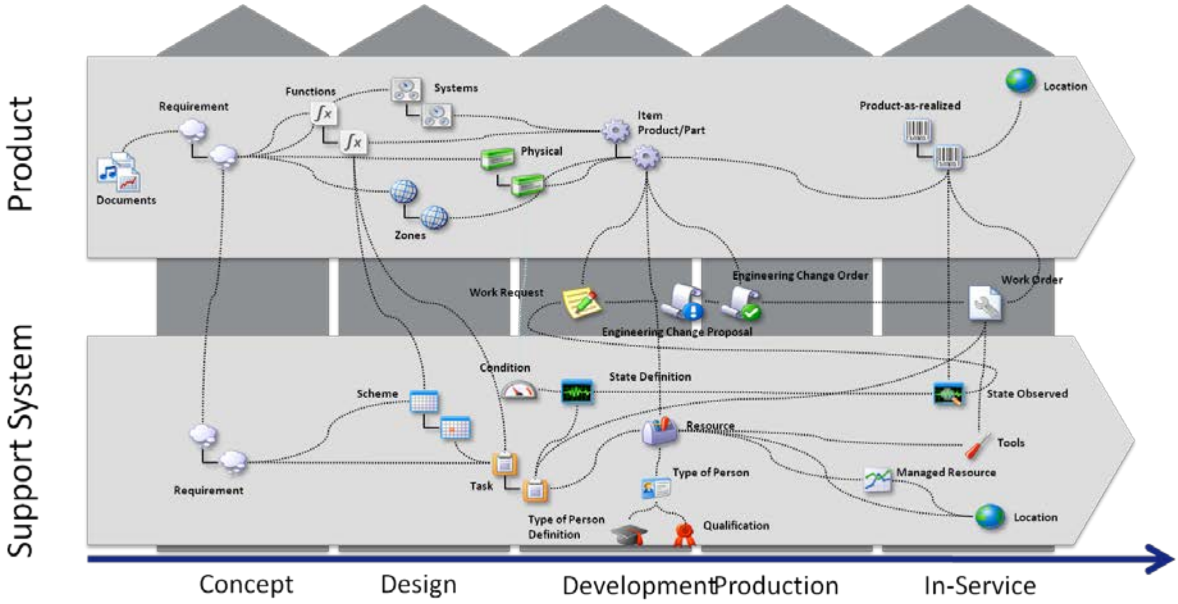

FIG. 5: The business objects in PLCS and Share-A-space for products and their support systems.

The PLCS standard has place-holders for requirements and characteristics for both the design of the product and the design of the support solutions. LMS information like characteristics for the product can be versioned and the different states which the product can have during its life-time can also be defined and described. The observation of the current state can be stored and related to a pre-defined state. All the maintenance tasks can be planned and related to a specific version of the products and also to the individuals of the physical building. The tasks carried out are linked to the planned activities and the possible deviation in time and resources utilized can then be traced, as well as the reason for this. To all the different versions of the products and the tasks, documents and characteristics can be linked to support the analysis of the maintenance processes.

3. SYSTEM FOR LIFE CYCLE DESIGN AND MR&R MANAGEMENT

3.1 Facility Management (FM) Systems

The essence of modern FM is to plan and organise the use and maintenance of buildings and aims to support and add value to the core business rather than being a cost (Svensson, 1998). Maintenance is however often seen as a necessary cost that does not add value to the core business. Maintenance activities disturb more or less the core business and become a source of annoyance that increases with relatively short-term planning and insufficient communication. In order to keep the maintenance as cost-effective as possible and adopting long-term planning, there is a need for systems that are capable of creating proactive solutions and handling large amounts of data. It is concluded that advanced data analyses, which are necessary in proactive systems, are too onerous to be managed without computerised systems (Shepard, 2005). Two example of computerised FM system are Vertex® by Mactec and BUILDER™ by the US Army Corps of Engineers. The systems are built on the Engineered Management System (EMS) standard developed by the US Air Force (Mactec, 2008, US Army ERDC, 2008). Both systems are partly built up on condition assessment procedures and include functions to predict the future condition of buildings. Within bridge management there are a number of so-called Bridge Management Systems (BMS) on the market. The most well-known BMS is probably PONTIS, but there are also DANBRO, BaTMan and BridgeMan (REHABCON, 2004). These BMS seem however to lack predictive functions that are capable of handling changes of performance-over-time of construction works. There seems also to be a lack of superior systems that give the controlling parameters and signals of the capital value development (Lerfald and Sund, 2003).

Promoted by an increased European focus on research and development on sustainable construction, three consecutive EU-projects, Wood-Assess, MMWood and Lifecon, (Haagenrud et al, 1999, Haagenrud, 2001, Sarja, 2004) have developed methods, systems and tools for predictive maintenance management in order to meet the demand on sustainability of construction works. The result of these projects is the predictive and generic Life cycle Management System (LMS), which aims at supporting all types of decision making and planning of optimal design, maintenance, repair and refurbishment (MR&R) activities of any construction works and systems therein. Due to its predictive function, it is possible to adopt a proactive planning approach. Short-term as well as long-term planning strategies are included, where the decisions may be based on economical, environmental, safety, cultural and social values.

The LMS was initially developed as a European model for predictive maintenance management of concrete infrastructures, where the general objective was to contribute to the development of FM and change the traditional reactive management approach into an open, predictive and integrated life cycle based approach. There are three main novelties in the LMS (Sarja, 2004).

- Predictive characteristic: The LMS includes integrated performance analysis functions that are capable of predicting the functional and performance quality of a structure and its components.
- Integration: Aspects of sustainable development such as human requirements, economic and environmental LCA and cultural requirements are included in MR&R planning, design and execution process
- Openness: Freedom to apply the LMS into specific applications using selected modules and freedom to select methods developed within or outside the system.

3.2 Description of LMS

LMS is a system by which the complete system or parts thereof, work in co-operation or as a complement to existing business support systems. The system is module-based, where each module represents a sub-process within the design and MR&R planning process. Fig. 6 shows the structure of LMS and its connection to other business support systems.

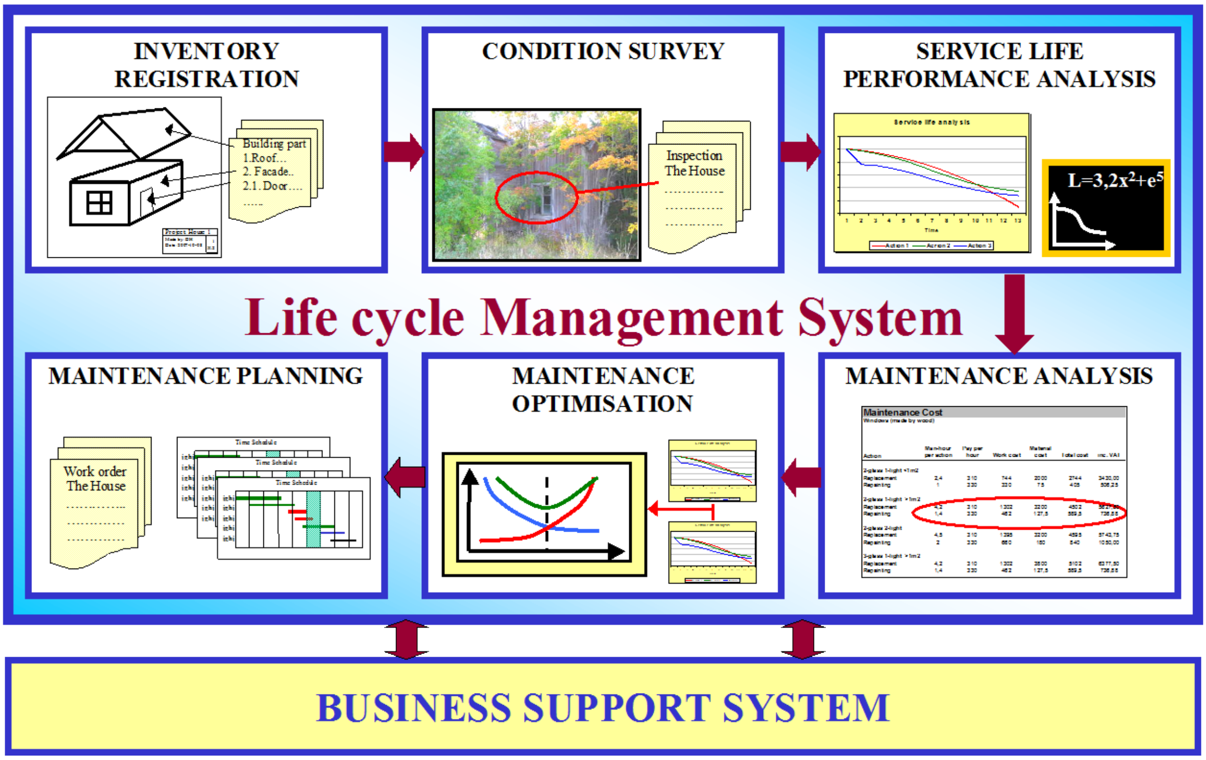

FIG. 6: Simplified structure of the module based LMS

The first module, i.e. the *Inventory Registration Module*, contains systematic registration, classification and description of technical and administrative data of the objects/systems. The *Condition Survey Module* includes systematic recording of condition data. This includes guidelines and protocols for condition assessment and survey in order to obtain consistent and reliable inspection/observation results on the items and their environment. The “heart” of the system is the *Service Life Performance Analysis* (SLPA) module. This module contains applicable degradation models and simulates the loss of performance-over-time of a material, component or a system. The *Maintenance Analysis Module* includes systematic analysis of different MR&R alternatives by utilising the predictive functions of the SLPA module in order to evaluate the efficiency of the MR&R alternatives. The *Maintenance Optimisation Module* contains models for optimisation of those MR&R actions suggested in the Maintenance Analysis Module. It takes into account optimisation on both an object level as well as a network level (population of buildings). Methodologies on economic and environmental LCA are utilised. The final module within the LMS is the *Maintenance-Planning Module.* This module serves to establish optimised long-term plans of MR&R actions on both an object level as well as a network level.

3.3 Condition survey system

One of the corner-stones in LMS, as for many FM systems, is the condition survey system. The condition survey system, in which ocular inspections constitute the key-activities, seeks for systematic and consistent condition data recording and management. The inspections are used to assess the condition and identify emerging maintenance needs and give input to planning and budgeting of future maintenance actions. The demand of systematic and consistent data recording is of special importance when using the captured data for development of new damage functions or improvement of existing degradation models. In contrast to a number of other FM systems, the LMS condition survey module is object-oriented and built up on the prerequisite of having access to all basic information of the building and its components, structured in the inventory registration module. This approach makes the condition data capturing and data recording more consistent and certainly more efficient compared to other systems. A mobile-based condition survey system makes the condition data capturing even more efficient. In the WoodAssess project a Personal Digital Assistant (PDA) system for on-site data capturing was developed and evaluated (Haagenrud et al 1999). One of the difficulties of that system was to describe the location and orientation of the inspected object. Hammad et al (2006) described a Mobile Model-based Bridge Life cycle Management System (MMBLMS) in which different technologies together with 3D models were used to make the data capturing more efficient and simplified. Part of the technologies used in that system seems to be a promising aid in the LMS condition survey system. However, this requires that the LMS is based on BIM.

3.4 Service life performance analysis

One of the novelties of the LMS is the ability to predict the performance-over-time behaviour of structures and their components based on service life performance analysis. This ability provides for integration of sustainable aspects such as human requirements, life cycle economy, life cycle ecology and cultural requirements. The predictive capability is an essential ingredient in proactive life cycle design and MR&R planning processes. In Fig. 7 the principle of performance-over-time of a building or component is demonstrated. As the performance of a component reaches the performance criteria (or requirement) the service life is ended. In order to extend the service life MR&R actions are needed.

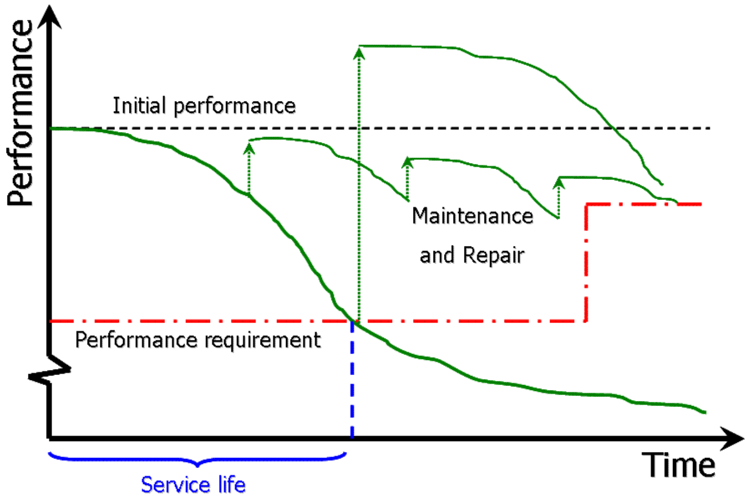

FIG. 7: Performance-over-time and the service life of a component.

The predictive function of LMS is basically based on a strictly technical approach in which degradation models constitute the kernel of the analysis and predictions. The complexity of these models varies. Some of the degradation models are quite complex and based on a strictly physio-chemical explanation. These models depend on the material as well as the environmental characteristic of the components and their exposures. Other models are of a more moderate complexity such as dose-response functions and damage functions. Such functions were used in the web-based lifetime analysis service presented by Bjørkhaug et al (2005) and in the web-based LMS-ByggaVilla tool presented by Hallberg et al (2008).

With the development and introduction of the ISO 15686 standard series producers of building products are given possibilities to declare the service life of their products and to some extent even develop material and product specific degradation models, at least to provide basic data for the development of such models. The standard is intended to help producers of building products and building designers to declare reference service life and service life performance of buildings and building products (ISO, 2000). The standard describes and gives guidance on the process of how to capture basic data for service life prediction, reference service life declarations and perform service life planning. An initiative to make description of the data requirements in service life planning IFC compatible is now taken by ISO 15686 and IAI (Sjöström, 2008).

3.5 Demand of efficient and easy-to-use system

More than 170 potential user requirements were identified in the Lifecon project. The conclusion is that the governing user requirements are:

- An attractive system/interface
- Easy to use system
- Quick system (where the results of the analysis is achieved quickly and easily)

The most laborious part of the information management in LMS comprises data entry, above all inventory data. A study of the more specific Lifecon user requirement on data entry and management makes the conclusion that the data entry should be as simple as possible. This requirement can be achieved with the use of templates, default values and import/export functions. User requirements on object searching are identified as functions with the ability to find object information from list of objects, ability of using object search criteria and ability of selecting objects directly from a graphical representation (drawings and maps). A third group of user requirements is on how to present the information. The conclusion is that the information should be presented in several ways, basically as text and graphics such as pictures and drawings (Lahus et al., 2003).

The use of SLPA in maintenance decision making and planning requires a large amount of data. The type of data involved in SLPA encompasses inventory, administrative, structural, material, historical, environmental, condition and MR&R data. Whether the data is downloaded from an external database or registered by hand it has to be arranged in a systematic (and hierarchic) manner. The systematic arrangement has to be applicable to any structure and suitable for a range of applications and have a common understanding (Söderqvist and Vesikari, 2003). Due to this demand the Lifecon project developed a hierarchic building information registration structure consisting of six levels (Söderqvist and Vesikari, 2003), see Table 1.

TABLE 1: The Lifecon building information registration structure

Type of level	Type of information
Level 1: Object	Type of building/structure
Level 2: Module	Division of the building/structure into the largest parts, e.g. roof, facade, foundation, floors, etc.
Level 3: Component	A component that fulfils a certain function, e.g. window, door, etc. Can consist of different materials and sub-components
Level 4: Sub-component/ resistance	The sub-components consist of one material.
Level 5: Surface/ environmental influences	The sub-components are divided into surfaces that are exposed to a certain environment.
Level 6: Detail/material	Description of inner layers of surface and details perpendicular to the surface.

The system can be simplified by merging two or several levels. Whatever the level of detail and need of accuracy, there is a great amount of information to be managed by the system.

To conclude, the data entry and management process has to be supported by a tool which makes the data entry and management systematic, simple and efficient, where a graphical representation of the entered data can be made instantly in a single medium. These requirements correspond to the functionalities provided by BIM-based design tools. According to the validation report of the Lifecon project it was concluded that the development and exploitation of BIM and the IFC-standard would have a large impact on the Inventory Registration Module of LMS (Sjöström et al., 2004). This is also proven in the USCG case in which it is shown that BIM can serve well as a database for facility information (Eastman et al, 2008).

4. VISUALISATION OF LONG-TERM PERFORMANCE OF BUILDINGS AND BUILDING COMPONENTS

4.1 Visualisation of building information

Historically it has been difficult to introduce expert system (or decision support system) technology within the construction industry. Several reasons for this have been concluded as (Kaetzel and Clifton 1995):

- User attitude - the technology has not delivered as expected
- Limitations of receiving knowledge about a subject
- Lack of easy-to-use tools

According to Kaetzel and Clifton (1995) the implementation of a visual representation of knowledge in an expert system may eliminate the number of questions required by the system and by that reduce the interaction between the user and system. As a consequence, the users will experience the system as more efficient. The concluding remark was:

Complex knowledge (e.g., building codes and mathematical models) will be integrated in many different forms. Visual information will become an increasingly important component to aid in the display of the experts system's knowledge. This will improve the usefulness of expert systems.

(Kaetzel and Clifton, 1995, p. 172)

Kyle et al (2002) made some general observation on visualisation during the development and testing of the decision support tool “Visualizer”. Two of the observations were:

- Visualisation can be a useful cognitive aid for grasping the large amount of data needed in decision making of asset management
- Conceptually structured information is needed when developing visualisation tools.

In the HUT-600 project visualisation tools were used to improve the communication between the end-users, construction client/owner and project team. By utilising a 4D model the client was able to ask what-if questions, receive cost and performance feedback and deliver additional and valuable input to the project team (Kam et al, 2003).

4.2 The use of 4D visualisation techniques in maintenance management and life cycle design

One major advantage of using 4D models as a tool for visualisation, simulation and analysis is its ability to show spatio-temporal and logical information through a single medium (Koo and Fischer, 2000). Since performance-over-time of buildings is characterised by spatio-temporal and logical oriented behaviour, adoption of 4D technology would be an appropriate approach in order to get a better overview and a more understandable presentation of SLPA results. By using the 4D technology it may be possible to visualise performance-over-time behaviour of buildings and components. There are on-going R&D activities within the area of 4D technology, especially in construction scheduling and workspace planning (e.g. Dawood et al, 2005, Dawood and Mallasi, 2006, Jongeling and Olofsson, 2007, Staub-French and Khanzode, 2007, Koo and Fischer 2000, Kam et al, 2003, Eastman et al, 2008). Heesom and Mahdjoubi (2004) concluded that most of the commercial 4D applications are focusing on simulations for aesthetic visualisation purposes. Only a sparse number of papers, demonstrating and discussing the use of 4D models in service life planning, have been found. For example, Kyle et al (2002) developed a 2D decision-support tool for service life prediction in assets management. However, it was concluded that the tool required user’s effort and solutions for data updating and consistency in order to associate shapes with database records. To meet this need it was suggested to use model-based systems or integrated CAD databases. Model-based systems provide a “richer” vocabulary by its allowance of generically different representations of entities, e.g. 3D models (Kyle et al, 2002). Hammad et al (2006) developed a Mobile Model-based Bridge Life cycle Management System in which information of different life cycle stages of bridges were linked to and presented through a 4D model. The system also included methods for condition data entry as well as workspace planning of maintenance actions. Rad and Khosrowshahi (1997) discussed the use of 4D visualisation and its representation through VRML in building maintenance. They demonstrated a 4D concept where building maintenance of lighting, painting and carpets was taken into consideration. The lifetime and life expectancy of the objects were mathematically described by the use of probability density functions. Khosrowshahi and Banissi (2001) further developed this approach with a focus on flooring systems. It was concluded that the 4D visual model could be used as a tool to evaluate life cycle performance and develop long-term maintenance plans. Linnert et al (2000) demonstrated a system where the life cycle behaviour of a single-family house was visualised in a 4D model. Two visualisation modes were presented. One in which the building parts were displayed as transparent when the service life was reached. The second mode was based on a colour scale in which the building parts shifted in colour as the parts became older. As the life cycle estimations were based only on tabulated values it was recommended as further work to include the influence of geographical locations, orientation, climatic zone etc in the life cycle estimations (Linnert et al 2000).

Despite that visualisation of items and processes is one of the major benefits of using open BIM none of the projects on visualisation of life cycle performance presented above was based on the open BIM concept. Kyle et al (2002) discussed the need of model-based system, product modelling, integrated CAD systems and the standardisation of open standards for interoperability. Bjørkhaug et al (2005) presented a web-based and IFC-compatible application for lifetime analysis service based on dose-response functions. However, lifetime analyses results were not visualised in 3D models.

5. CASE STUDY

5.1 The LMS-Locum project

Locum AB is one of the larger property managers in Sweden, responsible for about 2.2 million m^2 of floor area within the Stockholm County (Locum 2008). Most of the properties are hospital buildings owned by the County Council and by private healthcare actors. The properties are divided into strategic properties and market properties. The market properties are those that the County Council intends to sell once the market is favourable, while the strategic properties are intended to be owned and utilised over a long time (Locum 2008). The owner's demand on economical return requires efficient management and development of the property, both in a short-term as well as in a long-term perspective. The latter certainly requires proactive and long-term strategies. However, the FM system of Locum is lacking tools that are able to support proactive maintenance management strategies and decisions.

At the end of 2005 Locum AB and The University of Gävle launched a pilot project in order to develop a customised LMS demo to support proactive maintenance management. The project mainly focused on data management and SLPA of the exterior part of a hospital building at Norrtälje, which is located in the north part of the Stockholm County. The LMS demo project was divided in two phases. The first phase focused on data capturing, data management and SLPA. It included development of a relational database and demonstration of three different types of SLPA models. The second phase focused on development of a BIM and 4D visualisation of performance-over-time behaviour of components. This phase was partly initiated by Locum's current effort in implementing and evaluating BIM as part of their FM business, partly within the current trend of adopting the BIM concept in general.

5.2 The basic BIM design of Norrtälje Hospital

The basic BIM of Norrtälje Hospital, Fig. 8, is developed in Revit Architecture and encompasses the exterior part of the building. The roof and the topography are excluded in the basic model. The geometrical input variables are based on available 2D CAD drawings, representing the façades and floor plans.

FIG. 8: The basic 3D BIM of Norrtälje Hospital

Virtual building components such as windows and doors were downloaded from building component libraries and added to the model. No exact digital object representatives of e.g. windows and doors of Norrtälje Hospital were found. A similar problem was identified by Manning and Messner (2008). However, there is a continuously growing number of parametric objects to be found in different design tools and on different community sites on the internet. The lack of parametric objects of old buildings is on the other hand to be expected since old building components are often locally produced and not digitised, at least not as parametric objects.

On top of the geometrical model, additional object specific properties were added, above all material property data and condition assessment data. Revit Architecture includes possibilities to predefine a number of physical parameters for the most common materials used in construction works. However, these parameters refer to strength and bearing capacity, thermal expansion and unit weight. Material property parameters in the context of durability are not yet available in the material property set menu.

The build-up of the information was simple, more clear and efficient compared to the data entry in the relational database (phase one of the LMS-Locum project). The information, presented in 3D views, consisted of much more enriched data than the traditional relational database.

Generally, only a sparse amount of digitised information was available. CAD drawings, some administrative data, and condition survey data were captured. Information about the past MR&R actions was not found. Present employees as well as retired personnel were interviewed in an attempt to gather undocumented data, yet without success. Much of the information that has been generated during the years has not been documented.

5.3 Input and presentation of condition assessment data

In 2004 a major inspection of the facilities at Norrtälje Hospital was carried out. Some of these inspection data have been entered into the BIM-based design tool in order to analyse the possibilities to store and present inspection data directly in the 3D model. Attributes such as "Date of inspection" and "Condition class" have been added as additional object attributes. By the use of schedules the data can be categorised and presented in different formats. In Fig. 9 windows in condition class 3 are presented in a schedule and as highlighted objects in the 3D representation of the BIM. Inversely, an object can be marked in the 3D model, whereupon the object information is displayed in a pop-up window. By the use of a query-builder it is possible to search for certain object parameter values and present the matching objects in the 3D model as highlighted items. Due to the 3D graphical representation, the search results become clear and grasping, a feature that is valuable when planning for e.g. maintenance actions. Adding Uniform Resource Locator (URL) addresses as attributes makes it possible to link e.g. pictures of damages (or other documents) to each component. However, the ability to establish data history of inspection results is limited.

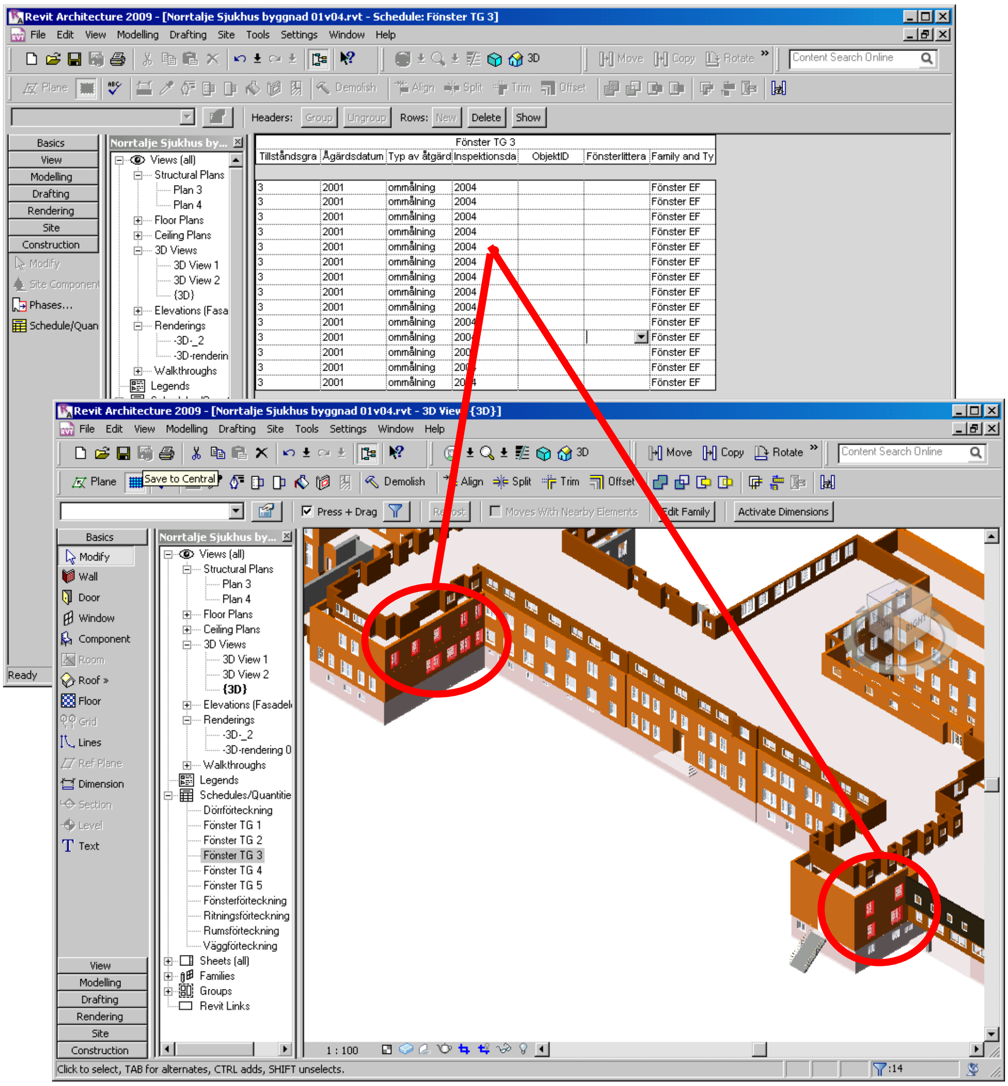

FIG. 9: Windows of condition class 3 presented in a schedule and the 3D model.

5.4 4D visualisation of life cycle performance of Norrtälje Hospital

Two different degradation models are used to describe and visualise the performance–over-time of windows and the concrete structure in the 3D model. The first degradation model, describing the performance-over-time of windows in terms of condition classes, is based on data from the MOBAK study (Tolstoy et al 1990) and takes the orientation of the windows into consideration. The condition classes used in the model are based on Locum's 5 grade scale condition classification system, in which condition class (CC) 1 corresponds to an extremely bad condition and CC 5 corresponds to "as new" (Locum 2004). Each condition class is represented by a colour. As the time goes by the performance loss will increase and the condition of each component will change from one class to another. Likewise the colour representing the condition of the components will change. The conditions of the windows at certain times are showed in Fig. 10 (colour scale at the upper left corner).

The second degradation model is a carbonation model that describes the dynamic relation between the depth of carbonated concrete and the depth of the protecting concrete cover. As long as the carbonation front does not reached the reinforcement bars, the concrete cover is assumed to be in service. However, once the carbonation front reaches the reinforcement bars, the concrete cover is assumed to have reached its service life. The basic carbonation model (Eq. 1), presented by Sarja and Vesikari (1996), takes both material properties and environmental properties into account.

$$
\begin{aligned}
&d(t) = K_c t^{1/2} \\
&where \\
&K_c = c_{env} c_{air} a f_{cm}^{b}
\end{aligned}
\qquad \text{Eq. 1:}
$$

K_c is the carbonation rate factor (mm/year^{½}), d(t) is the carbonation depth (mm) at a certain time t (year), d_{crit} is the depth of concrete cover (mm), c_{env} and c_{air} are coefficients due to rain exposure and air content in concrete, f_{cm} is the mean compression strength factor (MPa) and a and b are coefficients due to the binding agents.

The time dependent rate of carbonated concrete in relation to the depth of concrete cover, i.e. $d(t)/d_{crit}$ (%) is visualised by the use of a colour scale (upper right corner of each snapshots), see Fig. 10.

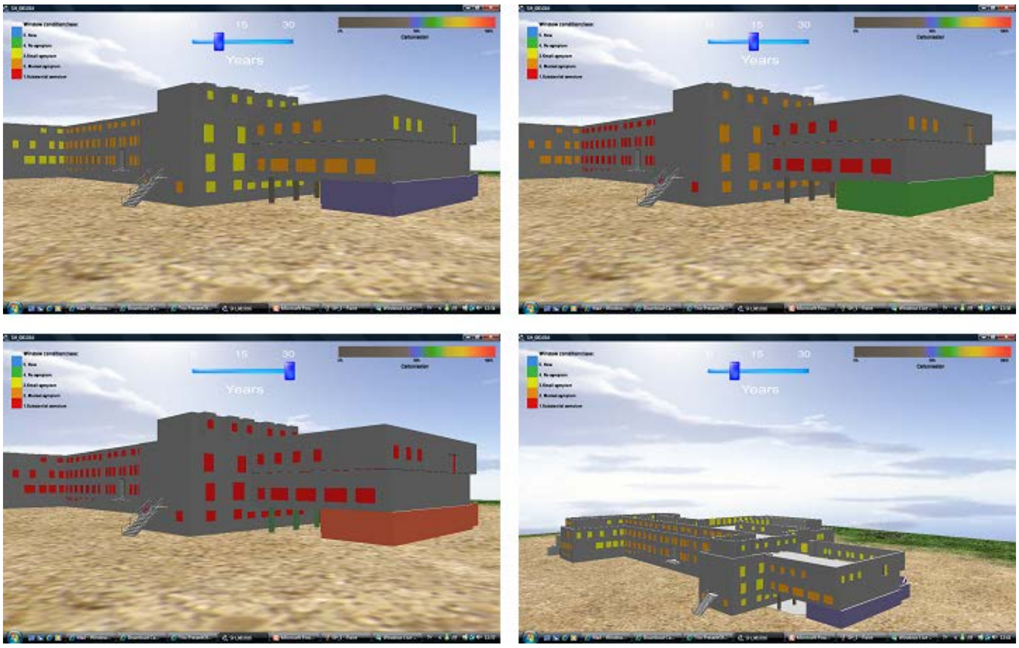

FIG. 10: Simulation and visualisation of the performance-over-time of windows and concrete structures at different times

The visualisation of the performance-over-time is done in World Viz based on a wrl. file, transformed from a dwg. file by the use of the NuGraf software. This stepwise process is necessary since World Viz is not compatible with the different BIM-formats. The interactivity, controlled by a time-slider, is done with python script. The time-slider is movable back and forward, which makes it possible for the user to analyse the condition of the different components at different moments. This makes it possible to compare the life cycle performance behaviour of the different components, and identify maintenance "intensive" components or analyse the impact of a maintenance action.

6. DISCUSSION AND CONCLUSIONS

The paper discusses how BIM and open BIM may facilitate the implementation of a predictive Life cycle Management System and by that improve the feasibility for adopting long-term and dynamic maintenance strategy in the FM process. The conclusion is that the use of BIM in general enriches the building information, rationalises the information management and simultaneously minimises the errors that may occur during the building process. These benefits will save time and provide scope for new innovative solutions which may add value to the business on all levels. This in turn may lead to a more efficient and reliable business. The time saving potential that is associated with BIM, and certainly open BIM, is one of the major arguments for utilising BIM as promoter for implementation of long-term and sustainable strategies in the building process. The time saved will make way for thorough life cycle analyses, service life planning and more solid life cycle optimisations of the design and use of the buildings. The full success of BIM lies within the adoption and integration of open standards, e.g. IFC. As the AEC/FM sector is heterogeneous, fragmented and works more and more on a global market the ability to communicate and exchange information between the actors will be an important success factor in order to make the sector more efficient, competitive and reliable. The current effort in developing and demonstrating the benefits of open BIM, led by IAI via the buildingSMART mission is a promising initiative to make the AEC/FM sector aware of the inherent potential of open BIM. With the introduction of model servers the support for life cycle management of the building will improve. The more examples and demonstration of best practices, the more the sector will realise the benefits of open BIM, which will increase the adoption of the concept, and by that make the sector more efficient, sustainable and competitive.

In the case study presented above it is shown that commercial BIM-based design tools may serve as information repositories of basic data for use in a predictive LMS. BIM-based design tools, such as Revit Architecture, meet the requirements of an efficient and easy-to-use system for basic inventory information management stated in the Lifecon project. The build-up of the information becomes simpler, more clear and efficient compared to a traditional database solution, as it is done with parametric objects. Parametric and object-oriented BIMs presented in 3D views consist of much more enriched data than traditional database-oriented FM systems. Once the basic BIM is created it will be possible with small efforts to utilise, maintain and upgrade the model, e.g. link pictures (documents) to each component. However, the basic BIM can not serve for all LMS functions. There is still the need for development of a BIM integrated LMS solution that may support prediction of life cycle performance and maintenance needs. Such a solution needs to be communicative to any open BIM software and thus has to be built upon open standards for exchange of building information, e.g. the IFC standard, and life cycle oriented standards like PLCS.

Visualisation and communication of building information in 3D and even 4D have become an essential part in the strive for an improved, more reliable and efficient building process. The use of 3D visualisation has been shown to be an efficient way to avoid collisions and mismatches in the building process. This has also been confirmed in the case study in which the use of 3D BIM has identified mismatches in the existing 2D CAD drawings. With the rapid development towards more complex building projects it has been more and more important to simulate and visualise the building process over time. A number of projects demonstrating and discussing the use of 4D techniques in construction scheduling and workspace planning have been identified. Only a few projects in which the 4D technique has been utilised to visualise the building performance-over-time have been found. In this case study degradation models have been utilised to visualise the performance-over-time of different building components in a 4D model (3D + time). The 4D model is based on the 3D model derived from the basic BIM. Despite that the import of the 3D model in this case has not been straightforward, (some hands-on data format converting has been required) it still shows the advantage of having a 3D BIM available. Nevertheless, practitioners showed interest in the 4D model. However, more research is needed to indicate whether 4D visualisation of service life performance of building components is a solution that may add value to the FM business.

The initiative to make the description of the data requirements in service life planning IFC compatible is now taken by ISO 15686 and IAI (Sjöström, 2008). This is a good first step to make the service life information more available for use in e.g. LMS. It would be preferable to make the complete building product declaration and the ISO 15686 standard IFC compatible and thereby make the information and use of data more accessible. An overall goal would be to incorporate IFC-based building product declaration data as a natural part in building product models and thereby provide important input to sustainable construction. To achieve this goal the market has to support the development of open standards and open BIM concurrently as they implement the technology into the business.

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