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# AI-Supported Commissioning of Buildings: Verification of Collaboration Achievements as Pre-requisite for Intelligent Building Operations

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**Abstract.** The handover and commissioning of buildings are highly collaborative tasks since multiple sub-systems, designed by numerous experts from different disciplines will become operational. This means, the commissioning process is the final proof of concept for architects and engineers' design efforts. Additionally, construction companies must verify that all materials used are certified according to national standards. Finally, certified inspectors must approve the operational capability of critical systems and document each approval step using so-called operational certificates. This paper describes a novel, AI-guided approach, which will assist main contractors, investors and building owners in compiling, storing and managing all related product models, certificates and data sources for real-time monitoring (e.g. sensors) in a federated 'distributed Digital Twin Information Model' (dDT-IM). Furthermore, the paper explains why the availability of a complete, consistent, and comprehensive dDT-IM is an essential pre-requisite for the successful execution of collaborative, intelligent building operation.

**Keywords:** Hybridization of collaboration · Facility Management

## 1 Introduction

Commissioning and handover of buildings (or more generally built artefacts) involve a huge number of participants; such as:

- (i) architects, engineers from different disciplines – in their role as designers,
  - (ii) construction practitioners from up to 60 different trades, construction managers, project controllers and engineers as so called 'field experts',
  - (iii) public authorities, and
  - (iv) the client and its representatives including quality managers, and building operators.
- Depending on the subsequent contractual model, chosen for facility management, the number of operators might be also very high.

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The above illustrates impressively that the handover and commissioning phases are certainly highly collaborative. L.M. Camarinha-Matos et al. highlighted the significant role of Collaborative Networks (CNs) in promoting effective knowledge management and fostering collaboration among teams engaged in a project [1]. Therefore, an in-depth understanding of the networked collaborative activities is essential [2] and needs formalized modelling approaches [3].

This paper is organized into four sections. The first section examines the documentation of material and system component approvals, as well as collaborative design verification. The second section focuses on commissioning processes, presenting process models and discussing information requirements. The third section explores the use of Knowledge Based Systems (KBS) in commissioning, covering complex systems, stakeholder interaction, and KBS applications. It discusses knowledge graph population, interdependency rules, sequencing guidelines, and documentation. The paper concludes by summarizing key findings and suggesting future research in commissioning for improved performance and reliability.

## 2 Related Work

Over the past decade novel, mostly wirelessly connected, monitoring and automation devices were added to buildings [4], providing the base for IoT-driven applications [5] to improve building performance [6]. However, the increasing number of data points in buildings required alternative approaches for information management [7, 8] and context-sensitive information representation [9]. Consequently, the appearance of IoT in combination with the traditional building automation and control (BAC) technology requires additional efforts during handover and commissioning of buildings, since the integration of these systems needs additional attention [10].

Finally, the development of innovative business models, such as performance based contracting [11], continuous commissioning [12], or energy contracting [13] provide additional needs for an extended scope and increased quality of handover and commissioning processes, since the commissioning phase is the starting point for these business models.

### 2.1 Documentation of the Approval of Materials and System Components

Building materials and system components used for construction and renovation must be certified by European or national certificates [14]. The so called CE-certificates verify that products can be freely traded in the European Union (EU). The abbreviation CE originally stood for ‘*Communauté Européenne*’.

On German national level so called general building authority approvals (‘*abZ: allgemeine bauaufsichtliche Zulassungen*’) always relate to a specific construction product or product system. An approval notice describes the properties of this product, which are relevant to the building authorities. The issued abZ serves as technical proof that his product can be used in accordance with the German building regulations.

In contrast to the abZ, general type approvals (‘*aBG: allgemeine Bauart-Genehmigungen*’) approves the usage of materials and components for a specific design.

The aBG specifies how certain construction products are to be assembled into larger (structural) systems so that the construction type created in this way is in accordance with the national building regulations.

Furthermore, so-called critical systems require an operating license. Examples are elevators, escalators, or fire safety systems. Operating licenses are issued by 'registered engineering services', e.g. TÜV or DEKRA. The successful execution of inspection activities related to the issuing process of operating licenses must be transparently documented. AI-systems can provide guidance when, how and by whom operating licenses can be issued and where journals, log-books etc. are stored.

Additionally, it shall be mentioned that data and information about the status of systems and components can provide valuable input for continuous commissioning [12] or decision support systems to plan building renovation activities [15].

Further, optional certificates, such as DGNB, BREAM, or LEED, document sustainability criteria, such as the energy required for production of building components and the emissions caused by this, the durability, and the ability to be dismantled and recycled. Numerous non-for profit agencies issue guidelines for the determination of the environmental impact of buildings according to multiple criteria, such as: (i) risks for the local environment (DGNB ENV1.2), (ii) environmentally compatible material extraction (DGNB ENV1.3), (iii) classification of building materials with regard to their chemically hazardous components (Giscode), and (iv) volatile organic compounds (VOCs).

In all of the above cases relevant certificates must be linked to the BIM-Model. During the handover phase it must be checked, whether these certificates are linked to the relevant parts of the BIM-model or the digital twin. To achieve this in a complete and consistent way, guidance is required, preferably in an electronic form.

For linking the above mentioned information to the BIM models, two ways are currently used. Either the required information is stored directly in the BIM authoring system as parameters or it is added to the IFC models. For this purpose, the CAFM Ring, for example, offers the possibility of using the CAFM Connect tool. CAFM-Connect includes a standard catalogue for this purpose, which expands the existing structures in DIN 276 and provides clear specifications for the individual component types. Furthermore, documents can also be inserted into CAFM-Connect on the basis of a classification according to GEFMA 198.

## 2.2 Verification of Collaborative Design Activities

In nonprofessional terms, the commissioning phase of buildings is the first 'real-world-test' for the systems and subsystems designed. In this phase, it will be verified that a building functions as "an overall system" and to the satisfaction of the client and his/her representatives. The sequence, in which systems and components shall be activated is determined by their 'systemic interdependencies'. Thus, guidance is required how to activate these systems.

However, BIM-models provide valuable information about (i) the availability of systems and components, and (ii) the availability of dependencies, e.g. using separate or joint control systems. Information about the availability of systems can be compiled from object-relational model representations. Furthermore, semantic model representations

(such as IFCowl) provide the methodological base to derive further knowledge through reasoning from openBIM [16, 17].

The utilization of shared vocabulary specifications is crucial in scenarios where the construction of knowledge-based systems is costly in terms of development, testing, and maintenance [18]. Research conducted by L.M. Camarinha-Matos et al. highlighted the potential contribution of ontology engineering in information and knowledge management within Collaborative Networks (CNs) [19]. Additionally, several research efforts support the incorporation of ontologies in CNs [20, 21].

### 3 Commissioning Processes

The definitions below are based on publicly available definitions [22], the ‘Whole Building Design Guide’ [23] and material published by Texas A&M University [24] “Historically, building commissioning referred to the process by which heating, ventilation, and air conditioning systems were initially brought to operation according to established standards prior to the owner’s acceptance. Today, building commissioning (BC) facilitates the planning, design, construction, installation, testing verification, documentation, and operation of facilities to conform to the Owner’s Project Requirements. One can distinguish into different types of BC, such as: new construction building commissioning (n-BC) and existing building commissioning (e-BC). e-BC can be broken down in three subtypes, such as: (i) Retro-commissioning (ro-BC) aims to resolve integration problems that originated from design or construction, or have developed throughout the building’s operation. It aims to improve how building equipment and systems function together. (ii) Re-Commissioning (re-BC) occurs when a building that has already been commissioned undergoes another commissioning process. It may be triggered by a change in building use or ownership, the onset of operational problems, etc. A Recommissioning-plan is developed based on the original commissioning plan (n-BC) or as a result of ro-BC activities. (iii) Continuous Commissioning<sup>®</sup> (c-BC) is an ongoing process to resolve operating problems, improve comfort, and optimize energy use for existing buildings, including central plant facilities. It incorporates and extends existing building commissioning practices by combining manual inspection and real-time data collection with automated analysis techniques to uncover anomalies”.

#### 3.1 Process Models for Commissioning

After the completion of BC processes and documentation O&M-staff and building occupants successfully completed a thorough quality assurance process. Thus, BC establishes and documents the ‘Owner’s Project Requirements (OPR)’. OPR are a set of criteria for system function, performance expectations, and maintainability. The BC-process verifies and documents compliance with OPR-criteria across all phases of a construction project (see Fig. 1 overleaf).

With the high number of systems, sub-systems and components requiring, or affecting, interaction of each other, BC-processes are very complex and provide many points of failure or inappropriate configuration leading subsequently to sub-optimal operation. Furthermore, building commissioning procedures are a collaborative team effort

and include training of operations and maintenance (O&M) staff and of building users during the initial occupancy phase and into occupancy.

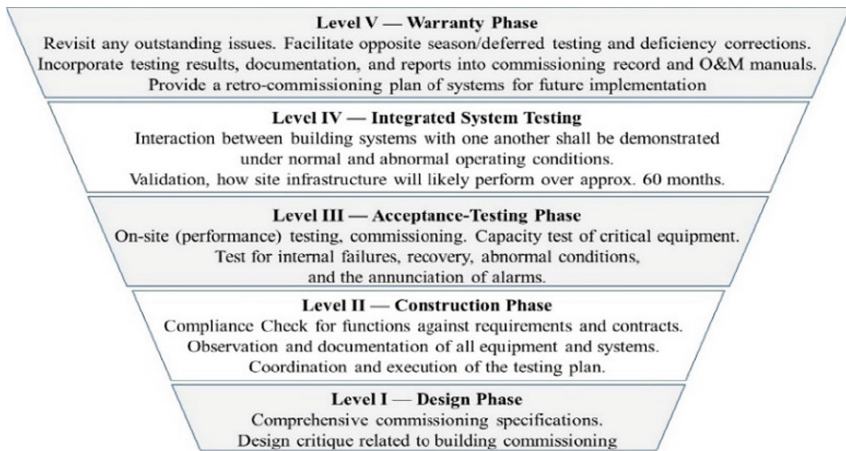


Fig. 1. The five levels of building commissioning (text adapted from: <https://www.sys-tek.com>)

### 3.2 Information Requirements for Commissioning

n-BC involves systematically testing and activating the various building systems. Despite the apparent clarity of the standard in describing the handover process, high-quality procedures for information sharing and management between the various stakeholders involved in n-BC [25] is a major challenge. The use of Building Information Modelling (BIM) and digital twins helps to support seamless information sharing. Therefore, it is essential to clearly define the distinct information requirements in order to effectively share information (see Table 1).

The primary information requirements for building commissioning on the German market are specified in ‘DIN 32835: Technische Produktdokumentation - Dokumentation für das Facility Management’ (parts 1 and 2) and DIN’s Special Report No 151. These documents specify the scope and content of building documentation during initial commissioning. Part 1 specifies the methodology and part 2 the ‘Documentation for Building Operation’.

A methodology how to document and label buildings and technical systems in buildings is laid out in DIN 6779-12. This standard applies to the function, product and location-related labelling of technical objects and their documentation in the area of buildings and technical building equipment.

The standard DIN EN 61355-1 provides rules and guidelines for the classification and identification of documents related to electrical systems. It serves as a basis for agreements to create structured documentation, which is mainly required for larger facilities, such as plants with their systems and equipment.

Furthermore, it shall be noted that buildings and technical facilities can be integrated into higher-order systems without changing the defined identifiers, provided they are labeled according to the rules of the DIN EN 81346 series of standards. This standard applies to systems in the sense of functional units of objects within a building.

Finally, DIN EN ISO 10209 provides specifications for Technical Product Documentation - Vocabulary - Terms for technical drawings, product definition and related documentation.

**Table 1.** Information requirements for initial building commissioning

OPR and Goals of Commissioning	
1 Usage Information	2 Building Management products
• User Profile	• Product strategy
• Processes	• Scope of services per product (SLA)
• Organization/company organization	• Evaluations
PLANNING DOCUMENTS, BIM, INVENTORY OF INSTALLATIONS	
Information related to DIN 32835	
3 Documentation specifications	4 Project data
	• Real estate/building data
	• Participants (tenants, operators, etc.)
Information related to DIN 6779   DIN 61355 and DIN 81 346   DIN EN 10209	
5 Building documentation	5 Building documentation
• Space program/Techn. Room book	• Operationally relevant data (BS)
• Cross floor area etc	• Equipment
• Construction documents	• Building handover protocol
• Specialist planning	
Regulations and stipulations to be complied with	
6 Management services	7 Costs
• Property inspections	• Total cost of ownership
• Reporting	• Initial building costs
• Quality Management	• Repair and maintenance costs
Acceptance procedures	
8 Contract documents	8 Contract documents
• Lease Agreements	• Service agreement (tenant)
• Construction contracts	• Service Agreements (FM-providers)

## 4 Commissioning Assisted by Knowledge Based Systems

The handover phase marks a critical point in the transition from construction to operation. During this phase, conducting commissioning procedures is one of the major activities apart from the development of as-built models and post-occupancy evaluations. The objective is to guarantee that all building services installations operate according to the planning intent and meet the building owner's requirements [26].

Commissioning processes capture two distinct aspects, (i) the technical part and (ii) the strategic part. Data and information management for the technical part can be described as 'deterministic', since systems and components are designed and constructed. Interdependencies between systems are specified and 'tangibly implemented'. The need for certificates can be specified based on relevant standards and regulations. Requirements for compiling data from monitoring devices (e.g. sensors and meters) can be concluded from those standards and maintenance manuals of manufacturers. Major deficits of current building handover/commissioning processes identified in the literature are defects, inadequate attention to owner requirements, or insufficient information quality due to limited interoperability between BIM and Facility Management (FM) technologies [27].

In comparison data and information requirements for the strategic part depend strongly on the contractual models and the underpinning legislation, including tax-incentives, targeted financial support programmes aiming to motivate changes on societal level etc. The development of a generally applicable methodological approach for data capturing and structured information aggregation and analysis is not possible, since national law and legislation have a strong impact on the development of workflows. Therefore, we focus on the technical aspects of building commissioning.

### 4.1 Complex Systems and Stakeholder Interaction

Buildings are complex "systems-of-systems". The most prominent openBIM meta-data model, IFC, is capable to represent such systems comprehensively. Figure 2 depicts the relevant part of the IFC-inheritance tree. A total of 59 classes exist in the current model version to represent building services systems components.

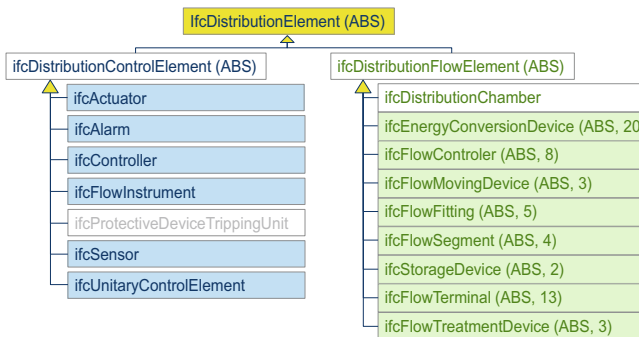


Fig. 2. BAC-Devices (le.) and Building Services Systems Components (ri.) in IFC

## 4.2 Ecosystem for Building Commissioning

Emerging data-driven business models rely on Data Ecosystems, which facilitate automated exchange between participants and provide access to vast and diverse data sources [28]. Data Ecosystems exhibit self-regulation as actors perform multiple roles and establish relationships with one another, leading to both collaboration and competition. Thus, the actors promote the stability and balance of the ecosystem.

Data Spaces are “interoperable and portable (Cross-) sector data sets and services” [30]. A Data Space refers to a group of participants or entities and their interconnected relationships [31]. In a data space, all data sources related to an organization can be included, irrespective of their format, location, or model. These individual data sources are referred to as participants within the data space [32]. One benefit of utilizing a shared data space is the ability for other partners to join at any given time and access historical data as needed. This means that even if there is a change in building service providers, existing inventory information and AI models can still be utilized without the need for retraining. Ultimately, this promotes sustainable building usage.

## 4.3 Knowledge Based Systems: Commissioning

Knowledge Based System (KBS) stores symbols of a computational model as statements related to a particular domain and this system conducts reasoning by manipulating these symbols [33]. It is composed of a knowledge base, a rule base, and an inference engine. The knowledge is stored in the form of knowledge graphs. A knowledge base (KB) is made up of two parts, namely the TBox and the ABox. The TBox defines the terminology or vocabulary used in a specific application domain, while the definitions of individuals are stored in the ABox [34]. The rule base comprises IF...THEN rules that are formulated based on the domain expert’s input or past system behaviour. The inference engine utilizes these rules to deduce new information from the knowledge base by applying rules to incoming information [35]. KBS-Commissioning is an intelligent service system that operates on knowledge graphs. It comprises three primary modules, namely knowledge graph population, knowledge graph management, and semantic AI module.

## 4.4 Knowledge Graph Population Through Component Analysis

The knowledge graph population module stores domain-specific ontologies related to building systems, spatial structures, etc. The knowledge graph management module encompasses query functionalities, information management, and linking domain vocabularies. OpenBIM-repositories are supported by meta-data models. Thus, digital twin models (or parts of them) can be analysed and checked whether instances of certain classes are contained in such models or not. The result can be compared with ‘Identification Templates’, e.g. matrix-like structures mapping single components to building systems or sub-systems (see Table 2). The Commissioning plan (CxP) will be generated based on the Template: Commissioning plan (CxT) (see Fig. 3) and populated with the results of the analysis of the Mapping-Matrices.

**Table 2.** Mapping-Matrix ifcClasses to technical systems (example ifcEnergyConversionDecice)

	ifcEngine	ifcEvaporativeCooler	ifcEvaporator	ifcHeatExchanger	ifcHumidifier	ifcMotorConnection	ifcSolarDevice	ifcTransformer	ifcTubeBundle	ifcAirToAirHeatRecover	ifcBoiler	ifcBurner	ifcChiller	ifcCoil	ifcCondenser	ifcCooledBeam	ifcCoolingTower	ifcElectricGenerator	ifcElectricMotor	
Mechan. ventilation						★													★	
Hydronic heating	★			★		★			★		★	★		★					★	★
Air-based heat/cool		★				★			★	★			★	★			★	★		★
Air conditioning		★	★		★	★			★		★		★	★	★	★	★			★
Solar Thermal				★			★		★											★
Photovoltaic System							★	★											★	

#### 4.5 Interdependency Rules Derived from Relationship Analysis

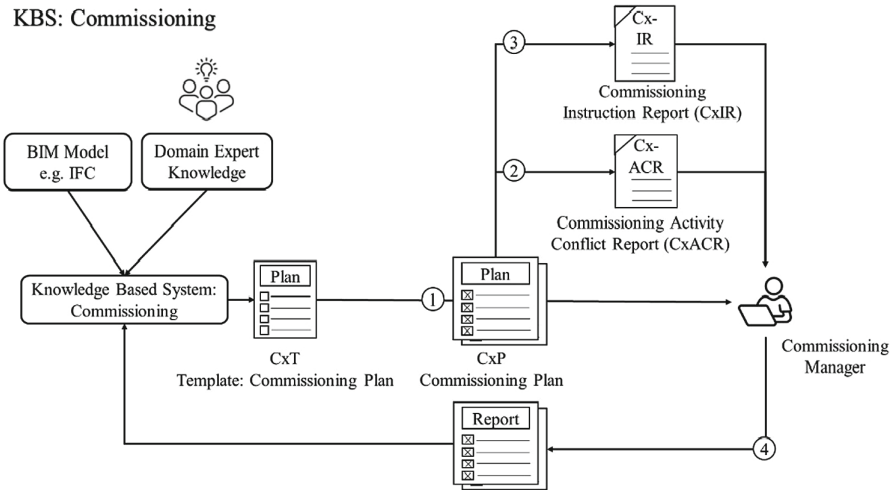
The semantic AI module utilizes deductive reasoning technique such as rule-based method. Rule-based methods involve a knowledge base that comprises both a rule base and fact base, along with an inference engine. To generate new knowledge, the inference engine applies the rules over the knowledge base, where the inputs are stored as facts derived from expert knowledge [36]. Interdependencies between systems can be automatically identified by analysing the appearance of so called ‘objectified relationships’ in openBIM models (see Table 3).

**Table 3.** Potentials for reasoning based on ‘objectified relationships’ in IFC

PortNesting	This concept is used to conclude what media is connected to a component. Supply systems must be commissioned before the connected system can be commissioned
PortConnectivity	This concept is used to conclude what circuits and sub-circuits are connected to a component. All components connected to these circuits can be commissioned after the component was commissioned
ControlFlow	This concept is used to conclude what Control Systems (CS) are available. CS depend on actuators. Thus, CS must be commissioned after the system(s) to be controlled
SpatialContainment	This concept can be used to conclude what Building Services are available in a spatial structure element (e.g. Space). Spatial structure elements can be commissioned after all building services and control systems were commissioned

### 4.6 Guidelines for Sequencing

The sequencing of n-BC activities can be derived through reasoning from the analysis of the interdependencies of systems and components specified by the above explained concepts (Table 3). The results of the reasoning process will be used for the population of the Commissioning Instruction Report (see Fig. 3).



**Fig. 3.** Information Flow and major components for information processing (source: authors)

The Commissioning Instruction Report (CxIR) will be generated based on the Commissioning plan (CxP) and the above mentioned results of the reasoning process.

The Commissioning Activity Conflict Report (CxACR) is also derived from the Commissioning plan (CxP). It is used during the execution of the commissioning activities to document failures and anomalies as well as the measures taken to correct failures and adjust systems’ and components’ anomalies.

The CxIR and the CxACR are used to compile the Commissioning Report. This document will be sent to the client but will also become a part of the knowledge base.

### 4.7 Guidelines for Documentation

In Sect. 2.1 we explained the need for compiling and managing various certificates required for documentation. Jointly with a sister project we work on a ‘Schedule of Certificates’ which provides initial information what certificates are required when.

The integrated application of this ‘Schedule of Certificates’ and the ‘Mapping-Matrix’ method (see Sect. 4.4) provide the required guidance for the structured collection and management of relevant certificates (Table 4).

**Table 4.** Example for Documentation Guidelines (decision criteria)

No.	Approving body and system or component	Building type	One-off Certificate	Initial Check	Repetition Cycle
<b>1</b>	<b>State-approved expert</b>				
1.a	Ventilation Systems	Office	No	Yes	3 years
1.b	Mechanical Vent. System	Parking garage	No	Yes	2 years
1.c	CO-Alarm System	Parking garage	No	Yes	1 year

## 5 Conclusion and Future Work

In our paper we presented the fundamental concepts and pre-requisites for the development of AI-driven commissioning services. We could illustrate that openBIM-based data models provide a solid, robust and comprehensive knowledge base for the implementation of AI-assisted software services.

Furthermore, we could illustrate that through the integrated usage of multiple software services a structured approach from building commissioning to documentation, certification and thus trust-building in highly collaborative scenarios becomes possible.

**Future Work.** The iECO-team envisages to implement the presented concepts within the next eighteen month of the project. Demonstrator buildings were selected and will be used as ‘data sources’ and for verification purposes. The work will be an integral part of the iECO-project, which is part of the European Gaia-X initiative. Through GAIA-X we will get access to further cloud services, such as encryption, digital signatures and blockchain-technology. These ‘general services’ will contribute to secure and high-quality management of building commissioning documents and data sources. Furthermore, these services will provide transparent workflow specifications, supporting the holistic management of manuals, performance data and other BC-information.

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