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Interoperability requirements for automated manufacturing systems in construction

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Abstract Multi-disciplinary software interoperability in the Architecture, Engineering, Construction and Operations industry is becoming a new and widely adopted business culture. Technical advances in interoperability architectures, frameworks, methods and standards during the last decade resulted in higher maturity of product and process models. Mature models, in effect, enable data exchange by an increasing number of software applications in the industry. This establishes trust in data exchange and results in the lower cost impact of inefficient interoperability. The negative cost impact increases with advancing life-cycle phase, from planning and design phase to construction phase and to operation and maintenance phase. Interoperability in the planning and design phase is most mature and well published, while interoperability in the construction phase and for automated manufacturing is less researched. This paper reviews state-of-the art automated manufacturing systems in construction and researches interoperability requirements for automated construction in context of the entire building lifecycle. Our research is based on experimental free-form clay building, designed with embedded simple HVAC components, and manufactured with additive layer technology. Conclusions provide valuable results for interoperability research and practice in construction projects with automated manufacturing systems in place.

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Introduction

Architecture, Engineering, Construction and Operations (AECO) industry is a major business driver; however, in the recent history many periods of decline of certainty for the industry are reported. In the days before interoperability (1979–1998) major issue was labour productivity because researchers reported significant decrease of labour productivity in the construction industry (Rojas and Aramvareekul 2003). Studies identified different reasons for loss of labor productivity: over-manning during project (Hanna et al. 2005), labor inefficiency associated with shift work (Hanna et al. 2008). Early solutions proposed modelling of construction labor productivity (Thomas et al. 1990) and use of predictive behaviours models based on neural networks for concrete tasks, formwork and concrete finishing tasks (Sonmez and Rowings 1998). Latest research proposes agent-based modelling of construction productivity (Watkins et al. 2009). When these productivity models are applied to collections of data from past projects, they provide basis for research in productivity measurements (Song and AbouRizk 2008). Metrics have been developed that measure productivity at a company, project and/or task level (Wang et al. 2010). Once produced, these metrics and tools can help construction industry stakeholders to make more cost-effective investments in productivity enhancing technologies and improved life-cycle construction processes (Chapman et al. 2011).

In parallel, construction management research has elaborated inefficiency in construction as project scheduling problem (Bogus et al. 2005; Lorterapong and Ussavadilokrit

2012) for which solutions are proposed towards the minimization of the Project Completion Time (PCT) and the minimization of the Project Completion Cost (PCC) (Bogus et al. 2011). Methods for both minimal PCT and PCC can be grouped into the optimization-based scheduling and concurrency-based scheduling. Optimization-based scheduling assigns additional resources or substitutes construction methods in the construction workflow in order to minimize PCT and PCC. Concurrency-based scheduling minimizes PCT and PCC without assigning additional resources, but optimizes the overlap of predecessors and successors tasks in the construction workflow.

Where does interoperability comes in? More recently, interoperability was regarded as the driving force behind efforts for improved productivity in the construction industry (Wang et al. 2009; Coleman and Jun 2012). It is widely believed that the establishment of interoperability of the information systems between project stakeholders can generate significant business value and enable profitable growth (Loukis and Charalabidis 2013), if the AEC industry would minimise cost of interoperability inefficiency (Gallaher and Chapman 2004) between stakeholders in the construction processes. Therefore, interoperability in the construction industry improves construction labour productivity thru diminishing duplication of effort and reducing the chance of on-site mistakes, which in consequence, saves time. The negative cost impact increases with advancing life-cycle phase (Fig. 1), from planning and design phase (17 %) to construction phase (26 %) and to operation and maintenance phase (57 %). Interoperability between stakeholders in the planning and design phase shows the highest take-up rate and therefore low cost of interoperability inefficiency, while interoperability inefficiency in the construction, operations and maintenance phase grows exponentially.

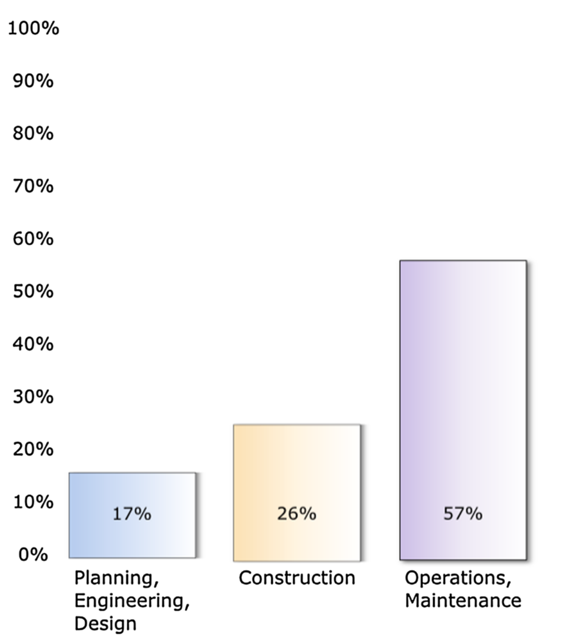

Fig. 1 Cost share of inefficient interoperability in construction projects (Gallaher et al. 2004)

Interoperability is a vibrant research topic in many other industries. For example, design and analysis process interoperability for mechanical industry (Aifaoui et al. 2006) and interoperability between major product data management systems in the supply chain for automotive industry (AIAG-NIST 2003; Ray and Jones 2006). In this paper we research interoperability requirements for use of automated manufacturing systems during construction phase of a building. We believe that interoperability, which involves more automation in the construction phase, can decrease overall interoperability inefficiency. Introductory sections provide the necessary context by reviewing existing automated manufacturing systems. In the main section a mathematical foundation for interoperability demand is developed. Based on research experiment, where a free-form clay building was designed and manufactured, interoperability criteria for automated manufacturing systems in construction were specified. Concluding section summarizes results of our research.

Review of existing automated manufacturing systems in construction

First automated systems to erect a whole building have been the so-called building factories developed in Japan from mid-1980 on. They are based on various robotic systems integrated into a factory, which is erecting together with the building.

Another approach, which emerged in the beginning of the new millennium, is based on the additive layer manufacturing technology concept, also called 3D printing, where layers of building material are printed or produced one onto another. 3D printing has already been recognized as the manufacturing technology of the future (Wright 2001).

In this section review of the automated manufacturing systems in construction falls into two categories: Integrated Robotic Systems (IRS) and Additive Layer Manufacturing (ALM) technologies.

Integrated robotic systems

Prefabricated building is in use for over a century, motivated by low costs and fast erection. Typical building structures include reinforced concrete structure, steel structure and steel framed reinforced concrete structure. Automation in the building construction has developed for each type of structure (Shinko Research Co. 2007). In the mid-1980s Japanese building contractors made intensive investment to develop automated building systems, as well as a variety of robots for different construction tasks. Steel fabricators started introducing welding robots at the same time.

Building factory

Development of automated systems for entire building construction started around 1990. The systems combine building robots and automatic transferring system, prefabrication and unitization, and computer technology for controlling the systems. Various systems have been developed, for example Automated Building Construction System (ABCS) (Kudoh 1995) for steel structures, and "Shuttle rise" and "Big Canopy" (used mainly for the construction of high-rise reinforced concrete apartment buildings, (Wakisaka et al. 2000)) for reinforced concrete structures. They have significantly improved quality, reduced heavy manual labour and enabled a factory type and look environment, which was safer and independent of various weather conditions. After the economy bubble the development of the "building factories" slowed down due to the reduction of research and development investments, but such systems are still in use.

In the literature about Japan Building Factories (BF) we could not find discussions related to the requirements regarding design. It is, however, obvious that robotic systems need digital instructions in the same way as Computer Numerical Control (CNC) machines in manufacturing industry. Following the analogy of manufacturing, where CNC systems are highly automated, using CAD and CAM programs and models (Reintjes 1991), we can assume that Building Information Models (BIM) are used today as information input for the building factories.

Future home

In 1999 a European FP5 project started under the name FutureHome (FH) as part of the Brite-Euram program as well as a part of global programs IMS (EU, Japan and Canada). The main objective of the project was Housing for Europe in the next century: Affordable, high quality homes for all. FutureHome can be seen as a next step of "Building factory" as it is following the concept of integrated construction automation using various robotic systems. It covers all stages of the house-building construction process from architect's desk to site robots:

- Design the buildings in modular way taking in mind its robotic erection
- Automatic planning and real-time re-planning of the off-site pre-fabrication, transportation and onsite assembly
- On-site automatic and robotic transportation and assembly of the buildings pre-fabricated parts.

The FutureHome project tried to avoid the disadvantages of previous attempts in solving three main problems: a) quality of the modular houses, b) flexibility in the design, i.e. different interior and exterior design is made by the set of predefined modules, and c) robotic on-site assembly of modules. A planning tool AUTOMOD3 has been developed for modular building system. It is composed by several tools for design, planning and simulation, which are linked and able to interchange their data. The tools have been integrated in a well-known CAD system (Diez et al. 2007).

Additive layer manufacturing technologies

Additive Layer Manufacturing (ALM) technologies are creating three-dimensional objects in a way similar to printing images on paper and are therefore also known as 3D Printing (3DP) technologies. A 3D printer is depositing thick layers of material that are able to harden fast enough to bear the following layers. The "printing head" is moving vertically stepwise as layers are printed one on top of another. Many 3D printing technologies have been developed for production of prototypes or models, and even to produce series of objects. Contour Crafting (CC) and D-Shape can be categorized as 3D printing automated construction technologies, while n2mBuild is only comparable to 3D printing in some basic principles.

Contour crafting

Contour Crafting (CC) is a robotic system based on additive fabrication technology. It exploits the surface-forming capability of troweling to create smooth and accurate planar and freeform surfaces (Khoshnevis 2004). A wide variety of materials can be used. Contour crafting uses two computer-controlled trowels to create surfaces on the object being fabricated. The layering approach enables creation of various surfaces. CC is a hybrid method that combines an extrusion process for forming the object surfaces and a filling process (pouring or injection) to build the object core. In building construction a gantry system carrying the nozzle moves on two parallel lanes installed at the construction site (Fig. 2). A single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run. Conventional structures can be built by integrating the CC machine with a support beam picking and positioning arm, and adobe structures, may be built without external support elements using shape features such as domes and vaults.

The process shall allow a design of structures with various architectural geometries that are difficult to realize using the current manual construction practice. Various materials may be used for outside surfaces and as fillers between surfaces. Materials that chemically react with one another may be fed through the CC nozzle system and mixed in the nozzle barrel immediately before deposition. The quantity of each material

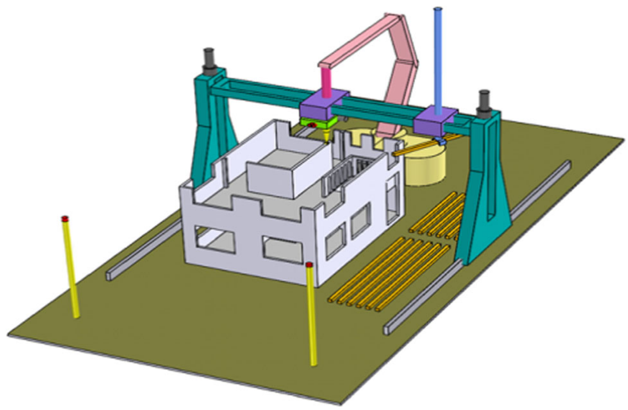

Fig. 2 Contour Crafting: Conventional structure construction (California 2013)

may be controlled by a computer and correlated to various regions of the geometry of the structure. Utility conduits may be built into the walls of a building structure precisely as dictated by the CAD data.

From the attainable publications it is not clear how an existing Building Information Model can be integrated with the CC system. The authors of the CC technology want to develop a planning system that will consist of various engineering models and simulation programs to verify the feasibility of constructing a certain section of a curved roof. They also plan to include fluid dynamics and material science models to assure specifications of feasible materials and process parameters.

D-Shape

D-Shape is an automated building system using sand and binder to create stone-like free-form structures (Dini 2009). The robotic system enables full-size sandstone buildings to be made without human intervention, using a stereo lithography 3D printing process.

After the robotic system is installed the fabrication process begins with depositing a 5–10 mm layer of sand over the entire build area. The "printing head" attached to a gantry then moves across the surface and prints an inorganic binder onto the sand according to the cross-section of the digital model. This process is repeated with subsequent layers of sand and deposition of the binder until the building process is complete. After the printing, the remaining sand has to be removed and the building surface treated in a way to reach its final form (Fig. 3).

The system has many advantages over traditional formative processes (use of formwork with concrete) as well as other additive building processes (e.g. brick lying). It can use any sand-like material and produces little waste, as the remaining sand can be reused. The materials used are all naturally occurring substances, which require little processing before use in the fabrication process. The material produced is very similar to natural stone, although created in much shorter time.

D-Shape can print any feature that can be enveloped into a cube of 6-m sides. It can therefore not only produce full sculptures and structures, but also portions of constructions like bridges, section beams and columns etc. The actual building will correspond to the CAD design to within planned tolerances of 5–10 mm.

The digital model of the building is a freeform 3D model typically consisting of non-uniform, rational B-splines (NURBS). Since the building material is homogeneous there is no need to add any attributes to the geometry, except material characteristics that are relevant for static analysis of the structure. Solid modelling techniques would also result in useful models.

Actually, any 3D geometrical model can be uniquely converted into a homogenous 3D model that is useful for D-Shape or any other kind of 3D printing. One such formats is STereo Lithography (STL), another, more recent, Additive Manufacturing File Format (AMF).

N2mBuild

N2mBuild (N2MB) (Rebolj et al. 2011) is a concept that has been developed with a strong motivation to reduce

Fig. 3 D-Shape process phases: digital model, 3D printing, cleaning, and polishing

waste, pollution and energy consumption caused by traditional building technologies. The first decision therefore was to use materials, which exists on site and can be transformed into building materials. Since carbon exists in nature in vast amounts, the next decision was to use carbon as the basic material and to extract it from CO_2 from the air. To avoid transportation and installation of complex production machinery the further decision was that the building process is to be executed on the Nano level using active Nano devices (Nano-robots), which are capable of capturing CO_2 from the air and extracting C molecules from it, releasing O_2 back into the air, and building 3D carbon nanotube structures with characteristics required for a specific area (strength, conductivity, colour, transparency etc.). The whole process shall be controlled using a detailed Building Information Model (BIM) as the only source for all necessary information.

Nano robots are controlled and powered externally by light, whereby instructions are coded using specific wavelengths. A projector installed above the site emits light. To avoid interference with light emitted by other sources, an adequate wavelength spectrum has to be chosen. The projector is using the detailed BIM model as input, and transmits continuously the horizontal cross-section (Fig. 4), going from the bottom to the top height of the model. Openings of the final model are temporarily filled with carbon nanomaterial, which transforms back into CO_2 after a specific time period (or under specific conditions), when its function as a supporting structure is fulfilled. All utilities (e.g. pipelines, power lines, communication lines) and coatings are built at the same time, together with the bearing structure, and are part of the building.

The building process starts with designing a detailed BIM model with all necessary utilities and coatings, as well as temporary fillings, which can be added automatically after the building model is finished, by following the rule that every

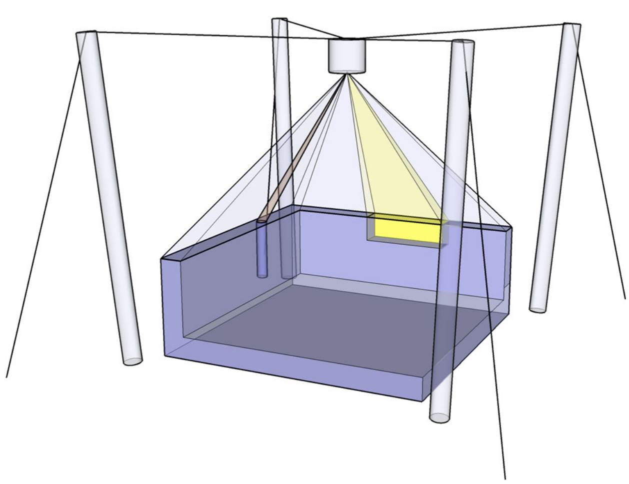

Fig. 4 nano- to meter scale building using light projector to send energy and information to Bio Nano robots on the building plane

part of the structure has to be vertically supported down to the base level. Site preparation is the next step and includes excavation and projector installation. Deploying Nano robots onto the maximal extent of the building layout follows this phase. The site is then ready and the automated construction starts by continuously emitting energy and instructions represented as specific light wavelengths to build 3D CNT (Carbon Nano Tubes) structures with required characteristics, until the top of the building is reached. After the light is off for a certain time, the Nano robots stop to function permanently, thus preventing any unwanted activity after the process is finished. The load bearing material is in function instantly, therefore the temporary supporting material can dissolve after the building is finished. It disappears off the building in the form of CO_2 gas (e.g. from rooms, niches, pipelines and any other volumes designed empty). With this the building is finished. The N2MB concept is based on four main technologies that have to be developed:

- Nano robots, capable to fulfil the required tasks; synthetic biology with manipulating bacteria to perform various required programs is on a good way to research possibilities to design and grow the required bio Nano robots,
- 3D CNT structures; a Schwarzite tube junction has been designed to connect single-walled CNT into a compact structure; CNT is known to have extraordinary characteristics that can be varied by design (e.g. electric conductivity), which makes it possible to use the same basic material for all necessary elements and systems of a building,
- The light projector to transmit energy and instructions to the Nano robots
- A fully integrated and detailed Building information model, which doesn't yet exist in the required precision.

A network of researchers has been organized to define the research roadmap, which shall conduct the research in the areas of biotechnology, Nano-materials, physics and construction informatics. It will be a long way to reach the target, but taking into account the enormous benefits of such automated building technology, it is worth a new research.

Interoperability requirements for automated manufacturing systems in construction

Information systems in construction sector follow general manufacturing interoperability patterns (Ray and Jones 2006). Most common interoperability patterns are (a) interoperability standards focused on systems architectures, (b) sector specific content standards, (c) methods for automated systems integration. However, in terms of lifecycle of a product these interoperability patterns only emphasize conceptual model and engineering (physical) product model. Hence,

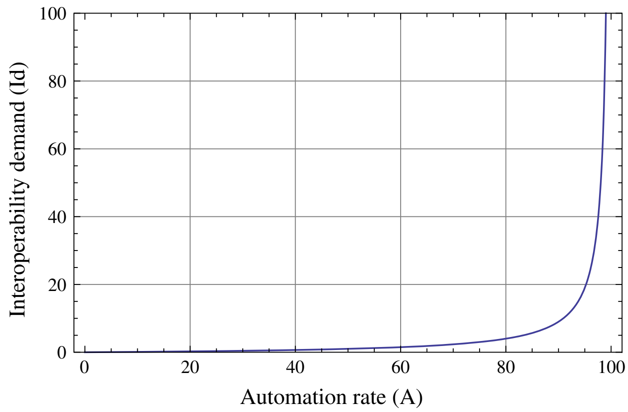

Fig. 5 Interoperability demand function I_d

manufacturing tasks, much less automated manufacturing, are not sufficiently included in interoperability research. In construction industry, manufacturing tasks include technological (manual, automated) operations, management of labour and material resources to achieve erection of a building. Erection of a building is a complex process with sector specific constraints. For better understanding of interoperability in automatic manufacturing systems our idea is to define a new *interoperability demand function* I_d according to the evolution of automated versus manual operations in manufacturing tasks (Fig. 5). The function I_d is defined by the following formula (Eq. 3.1):

$$I_d = \frac{A}{M} \tag{3.1}$$

where A is a percent of project's time completed in an automated manner (i.e. automated data exchange, automated manufacturing systems) and M is percent of project's time completed in traditional, manual way (i.e. manual data exchange, manual field work). Following this reasoning M can be expressed as the following formula (Eq. 3.2):

$$M = 100 - A \tag{3.2}$$

where the percentage of automated work is subtracted from the worst-case scenario where all 100 % of tasks are completed manually. The interoperability demand I_d shows exponential trend with the increase of automation in a project (Fig. 5, logical input interval is $0 \le A < 100$).

The formula I_d has realistic interpretation for interoperability demand in construction industry. The lower limit $I_d(0)$ means that there is no need for automation because the percentage of manual work in a project is 100 %, which in consequence means that there is no demand for digital interoperability. The case $I_d(0)$ is still present in simple construction projects and/or countries with less developed construction industry. On the other side of the interoperability demand scale the upper limit $I_d(100)$ is virtually impossible to reach in construction projects because today's technology is far away from 100 % automated construction process. To put it simple, demand (or necessity) for interoperability inherently grows as more and more automation technologies are introduced in the lifecycle of a construction project. This statement can be related to the Fig. 1 where interoperability demand is expressed in terms of cost (cost share) of inefficiency. Inefficiency is regarded as lack of interoperability within individual phase and between the three phases.

The cost share of interoperability inefficiency in construction lifecycle is the highest in the operation and maintenance phase. This means that the phase has the greatest potential for interoperability improvement when we compare it to the cost share in the planning and design phase, and construction phase. Improved interoperability in the operation and maintenance phase would reduce the cost share in this phase. Reduced cost share of interoperability inefficiency in each single lifecycle phase would result in lower total (absolute) cost of a construction project.

Automated manufacturing systems correspond to the construction phase (erection of the building). More automation in construction phase would increase interoperability demand in this phase.

Although the interoperability problem in construction implies not only connecting information systems but also business processes, culture and values, and management of contractual issue (Grilo and Jardim-Goncalves 2010), focus of our research intends to contribute to the understanding of technical interoperability problems related to the automated manufacturing. To identify the interoperability problems we conducted an experiment that included: (a) digital design of a small free-form building, (b) preparation of tasks for automated manufacturing of the building, and (c) printing the building with the additive layer manufacturing technology (3D printing). The interoperability problems that we identified are: (a) design interoperability problem (standardized exchange of free-form shapes is missing in mainstream 3D modellers used in AEC sector, like ArchiCAD), (b) exchange of digital parameterized workflow model is not supported in IFC2x4 and (c) streamlined generation of tasks for automated manufacturing systems from BIM is not supported.

In the following part of the section we derive the main requirements for more interoperable use of automated manufacturing systems in the construction phase. The requirements are supported by an experiment where a small model house was manufactured in a fully automated manner with the ALM 3D printing technology. The house demonstrates a non-traditional design and embedded building accessory (ventilation canals). Our goal was to identify all interoperability problems in the process from design to automated manufacturing of the house. The identified problems are then analysed and improvement proposals presented as requirements for future projects.

First requirement: computer controllable lifecycle workflow model

Traditional and deep-rooted construction scheduling practice patterns deny the need for digital workflow model, which would enable stakeholders (investors, project managers, contractors, subcontractors, cost estimators) better control over the construction process. A digital parameterized workflow model is needed for future BIM maturity Level 3 (4D, 5D and 6D).

Today, construction workflow modelling is understood as construction scheduling task only. Construction scheduling consumes data from the mostly manual quantity take-off and cost-estimating task. In a fully integrated and collaborative process the construction scheduling task would consume design model and (a) trigger preparation of quantities and costs for materials, parts, labour and machinery (including automated manufacturing systems), (b) optimize scheduled tasks (activity id, activity name, preceding activities, succeeding activities, activity duration, activity cost) in a way to achieve minimal PCT and/or PCC, and (c) update single shared BIM with results from (a) and (b). These data, for example material and quantities, can be used for preparation of tasks for automated manufacturing systems.

In order to achieve more controllable construction workflow, traditional Corporate Performance Management (CPM) based software, for example MS Project, Primavera, Suretrack and ProjectLibre, must interface to already existing standard business process management models like Business Process Modelling Notation (BPMN) (Object Management Group 2013). Traditionally, construction schedule created with CPM software is digitally communicated in proprietary format within vendor lock-in processes as a list of tasks. The task list, visualized as Gantt diagram or work breakdown structure, seems to be just sufficiently formal and still comfortable for users in construction industry.

BPMN models have, apart from traditional Gantt diagrams, their XML representation, which enables exchange of workflow data between independent tools in a lifecycle of a (construction) product. BPMN based workflow model in construction, if extended with construction scheduling data, would be computer controllable alternative to existing traditional CPM software. Another advantage is that the BPMN diagram (its XML representation) can be mapped to the XML languages designed for the automation of business process behavior based on Web Services, Web Services Business Process Execution Language (WS-BPEL, shortly BPEL). BPEL is a vendor-neutral specification to specify business processes as a set of interactions between web services. As such BPMN is the bridge between modeling and immediate software implementation that supports the model. BPEL defines an interoperable integration model that should facilitate the expansion of automated process integration (Jordan et al. 2007). Two BPEL goals are especially interesting for construction: simulation of business processes and cross-enterprise (i.e. between contractors and subcontractors) automated business processes. BPMN enables higher degree of automation and more complex process sequencing, which supports interoperability demand in construction.

Requirement for computer controllable construction workflow is also in line with the ASCE's 24 priorities for civil engineering practice in the 21st century (ASCE 2008). Project management together with risk and uncertainty are listed in a group of 10 technical priorities.

BPMN and BPEL are possible solutions for implementation of the computer controllable lifecycle workflow model. The workflow model in BPMN on Fig. 6 involves tasks for the use of automated manufacturing systems in construction.

Companies involved in the lifecycle workflow of the building will be able to form a service-based manufacturing network (Gao et al. 2009) in the next generation collaboration environments (Klinc et al. 2009). Such networks will mediate between companies that provide services to one another. For example, a BIM design service company will provide a BIM with the wall and ventilation canal details, computer-aided process planning service company will extract relevant IFC2x4 data from BIM and prepare geometry in the neutral Additive Manufacturing File Format (AMF) consumable by 3D printers, and a manufacturing service company will use the AMF file for manufacturing (printing) of the entire building or its parts. The BPMN workflow on the Fig. 6 has its standard XML representation based on which a full set of Web Service Description Language (WSDL) and BPEL can be generated. WSDL is an XML based language for describing the interface of web services. The web services handle data exchange in the workflow.

In terms of BPMN participants of the workflow, such as BIM design services company, are modeled by pools. When dealing with the mapping from BPMN to BPEL, each pool represents a business process. The investor pool is the internal pool, while the other three represent external partners or external processes that interact with the internal pool. Usually, external pools are presented as black boxes. The BPEL process is deployed to the workflow engine service, which setups a web-based user interface that allows users to invoke the web service implemented by the BPEL process. The BPEL process enables modeling, enacting and monitoring of a large number of subcontractor workflows in the construction lifecycle.

Second requirement: detailed BIM

Planning and design process predominantly use BIM (data content industry standard IFC, BuildingSMART-International 2013) to support interoperability. In order to diminish interoperability inefficiency, BIM data created in the planning and

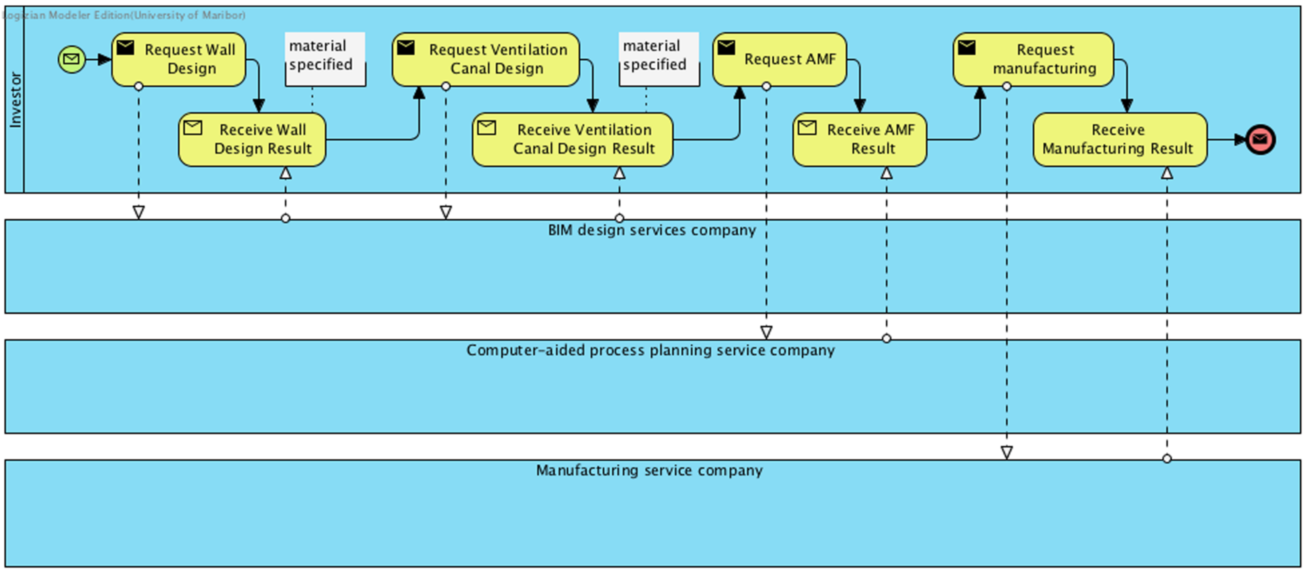

Fig. 6 Computer controllable lifecycle workflow for our experiemental building

design phase should be consumable by automated manufacturing systems in the construction phase and independent of the specific software or hardware device being used. This allows for model-based data sharing instead of file-based data sharing, which in consequence overcomes syntactical and semantic disharmonies.

According to the UK Governments's strategy paper (BIM Industry Working Group 2011) BIM maturity should reach level 2 by 2016:

- Level 0: unmanaged CAD probably 2D, with paper (or electronic paper) as the most likely data exchange mechanism.
- Level 1: Managed CAD in 2D or 3D format with a collaboration tool providing a common data environment, possibly some standard data structures and formats. Commercial data managed by standalone finance and cost management packages with no integration.
- Level 2: Managed 3D environment held in separate discipline BIM tools with attached data commercial data managed by an enterprise resource-planning tool (ERP). Integration on the basis of proprietary interfaces or bespoke middleware could be regarded as proprietary BIM. The approach may utilize 4D programme data and 5D cost elements as well as feed operational systems
- Level 3: Fully open process and data integration enabled by web services compliant with the emerging IFC standards, managed by a collaborative model server. Could be regarded as integrated BIM (iBIM) potentially employing concurrent engineering processes and utilizing 4D (3D in time for construction schedule), 5D (4D with construction costs), and 6D (5D with information for operations and maintenance) models.

Level 3 is necessary for fully interoperable automated manufacturing systems in construction. However, current BIM development (Level 1) in parallel with the development of ALM technologies (especially 3D printers) enable wide spectrum of possible research on use of BIM with automated manufacturing systems in construction.

First requirement for better interoperability in the succeeding phases is to exchange geometry from design applications such as ArchiCAD, Rhino, Revit, etc. to the above-mentioned automated manufacturing systems. However, IFC geometry was designed to support exchange of simple parametric models, such as wall systems and extruded shapes (Eastman et al. 2011), which means that the exchange of free-form shapes translates with missing surfaces and possibly other errors. In practice this means that any arbitrary surface (i.e. NURBs-like) has to be tessellated (triangularization), as the industry prevailing support for IFC2x3 does not support NURBs. It seems that IFC "is not yet good enough". This will change with the latest IFC 2x edition Release 4 (IFC2x4), which now includes additional entities for geometry resources based on B-spline surfaces and B-spline curves. The building on Fig. 7 is a result of our experimental free form building printed with a 3D printer fed with the very traditional construction material, natural clay paste. The model was designed with the tool OpenSCAD (OpenSCAD Community 2013) using proprietary, non-IFC, geometry description for arbitrary surfaces. The geometry could be re-designed with existing commercial or open source tools already supporting IFC2x4, which would extend design interoperability by eliminating "from-to" proprietary format conversions.

The importance of the detailed BIM for buildings like the free-form building in our experiment cannot be emphasized enough in case of automated and especially additive

Fig. 7 Experimental free-form clay building manufactured with additive layer (3D printing) manufacturing technology

Fig. 8 Wall detail of the experimantal free-form clay building: imprinted vertical ventilation canal

manufacturing. Integral design of all building accessories like internal heating, ventilation, and air conditioning (HVAC), water supply, and drainage network installations is essential when applying additive manufacturing. In our experimental free-form building (Fig. 7) ventilation canals are designed inside the wall of arbitrary (curved) shape (Fig. 8). In such a building it is impossible to build the ventilation network with traditional vertical and horizontal canals. Design of embedded installations and their manufacturing with additive layer technologies are very intriguing possibilities for the future. Additive manufacturing, layer by layer, is utilized with several "printing heads" for different materials. For example in micro structured clay wall plastic pipes for ventilation, water or even cooper DC power line can be printed in the same layer. In our experiment limitation was the 3D printer with only one material (clay), and therefore ventilation pipes inside canals were also made of clay.

With the advent of the interoperable BIM physical XML file based on the IFC2x4 also such compound design details like wall with ventilation canals can be transferred to the manufacturing (printing) process.

Figure 8 shows part of the experimental free-form building made of clay. It is horizontal layer of the wall with embedded vertical canal for ventilation (hole in the wall). The vertical canal, which is part of the detailed design model, was designed as a tube-like form, which was then manufactured layer by layer along with the rest of the building.

The requirement for the detailed BIM makes the planning and design phase very creative and time demanding, but then the final phase of the building process, manufacturing (printing), is almost completely automated.

Third requirement: streamlined generation of tasks for automated manufacturing systems

In a collaborative environment the detailed BIM is the source of design specifications, which are interpreted and converted to the required information for product manufacturing. The process of generating effective sequence of machining operations is generally known as Computer-Aided Process Planning (CAPP) and is a wide research field ranging from multistage machining processes (Zhang and Jiang 2013) to the machining precedence of interacting features in a feature-based data model (Mokhtar et al. 2009; Mokhtar and Xu 2009).

With the growing BIM maturity, collaborative processes involved in construction lifecycle will rely on bespoke interfaces converging on the IFC XML for data exchange. Such development is also expected for data delivery from BIM in order to prepare data for tasks for manufacturing machines on construction site. Machine's (i.e. 3D printer) processing of a task is execution of a series of commands without manual intervention (like a batch job).

Automated manufacturing machines are never fed with raw geometry data because the machines "speak" different language (i.e. G-code). Therefore the geometry needs to be processed with a computer-aided manufacturing (CAM) software or with a CAM plugin in the software for modelling. The CAM software then actually generates jobs for the manufacturing machines.

For 3D printers geometry is exchanged in the AMF format. The format is derived from the STL format from which it inherits the triangular meshes to represent object shapes. The AMF is XML based format file and is standardized interchange file format by ASTM (American Society for Testing and Materials) under ASTM F2915-12 "Standard Specification for Additive Manufacturing File Format Version 1.1" (ASTM International 2013).

The AMF format is a result of current and future needs of additive manufacturing technology and is well prepared also for needs in building industry. STL file format as current de-facto industry standard for transferring information between design models and production equipment contains only information about surface mesh and describes only the shape of an object as shown in the following STL file fragment for our free-form experimental clay-building:

```
solid OpenSCAD_Model
  facet normal 0.207862 -0.0218472 0.977914
    outer loop
      vertex 1.02244 -0.217327 9.94522
….
    endloop
  endfacet
….
```

In all kinds of additive manufacturing and especially in the future building industry far more information from our model is needed, for example color, texture, material and especially substructure of the fabricated target object. Multi-material and microstructure geometries are essential in the complex building production.

The AMF file contains information about shape but also composition of targeting object with native support for colors, textures, materials, constellations and substructure. The following code fragment shows AMF file content for our experimental free-form clay building, which was converted from STL:

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<amf>
  <object id="1">
    <metadata type="name">Default</metadata>
    <mesh>
      <vertices>
        <vertex>
          <coordinates>
            <x>1</x>
            <y>1</y>
….
<volume>
  <metadata type="name">tmp</metadata>
  <color>
    <r>0.8</r>
    <g>0.8</g>
    <b>0.8</b>
  </color>
  <triangle>
    <v1>0</v1>
    <v2>1</v2>
    <v3>2</v3>
    <map gtexid="2" btexid="3" rtexid="1">
      <u1>0</u1>
      <u2>1</u2>
  ….
  <texture width="256" height="256" type="grayscale" id="1"
depth="1" tiled="false">//////////////////////7+/v7+/v7+///+/v7+/
….
```

Conclusions

Thanks to interoperability research, AECO industry can operate within a common technical context by applying interoperability standards for system architectures and information sharing. Interoperability impacts all three phases in the lifecycle of a building, starting with planning, engineering and design, continuing with construction phase, and ending with operations and maintenance phase. Practical need for interoperability decreases with the phase order. Growing BIM maturity organically promotes interoperable solutions also in the construction, operations and maintenance phase. In the paper we have identified technical requirements needed for more interoperability between investors, BIM design services, computer-aided process planning services and manufacturing services. Our research focus was on automated manufacturing systems because they present island of automation in the construction phase. Isolated automated manufacturing systems are also bottlenecks for new engineering collaboration environments like service-based manufacturing networks. In the comparison of automated manufacturing systems in construction two categories were reviewed, Integrated Robotic Systems and Additive Layer Manufacturing. In the ALM category concepts of Contour Crafting, D-Shape and N2mBuild were presented. Because of better availability of ALM technologies, we included 3D printing in our main research experiment.

First theoretical result of our research was definition of the interoperability demand function I_d, which explains that the need for interoperability inherently grows as more and more automation technologies are introduced in the lifecycle of a construction project. This was a foundation for our experiment that pursued process model, design, engineering, and manufacturing of a small house with non-traditional design and embedded building accessory (ventilation canals). In the experiment the house was manufactured in a fully automated manner with the ALM technology, namely 3D printer. Practical research experience gained in the experiment was that the use of automated manufacturing systems significantly increases the interoperability demand in the early lifecycle phases. Following that practical experience we can report on the main results of our research, which present requirements for interoperability in a building lifecycle when automated manufacturing systems are in place. These requirements are:

- Computer controllable lifecycle workflow model. Construction process modelled in BPMN can be mapped to BPEL, which further enables immediate generation and execution of Web Service interfaces for data exchange between investors, BIM design services, computer-aided process planning services and manufacturing services.
- Detailed BIM with embedded building accessories. Such approach significantly intensifies engineering efforts in the planning, engineering and design phase. With the use of additive layer technology innovative designs are possible that must implicitly satisfy all relevant engineering requirements for structural stability, HVAC etc.

- Streamlined generation of tasks for automated manufacturing systems. Automated manufacturing machines are never fed with raw geometry data because the machines “speak” different language. The process of generating effective sequence of machining operations is generally known as CAPP. For 3D printers geometry is exchanged in the AMF format. The format is derived from the STL format from which it inherits the triangular meshes to represent object shapes. The AMF file contains information about shape but also composition of 3D object with native support for colors, textures, materials, constellations and substructure and is therefore well prepared also for needs in the AECO industry.

Future AECO projects fulfilling the three requirements meet minimal conditions for interoperable use of automated manufacturing systems in construction. Such projects will contribute to the decreased cost of interoperability inefficiency throughout the lifecycle of a building.

Automated manufacturing systems will undoubtedly expand and find their place in the future way of building. Additive manufacturing or simply 3D printing will play significant role in near future AECO industry. Additive manufacturing has potential to be “the next big steep forward”, because it allows advanced and brave design and free-form constructions inspired by nature. Design phase will significantly intensify the importance of embedded building details while in the construction phase less human intervention will be needed.

Application of large-scale additive manufacturing systems with 3D printers in the AECO industry is in early research phase. Future research directions are further parameterization of the interoperability demand function, BIM maturity, automation of workflow models, and new approaches for engineering of embedded building elements.

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