# Towards a comprehensive life cycle approach of building automation systems

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***Abstract*—The communication between different partners to handle the different tasks during the life cycle of buildings is far from being perfect. Fragmented engineering, lack of data consistency, insufficient system documentation or sensitivity for data sharing are only a few of many problems in this field that have not been efficiently handled through researches as well as in practice. This paper focuses on a deeper analysis of these problems mainly in the planning and engineering phases (they are the basis for all other phases) from both technical and economical point of view. An approach to handle these problems will be presented and thoroughly discussed.**

## I. Introduction

### A. Motivation

The fields of planning and engineering for building automation systems (BAS) elaborated within large-scale construction projects are inherently confronted with high complexity and the need to cope with multiple stakeholders, frequent changes and collisions. These issues of complexity cannot be solved by simple deterministic methods or reductionist approaches. Here, the disassembling of a project all the way down to its parts to solve all issues in a fractional manner is not the way how current and future engineering should work. What is needed is an integral approach on planning which assures collaboration, exchange and consistency of data between tools and data of any involved engineering discipline. The work at hand outlines a technology to improve integral planning and engineering to overcome the problems of data integration within fragmented engineering disciplines. This work is motivated by the demand for tools and methodologies to eliminate the failures of uncoordinated planning processes and the urge to mitigate the cost expenditures emerging by late collisions and unplanned changes within the construction phase.

### B. The costs of planning failures and fragmented engineering

It is hard to name any large-scale construction project that was not plagued by planning mistakes, setbacks, cost overruns and engineering failures. As one of these prime examples, the Berlin-Brandenburg Airport (BER) is still producing headlines about failed engineering, fragmentary planning, misguided subcontractors and technical complexity issues highly underestimated by key management professionals. Hammer wrotes in [1] about the general stakeholder overview:

> Several engineering and electronics companies, led by the German giants Siemens and Bosch, struggled to retain control over the complex fire protection system that included 3,000 fire doors, 65,000 sprinklers, thousands of smoke detectors, a labyrinth of smoke evacuation ducts, and the equivalent of 55 miles of cables.

Of particular importance is the one-dimensional perspective of engineering and the constant denial of responsibility to collaborate with other disciplines. Every technical player seems to accentuate his own narrow frame of responsibility by pointing out a proprietary outcome. As an illustration, the article from Hammer [1] further cites the Bosch spokesman Thilo Resenhoeft:

> Our part, the detection of hot air or smoke ... is functioning. The responsibility for the dysfunction lies with somebody else.

Just in order to show that the smallest aspirations of integral planning seem to disappear by a habitual accusation of the others. The issue of fragmentation and non-integral engineering within large scale construction projects illustrates the necessity of integral planning methods and a tool-backed software infrastructure to safeguard data exchange and consistency. Today, the incalculable costs of fragmented engineering in complex construction environments accelerates the search for comprehensive building information modeling (BIM) approaches. The work at hand is providing a technological method capable to mitigate or even circumvent the issues of fragmentation by means of consistent BIM data infrastructures able to reconnect the engineering disciplines.

The unnecessary costs resulted by fragmented engineering are not limited to the planning process. The operational cost of a building during its lifetime is about seven times the cost during the construction [2]. Low quality planning also means more frequent system malfunction, which reduces the productivity in cases of industrial systems, causes endangerment for the occupants (e.g. in case of residential building) and increases the maintenance costs.

### C. The essential shift of planning efforts to realize an early and integral BIM engineering

The aim of a comprehensive and integral engineering under the framework of BIM can only be reached by a shift of efforts to earlier planning phases [3]. These shift of effort facilitates the introduction of an integral viewpoint with regard to any further involvement of specific engineering disciplines. Only at the very beginning the building-owner's requirements can be described in a fully-fledged manner. This is the reason why the outlined approach decided to start with the adoption of integral requirements. The integral requirements serve as an early starting point to any comprehensive use of diversified planning tools or specific simulation environments. Furthermore, the consistency of data serves any life-cycle approach as a fundamental base of operation building management. Therefore, the establishment of holistic and upstream requirements interfaces is an important goal of that work simultaneously serving as the connection to current BIM methods.

In order to deliver the readers a better understanding of the constraints and problems within the current process for planning and engineering of BAS, the following part of the paper discusses various technical as well as economical aspects of the process. Through this analysis, a new methodology to overcome the mentioned problems is presented. Following part of the paper, a new approach that can handle these problems on a generic level will be presented and discussed.

## II. Current Planning Process for Building Automation Systems and impacts on System Life-Cycle

The planning and engineering process is the first phase of the multi-phases life cycle of a BAS. Following up by the tendering, construction and system runtime, the planning and engineering of BAS have an immense influence on the later phases economically and also decide the system performance from its runtime until its demolition.

The current engineering practice reveals many issues regarding the design of craft comprehensive, consistent and secure BAS. Today, planners and engineers typically overlook a very limited part of the system due to the lack of knowledge of the whole systems functioning. As a consequence, only the creation of a wholly integrated BAS prevents the current issue of unnecessary duplications of system devices.

It is well-known that fragmentation and disconnectedness is not a desired system attribute while the system is exposed to external complexity. Within the field of building automation the system fragmentation and disconnectedness are part of a broader issue which arises from the historical segregation of engineering professionals in planning. The planning process in each of these single professions is strongly dependent on the level of experience and knowledge of the distinguished professional in charge. However, in a world of highly networked and complex systems personal knowledge is obviously too limited to overview the whole picture. Therefore, many problems arise by the gap between the singular planning disciplines and the expected integrated output of planning, engineering and construction. Today, the issues of a high quality planning process are not at all rooted in the missing expertise of skilled professionals, but in an unsophisticated way of organizing information flows and data exchanges between all involved actors and stakeholders.

In the field of contemporary BAS, engineering professionals have to overview a vast amount of information regarding technical building services, components and overlying measurement and control technologies. Today, the challenge is to enable a seamless information flow between building-owners, architects, technical facility planners and civil engineers with the aim to fulfill an imperative of a more integral planning process. By integrating different planning perspectives into one meta model (BIM), the currently very limited and stand alone engineering perspective will receive. Therefore, the goal of computer aided engineering in seamless conjunction with automation technology can only be reached by a consciously implemented digital service flow model. This data flow model serves to integrate the fragmented disciplines in planning and engineering through a platform concept which is needed to bring together the amount of data of different stakeholders in the chain. The following part outlines the issues of informational fragmentation connected with the currently stand-alone engineering disciplines to pave the way towards a more comprehensive outcome of integral planning methods. Next, the main problems and their consequences are described in detail.

### *A. The planning of building services and the historical division of engineering disciplines*

The historically grown process of Planning - Construction - Operation is by its current appearance not built as a comprehensive life cycle approach. The part of planning is often poorly linked with the operation side of a building in the same way as the operation has to cope with the results of the construction phase originated in highly fragmented planning processes. Today, planning serves different crafts of construction under highly constrained, independent budgets while the costly building operation side has no influence on planning at all. A consistent life cycle approach for a more sustainable kind of building operation seems currently not practical.

In the case of BAS, planning as a precondition of the construction has a high influence on the later operation stage of a building. Building automation is currently planned on top of the technical building services and facilities with a strong focus on measurement and control of HVAC systems. A comprehensive and adaptive approach which integrates building automation in an earlier stage of planning needs an integral view on planning where automation systems are seamlessly integrated within the main facilities of the HVAC.

### *B. The issues of fragmentation in planning processes*

The planning process for BAS is currently divided into too many parts which are completed by different stakeholders. In case of public projects, this is partly resulted by the obligation on the public contracting authority to invite tenders. The owner and investor typically assigns or contracts different planning or engineering offices with specific planning tasks. The planning and engineering offices on the other hand think and plan in distinguished crafts under the use of different tools. This resulted in the fact, that the outcome is neither aligned with other crafts nor consistent with a standard data format for further usage. Moreover, the seamless integration of data with other planning disciplines as well as the further use of data for facility managers is not part of the current approach of engineering for building services.

### *C. Distinguished engineering crafts and the lack of data consistency*

During the planning and integration of BAS, information and data have to be exchanged between project stakeholders. This begins with the communication between project owners, architects and planners during the requirement analysis and only ends when the system documentation is delivered to the project owner after the system has been completely installed and established. One major obstacle for all stakeholders working in the planning and integration process of BAS is the variety in data models and data formats used in each and every steps or BAS disciplines. Inputs for the planning of BAS are mostly delivered to the planners as computer-aided design (CAD) data model(with typical formats like DWG or DXF [4]) from the architect through project owners. In case Building Information Models (BIM) [5] are to be created, CAD-files have to be converted into a data model like Industry Foundation Class (IFC) [6], which enhance the geometry data from CAD with detailed information from individual building structural components. From here, different data models exists that can be used for each or different aspects/disciplines of the system.

As an example, for the functional planning of BAS, the design can either be done manually using graphic oriented tools (e.g. CAD-based TRIC software [7]) or semi-automatically using object oriented tools (e.g. AUTERAS tool ). The automation systems are either described as a list of graphical objects with attributes [7], classical data model [2] or in form of an Ontology (e.g. BASont [8], DogOnt [9] or REFerence [10]). This prevents different design tools to communicate with each other, which leads to the need of tools that completely cover the whole functional planing step and difficulties for stakeholders that use different tools.

Engineering for technical building services is currently split into the following disciplines: Heating, Ventilation, Air conditioning and cooling, Sanitary and water, Electrics, Building automation (with measurement and control), Conveyor technique, Telecommunication and IT, and Fire protection. Each of these disciplines generates different data and documentary within their own tool world and there is currently no consistent data flow between disciplines.

Beside the lack of data flow in the horizontal direction between disciplines, the data flow in the vertically direction between phrases of the process can also be improved. Depends on the exported data format (CAD-formats, png, pdf, xml), the amount of information that can be transfered from one step to the next steps also varies. This results in information loss if the format for data exchange can not cover all aspects of the model of design tools or the following tools simply can not interpret all information due to the differences on data models. As an example, the functional system design described above is an important input for routing-, electrical design and device placement which use other data formats such as ecl@ass or ecl@ss-advance [11], [12]. While information such as devices' control logic is essential for the functional design, it is not observed during the routing process as only devices' attributes like network coverage in case of wireless devices or devices' physical I/O modules are important for this step. Even if the routing design tool can use result of the functional design tool as input, the preliminary results after the routing design don't include data from the functional design, which means this information is undefined for the rest of the process.

Given all of the mentioned problems, the further use of data for computer-aided facility management (CAFM) tools [13] needs a consistent database where integral planning results can be stored [14].

### *D. Missing or insufficient system documentation*

Beside the problem of incompatible data formats mentioned above, stakeholders working on the field of BAS also have to face the problem of uncompleted or missing documentation. The communication between project owners (clients) and planners at the start of a projects is often done verbally with no medium to document the exact functional and non-functional requirements of the clients. This is part of the fact, that planners still have very little support during the earlier stage of the engineering of BAS [14]. The lack of standardized methods to systematically document the considerations and requests of the clients often results in unclear definition of the system's functionality and consequently dissatisfactions of clients in later steps.This also leads to unnecessary project prolongation and cost overrun.

Another factor that negatively affect the quality of system documentation are undocumented changes during system integration. As the system documentation are sequentially created and modified during the planing and integration process. Changes during a later steps that affect decisions of earlier steps (e.g. electricians changes the routing in the system) are rarely documented. Stakeholders working at the beginning of the process are not informed about these changes and therefore are not able to verify the modifications. In case there are malfunctions in the system, it is then very difficult to diagnose the system due to the differences between the system and its documentation. This problem is very typical in the branch of building automation design and integration and should be solved to avoid unwanted time and financial cost during the maintenance process.

The above mentioning example also shows the need for the documentation of not only the system itself but also of the design and integration process. To improve the cooperation of multiple stakeholders, it is necessary to have a well defined work flow where each step of the process is described with the responsible stakeholder, required in- and expected output. This is not only important during the design and integration process but also utmost necessary in case there is unexpected problem happen in the system. E.g. if there is fire in the building, it has to be identified which system is at fault, where the mistake was done during the design process, which stakeholder is responsible for the malfunction, etc.. A clear defined work flow with agreement from all participants at an earlier stage of the process can make the whole design and integration process more transparent for project owner and other stakeholders.

### *E. The shift of costs and effort in BIM as an economic issue for comprehensive life cycle approaches*

The early fragmentation of planning tasks from II-B creates long lasting coordination problems and late collision between the engineered crafts. Under an economic viewpoint, early fragmentation creates unpredictable costs at later stages of construction and the typical issues of further amendments, supplements and claiming. Also during these later stages of construction, higher costs are the result of a non-integral planning approach of singular engineering tasks due to the unavoidable appearance data mismatches, physical collisions or misunderstandings.

The required solution for this economic challenge is the shift of costs to earlier engineering stages by improving the quality of the planning. This can be intensified by a more integral planning under the aim to create a digital BIM. An advantage of a well established BIM data model is the ability to pass on information from early planning over construction to operation, which allows comprehensive life cycle approaches that are profited from a complete system knowledge. Various costs during system construction(e.g. [15]) as well as runtime (e.g. [16], [17]) can be reduced. E.g. during the performance prediction for retrofitting, various variants for the modification can be tested beforehand on BIM before applied on the real system. Furthermore, building automation is currently engineered on top of the main building services with the goal to measure and control the facilities inside the building. A more integral viewpoint of building services and automation would therefore allow a much more sustainable operation stage under the use of CAFM tools and consistent data repositories.

However, the establishment of a sophisticated BIM method in planning stages has to overcome the short-term thinking of one-dimensional, cost driven planning under the constraints of investment objects. The cost challenge of a more integral planning for sustainable operation emerges from the gap between aims of an cost driven investor and the aims of the builder owner who finally operates the building. Without the data transparency during the engineering process between all stakeholders, it is impossible to close this gap. Additionally, a high quality integral BIM approach needs a more sophisticated data handling in early stages of planning to fulfill the requirements of data consistency and the possibility of further use for CAFM.

### *F. Sensitivity for data sharing and security aspects*

As mentioned above, many professionals take part in the engineering process of pass, each is involved in different process tasks (e.g. design, planning, constructing, integration of the automation components, managing the building. Due to this, there is the strong necessity to exchange data between the different partners. However, some problems, constraints and technical challenges occur, which (exemplary) are:

- Each partner wants to keep his own generated data and know-how to himself. Which leads to the fact, that only ”common and general” data can be shared among the partners. This results in extra work loads for different partners as they have to replicate various analysis or measurements in order to achieve the same ”high level” data.
- Only authorized partners should be allowed to see and use the shared data.
- It is hard (and time consuming) to describe all design decisions in a general way so that all involved partners from very different domains can correctly interpret.
- The communication must be secured against changing by any third party.
- The exchange of complete data, models and plans of buildings through the Internet between partners generates a huge network load (and is also very time consuming).

While the problems regarding the security of data transfer via the Internet have been analyzed by many current researches (e.g. [18], [19]), more analysis and solutions regarding the sensitivity for data sharing are needed in practice as well as in researches.

## III. How to generalize the Planning Process

### *A. A general architecture to reduce the mentioned problems*

As discussed in the last section, different participants of the processes of planning, constructing and operating BAS have their own models, data and communicate mostly using different terminologies. This results in an insufficient communication between all participants and unwanted additional costs during the system life-cycle. These problems could be reduced drastically by integrating the data from all disciplines and all phases. Based on this consideration, the authors provide a new concept involving different stakeholders/participants from the very beginning phases of planning and designing over the constructing phase up to operating and at last the restructuring/renovation/retrofitting and demolition phases of BAS.

Fig. 1 illustrates the outline of this concept. In the upper part of the graphic, various phases of the BAS life cycle are described together with the corresponding participants. The first 3 phases are the acquisition of necessary input for the whole process. This starts with the requirement for different trades of a building, which have to be defined by the building-owner and architect, following up by the information of tools for supporting the later life cycle phases of the buildings and component repositories containing descriptions of all the components of the buildings (e.g. devices, connectors, cables, materials etc.). The following blocks depict life cycle phases in their chronological order. The main focus of the concept

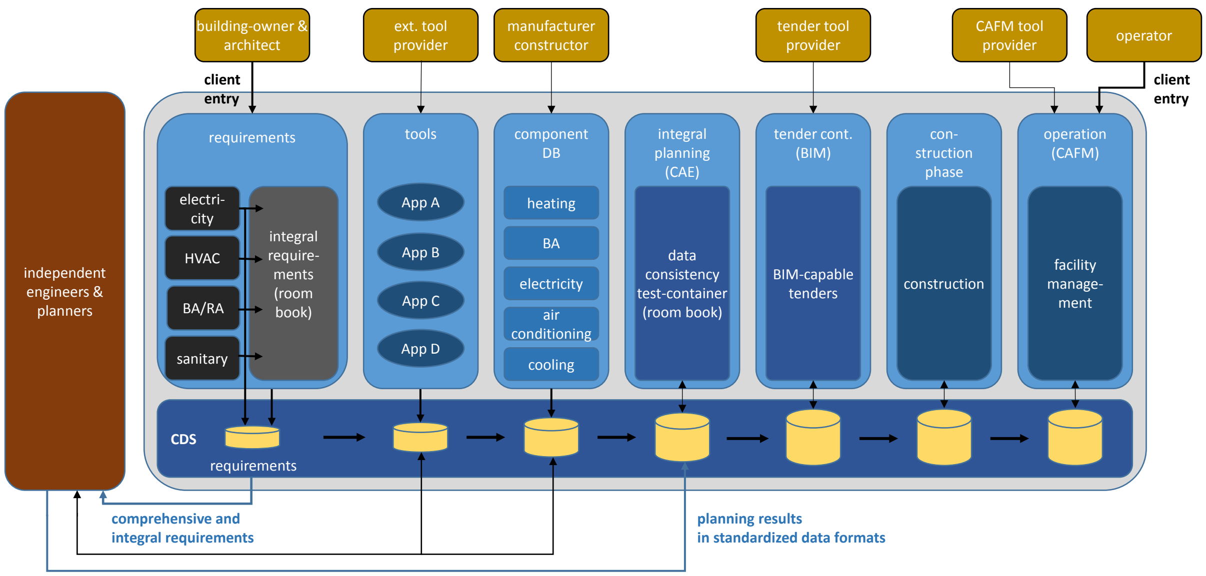


Fig. 1. Concept for a life cycle approach for BAS

lies on the Central Data Store (CDS). The data stored in CDS consists of the description of all elements within the building as well as the documentation of planning and engineering process an their results or system modification along the life cycle. CDS's content is enhanced after each phase of the building life cycle and is always accessible for any further usages by other tools in later phases.

Despite the disadvantage that this concept results potentially in an enormous amount of data, it has a lot of advantages:

- All participants can access all of the important data.
- Each participant along the life cycle can see the results of the other life cycle phases. Participants are now able to cross-check these results so that they do not affect their own results.
- As a result of the data transparency, the consistency of the different models and data can be checked.
- This allows an easy data sharing between the participants which saves communication time.
- The CDS has a general common data format. Despite extra effort required from all participants to adapt to this new data format, by using the same general terminology, the first steps toward general understanding between phases and disciplines of the planning, constructing and operating processes can be done. For the individual usage of tools using different terminologies, corresponding terminologies can be stored and linked in the CDS to ensure a correct interpretation when data is retrieved.
- The process documentation defined in CDS allows an easy identification of missing data or results. In case a participant needs specific results that have not been stored in CDS, the corresponding process phase and the responsible participant can be determined.

As a solution for the management of distinguished data models used between different participants and disciplines, the CDS has to provide an open, general data structure which is adaptable to further process extensions, new models and other tools aimed to be included.

Generally spoken, the used data structure is intended to be taken from a common standard. For any participant or stakeholder this approach lowers the time and effort of integration. The IFC standard, as one of the mostly common BIM data models (see sec. II-C) has besides all his advantages one single but important disadvantage: it can not fully describe the automation system in the building. IFC provides possibilities to describe building structures as well as many of the contained components and materials. But, to describe the semantics of functionalities in a complex system together with the contained devices and the complex data-network between devices, IFC is reaching its limits today. As a further important issue the standard is not able to integrate logical data as well as systemic control flows. This is also a challenge for existing building information model trying to handle the complexity of a whole and integrated building automation system. Therefore, the aim of the authors is to establish a mainly consistent "BIM-ready" data model which beneath the structural objects is able to integrate the semantics, causalities and relationships of systems and networks.

It was analyzed by the authors that the "lowest common denominator" of currently used BIM data models is the pure building structure (floors, sections, rooms...) as well as the contained physical components. These objects, or rather information, build the basis of the new data model. Any other information like the parameters of the room or the concrete binding between devices can be attached as a property to these general model items. This characteristic allows all stakeholders to seamlessly integrate any content of their specific models into the CDS. In general the basic model sets no restrictions to other models except of the rule to meet an ID pattern to fulfill the common assignment within the main building structure. The system does not have to include all the information into

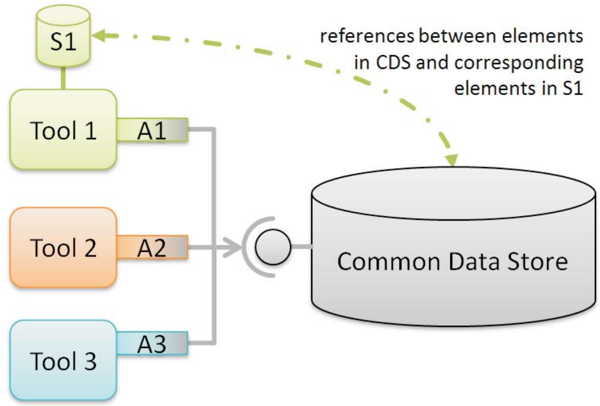


Fig. 2. General composition of different tools with CDS

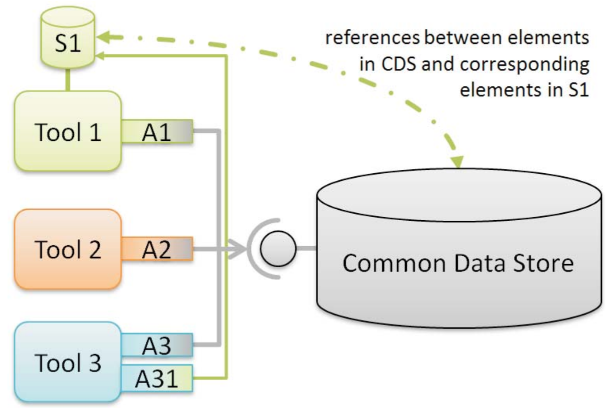


Fig. 3. Additional adapters to request data from far stores

the CDS, but can reference from another storing place to the corresponding element inside the CDS. As an example, inside the main model, a single room can be defined and referenced to any other data model. The objects, structure, parameters and functional descriptions associated to that room can be generated by different tools and stored in different sub-models, but will be unified inside the main model stored incrementally within the CDS.

All tools that want to use or enrich the data in CDS must simply implement an adapter (e.g. A1, A2, A3 in fig. 2) at their front end (see fig. 2). Tools and applications that need to handle the data in connection with the CDS have to implement a CDS data-adapter (e.g. A1, A2, A3 in fig. 2) at their front end (see fig. 2). Basically, the data-adapter has to perform the task of mapping the structural information and the component ID's from the sub-models to the existing elements inside the CDS to add further properties to the already mapped elements. The main advantage of this approach is that different tools and applications with highly distinguished data models are qualified to work together using a common model at the center stage. Besides the current practice where each single tool communicates with any another tool on the basis of a predefined and specific data model, the proposed CDS infrastructure model eliminates this kind of an unmanageable variety of bidirectional adapters between all of the tools involved in the main modeling task.

In addition to this, to allow the secrecy of private data of different participating partners, another concept is needed: The CDS should only store general data that can be shared and used between all participants, e.g. the building structure, the contained devices and their data points. All the other "special" data should be stored by the using tools themself.

To allow other tools to get knowledge about the non-private data which are stored in proprietary formats in the private stores (e.g. S1), the CDS must contain links to them (the green line-dotted arrow in fig.2).

In addition to this, in order to improve the extensibility of the CDS and to reduce the effort required when integrating new data models to the CDS, a special mechanism is used to link the content of CDS to other data bases used by specific tools (fig.2). While CDS directly stores data that is widely shared and used between all participants, e.g. the building structure, the contained devices and their data points, the other tool-related data-bases can contain data that mostly used locally by the corresponding tool.

The general request mechanism to get data is as follows:

1) the tool sends request for the data to the CDS
2) a) in case the requested data are stored in the CDS, the CDS responses with the data
   b) in case the requested data are not stored in the CDS
      i) the CDS responses with the location (address) where the data is stored and how to access the requested data in the corresponding store
      ii) the requester can now send request directly to that store and it sends the requested data directly back

With this mechanism the requester has to have knowledge about the data model in the requested data store, which is required for the correct data interpretation. The requester only needs to implement an adapter (e.g. A31 in fig 3) to translate the data format using in the requested storage into its own format. But this "specialized" adapters to foreign standards are only needed in case of information which are not stored in CDS.

In case specific data are accessible and editable by different tools, issues regarding the consistency of shared data have to be handled carefully and correctly. If a planner stores his designs in the data-network and another partner changes the designs without informing the corresponding planner, the edited data can be inconsistent to other data in the data-network. In this case, any change to a specific data should be registered in a temporary queue and all tools and users who use this data and are responsible for the data-consistency within their domain should be informed before the change is finally saved. If one of the users finds a consistency-problem resulted by the data-modification, the change will be reverted. The user or tool who made the change will be informed so that he can reedit the data before aiming to save it again. The detailed mechanism for consistency check requires more detailed analysis and is out of scope of this paper. Therefore in this paper only the general CDS is introduced.

All in all, this concept has many advantages in comparison to the solution with one centralized multi-model data storage. The main advantage of this solution is that each tool has to understand only its own data format and the very general model of the CDS. Moreover, each participant has the mean to monitor the access from external tools to their data, which means full control over his sensible data and can make case-by-case decisions who can access to these data. Hence also the mentioned sensitivity in data sharing and security aspects (see sec. II) are covered.

### B. Practical Implementation

To establish such a platform to connect the different stakeholders during the life cycle of BAS, the authors has prototypically implemented the CDS as an OSGi-based application, which is running on a server at the authors affiliation.

At the front-end side, to reduce the effort of participants on the whole process when using the platform, easy-to-handle interfaces are required. Therefore the authors decided to provide a SOAP-based web service interface as well as a RESTful interface. These are the most important and widely used interfaces for the interaction between different applications nowadays.

To ensure the security and safety of the transferred data between the tools and CDS, the communication should be encrypted and signed. At the current stage of implementation, which focuses on the testing of system principle functionality, these aspects are not necessary and therefore not yet implemented.

## IV. Conclusion

Along the multi-phases life cycle of a building automation system and especially in the processes of planning, engineering, there still exist many problems that reduce the overall quality of the planning and negatively influence the performance of the system. Some examples are the lack of data consistency, missing or badly defined system- and process documentation and the lack of information transparency between participants working together on the same process. These factors are derived from practical experience through collaboration of the authors as well as the result of information exchanges with different stakeholders in the field of automation system.

In order to overcome these challenges, a general platform solution with a central data store was presented in this paper. This platform is currently implemented as a prototype and the workability of the general idea was tested between some partners of the authors.

In the near future, the platform will be extended with the implementation of functionalities regarding the security and sensitivity for data transfer. Further research will focus on other remaining challenges along the life cycle of a building, including problems for retrofitting or maintenance.

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