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FILIPE MATEUS MOARES FINCO

REQUIREMENTS AND LIBRARIES IN BIM BASED REFURBISHMENT OF HYDRO-POWER-PLANTS

ZAHTEVE IN KNJIŽNICE PRI PRENOVI HIDRO-ELEKTRARN Z BIM

BIM A+ European Master in Building Information Modelling

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Izvleček:

Vedno večje povpraševanje po električni energiji povečuje potrebno po proizvodnji energije. Ker si svet želi najti okolju prijaznejše energetske vire, je zelo pomembna možnost obnove obstoječih hidroelektrarn, da bi povečali njihovo življenjsko dobo in zmogljivosti, ne da bi pri tem imeli pomembne okoljske posledice.

Uporaba BIM omogoča bolj kakovosten potek prenove hidro-elektrarn (HE), boljši nadzor nad izmenjavo informacij in s tem lažjo izvedbo, boljše upravljanje naprav ter delovanje in vzdrževanje. Zato se ta naloga osredotoča na razvoj smernic za uporabo BIM pri projektih prenove HE. V okviru naloge so izpostavljeni glavni vidiki izvedbe BIM, kaj se pri pristopu BIM uporablja za tovrstne projekte ter izpostavlja nekatere trenutne izzive, s katerimi se soočamo pri uporabi BIM v industrijskem sektorju, kar je prikazano na študiji primera BIM.

Za študijo primera uporabe BIM je služil projekt prenove HE Formin. Študija primera vključuje uporabo orodij, kot je Revit kot glavno avtorsko okolje, dodatek MagiCAD za načrtovanje sistemov MEP ter dRofusa upravljanje projektnih zahtev.

BIBLIOGRAPHIC– DOCUMENTALISTIC INFORMATION AND ABSTRACT

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The ever-increasing demand for electrical energy pushes forward the need for more energy generation. As the world seeks to find more environmentally friendly energy sources a very significant option lays on the refurbishment of existing hydro powerplants in order to increase their lifetime and capacity without adding any significant environmental consequences. Even though it is not a new practice, the refurbishment of HPPs can benefit from the increasing applicability of BIM methodologies that have been steadily spreading from the construction sector into the industrial sector. Using BIM in the refurbishment project allows for a higher quality overall process, more control over information exchanges and better management of the construction, the plant facilities and even generates benefits for operation and maintenance.

This thesis work will focus on providing guidelines on how to use BIM into HPP refurbishment projects by exposing what are the main aspects of the BIM implementation process, what BIM uses are most valuable for this kind of projects, defining some of the current challenges BIM faces when being applied to the industrial sector and providing a prototype for BIM implementation case study.

The refurbishment project for the Formin HPP in Slovenia served as case study for the BIM workflow. The case study make use of tools like Revit for design, review for decision making, MagiCAD for MEP libraries, and dRofus for requirement specifications and project management.

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To the beautiful and welcoming countries of Portugal and Slovenia, my dearest thank you for allowing me to inhabit your lands and to get to know your rich and diverse culture, nature and infrastructure. Living there felt just like home.

And to the reason of my everyday will of living, my love Karina, thank you for being my life.

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1 INTRODUCTION

This chapter provides a brief overview on what are refurbishment projects of HPPs and why it is of relevance to discuss this problem under the light of BIM technologies. It explains the selected approach on the development of this thesis and how this paper is structured.

1.1 Demand for refurbishment of HPPs and BIM applicability

Even though the equipment in most power generation facilities have an expected lifetime of 20 to 30 years, HPPs useful life expectancy can be greatly increased to more than a hundred years by applying good operation and maintenance practices [1]. Maintaining the longevity of a hydro power plant requires its facilities to be under constant care, but many times only maintaining current capacity and operations is not enough. As society progresses and energy demands grow, so does increase the load on the active power plants. On a growing economy maximum energy capacity is always on the horizon and one must seek solutions to fulfill the increasing demands.

Building new powerplants is an option but the concern over environmental impacts of fossil fuel powered facilities and non-renewable energy sources makes new constructions of this kinds of facilities almost unfeasible and unjustifiable during present times. Therefore, one must resort to greener and renewable energy sources, one of these solutions are HPPs.

Traditionally built by modifying rivers beds with the intention of creating a reservoir in order to convert the potential energy of stored water into electricity by means of turbines and generators, hydroelectric power represented in 2019 15.9% of the energy share of global electricity production [2]. Hydropower is the most important renewable source of electricity but generating hydroelectrical power is not without environmental impacts. Figure 1 shows the distribution of word electric power generation per source.

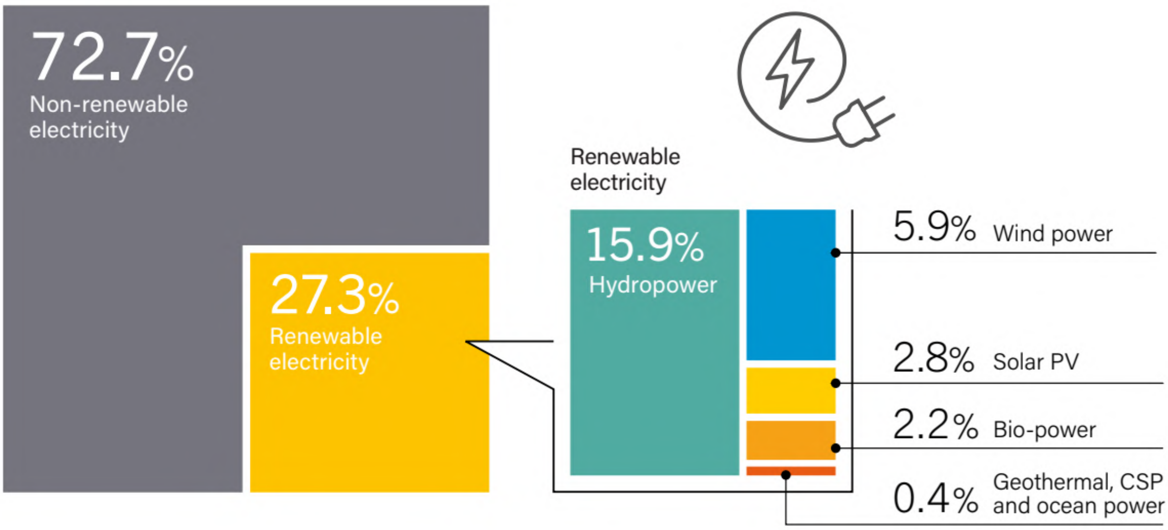


Figure 1 - Estimated renewable energy share of global electricity production, end-2019 [2].

Considering an installed capacity between 0.1 and >100 MW there are in Europe alone 21,387 HPPs, 278 more are in construction and additional 8,507 are planned to be built. From the existing HPPs, 3,936 are built in environmentally protected areas and from the 8,507 planned to be constructed, 28% would be placed in those areas [3]. Figure 2 shows the current distribution of HPPs across the European continent:

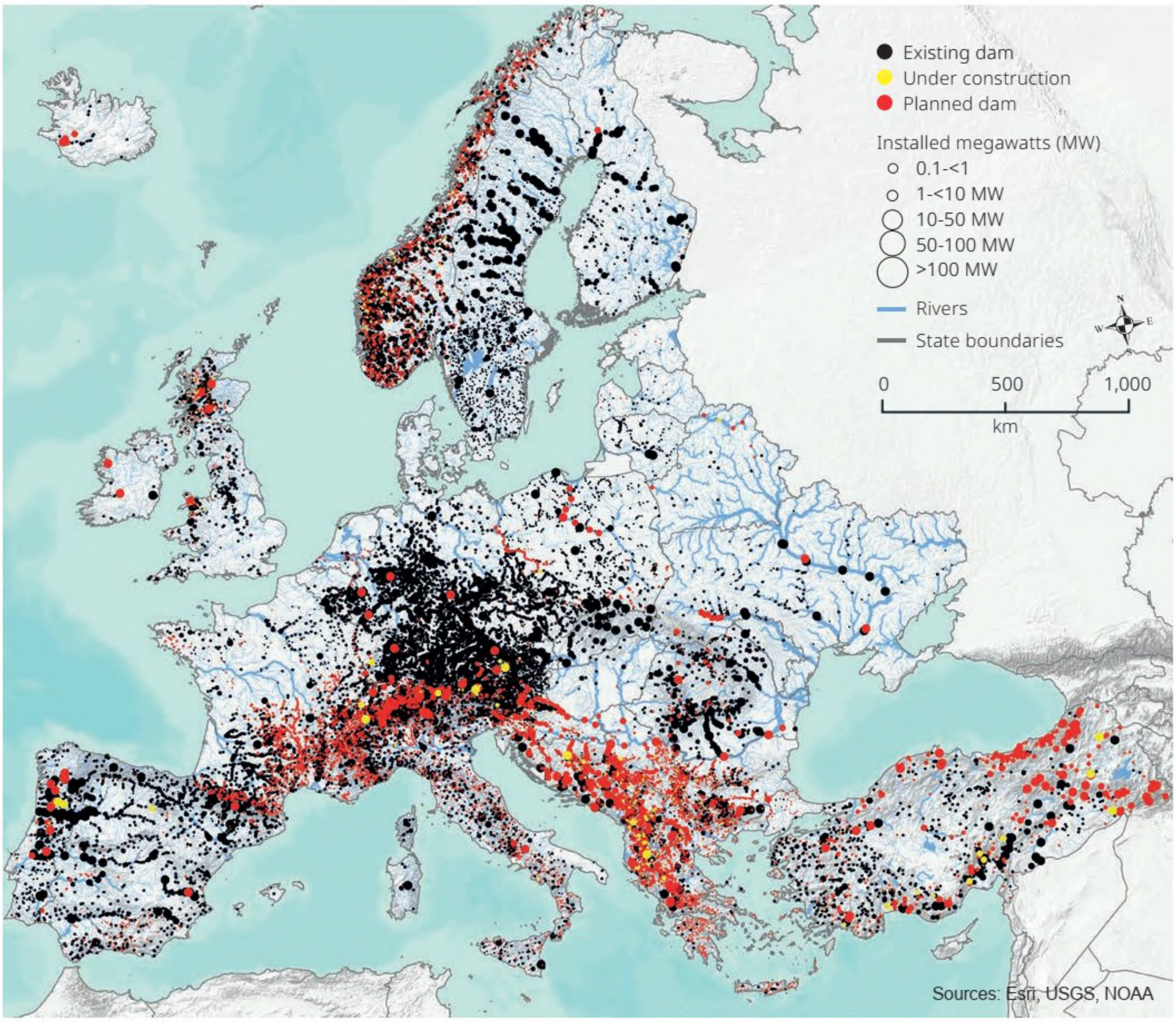


Figure 2 - Distribution of HPPs across Europe [3].

It is noticeable that some regions have already put massive pressure on their rivers, with a high density of constructed and planned HPPs.

On his study, U. Schwarz recommends that constructing new HPPs should be avoided due to the already massive pressure laid upon European rivers. Each new construction contributes to the deterioration of river ecosystems. The increase in energy capacity gained from building new multiple small sized HPPs is very limited, but the environmental impacts in most cases are considerable. He states that in some countries with the highest densities of HPPs, construction of new ones should not be allowed at all. He recommends that the only focus should be on refurbishment of existing HPPs.

Previous refurbishment projects demonstrate a significant annual power capacity increase. Modernization of Innertkirchen 1 and Handeck 2 HPPs in Switzerland, plants more than 60 years old, have achieved additional 70GWh production annually. The modernization of Ybbs-Persenbeug 236 MW HPP on the Danube river in Austria provided additional 60GWh. Statkraft four Norwegian hydro stations, Oevre Roessaaga, Nedre Roessaaga, Baatsvatn and Vessingfoss, which were installed between 1955 and 1975, received six new Francis units and an increase of 10% on power output [4]. The modernization project at the 1,000MW Mangla HPP is to increase the facility's power output by 310 MW [5].

But increasing the power output of currently existing HPPs, which can be up to +5% efficiency on 40-year-old turbines, is not the only benefit and goal of refurbishment projects. As decades old machines progress through time, modern technology finds a way to implement itself on these facilities. Modernizing works on HPPs can comprehend automation solutions based on optimized hardware architecture. On-line data and monitoring allow for the possibility of remote control and performance optimization and planning of maintenance actions through analysis of key performance indicators (KPIs) [6].

BIM comes into play into refurbishment of HPPs as a methodology for improving the overall work activities. A broad definition of BIM proposed by the BIM dictionary initiative by BIMe (BIM Excellence) is: "Building Information Modelling (BIM) is a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space. As a term, BIM has grown tremendously over the years and is now the 'current expression of digital innovation' across the construction industry" [7].

Despite demonstrating a wide range of possibilities and applicability for BIM that might be just too broad of a definition. B. Hardin defines successful BIM as being composed by 3 pillars: Processes, technologies, and behaviors [8]. The Processes pillar represent tools, like BIM software capable of generating 3D and non-geometrical models (meta data). The Technologies one represents how one makes each tool work together, BIM technology enables interoperability, an attribute that is fundamental to the interdisciplinary nature of construction, and in this case, refurbishment projects. The Behaviors compose how people (or companies) receive, react, and make use the tools at their disposal, as well as how they collaborate with others on a common project environment. BIM is all about having people in control of their individual roles in the project so that it functions as a whole.

A wide range of BIM uses can be applied into refurbishment projects, from point cloud scanning for generation of an as-is model, to a 4D and 5D time-cost simulation of the refurbishment project. Requirements specification software allow designers to better comply with project expectations. Design options linked to federated models help design decisions to be made. Data management solutions allow for maintenance of 3D and metadata assets, sharing information on a common data environment.

Implementing documentation like the BIM execution plan, EIR – Employer Information Requirements, BPRM – Business Process Reengineering Mapping, WBS – Work Breakdown Structure, RACI Matrix and many other tools help solidify each stakeholder position on the project hierarchy and clearly establish their roles.

1.2 Methodology

This thesis is an effort of conciliating BIM methods into the existing available knowledge about the industry's best practices, standards and regulations regarding HPPs refurbishment works. The idea is to acquire information through material that references HPP refurbishment works, extract the guidelines from the material and apply BIM into the practices to develop an improved HPP refurbishment workflow. Then, in collaboration with HSE-Invest, consultant to the owner of Formin HPP in Maribor-Slovenia, apply this proposed workflow into a prototype case study to take part into the planned refurbishment of that HPP.

1.3 Thesis structure

The next chapter provides an overview of currently available information regarding HPP refurbishment works and how BIM can be connected to refurbishment projects through the selection of relevant BIM uses. It also presents general guidelines for requirements of such refurbishment projects collected from industry relevant material and demonstrates how they can be used to define the employer information requirements document EIR.

Chapter 3 introduces Formin HPP and discusses information relevant to the refurbishment project under the light of BIM implementation for usage in a prototype case study on the subsequent chapters.

Chapter 4 presents main BIM techniques that can be used into the Formin HPP refurbishment project as a first step into implementing a BIM culture in the plant owner company with the intention of increasing its BIM maturity level.

In chapter 5 some of the BIM Uses and workflow improvement opportunities discussed through the paper are used into a prototype model for Formin HPP refurbishment project, with the main goal of testing out some of the proposed possibilities.

The conclusion on Chapter 6 provides the final statements and closing thoughts reflecting upon the work done in this paper and pointing out possible directions for future studies.

2 HPP REFURBISHMENT WORKS OVERVIEW

This chapter provides an overview of currently available information regarding HPP refurbishment works and how BIM can be connected to refurbishment projects through the selection of relevant BIM uses. It also presents general guidelines for requirements of such refurbishment projects collected from industry relevant material and demonstrates how they can be used to define the employer information requirements document EIR.

2.1 Life cycle of hydro power plants

HPP machinery deteriorates over time and use due to thermal, electrical and mechanical degradation of the materials used in the variety of components existing in its systems. Eventually this deterioration will lead to defects and even failure. Despite not being the subject of this study, aging also affects more sturdy components of the plant, like structures, which can have its lifetime reduced significantly by catastrophic events such as floods and earthquakes [9].

Countering this aging process is traditionally done by a variety of O&M (Operation and Maintenance) methodologies. At a certain point in time, after a prolonged and successful, or short and unfortunate, operation life, usually depending upon the capability of O&M practices, the condition, capacity and performance of the HPP reaches a point where it is either no longer cost effective to sustain operations or when the demand for power calls for increased output [9]. When facing an aging power plant there are usually the following available choices represented in Figure 3 for course of action.

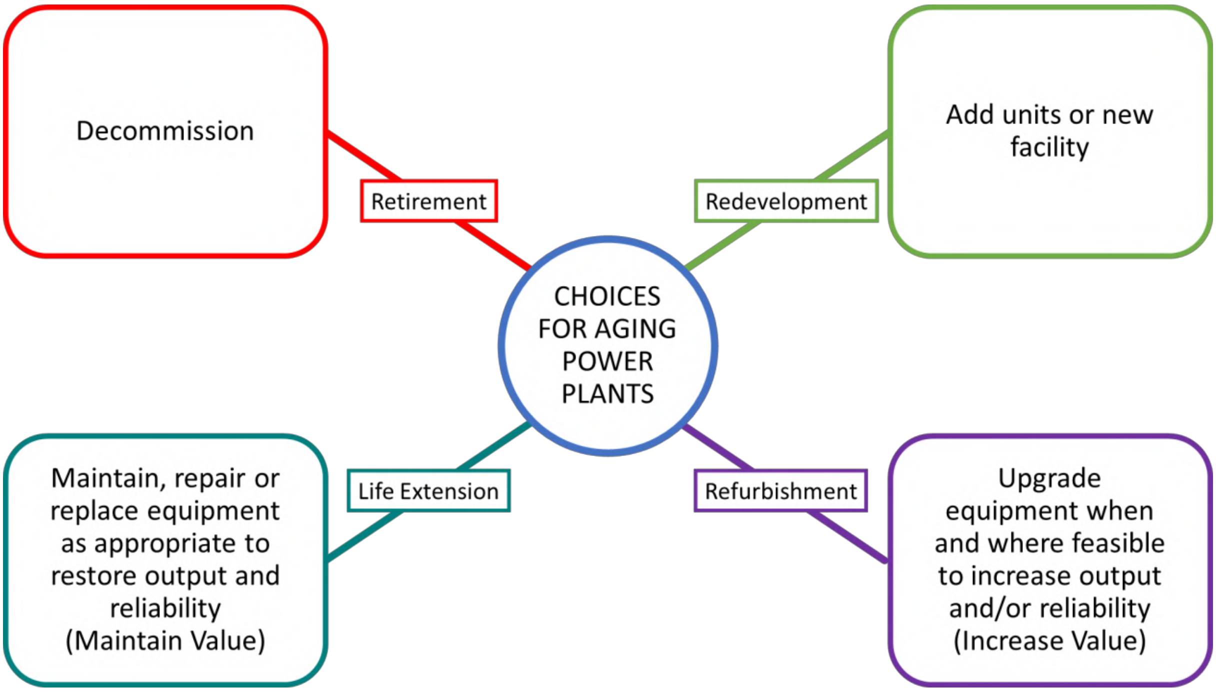


Figure 3 - Available choices for aging power plants [9].

Retirement: Removing the facility from operation to avoid the O&M costs.

Redevelopment: Installing a new plant and facility, basically replacing the previous one. It has the higher potential for production increase but is also the most costly option and has the highest environmental impact.

Life extension: Repair or replace components and structures to restore or maintain the plant output, when possible implementing new technology.

Refurbishment: This option covers upgrading (replacing older equipment with new modern ones), uprating (increasing the capacity) and modernizing main and auxiliary systems and components. Through refurbishment older plants become more reliable, cost-effective and productive.

The expected outcomes of a refurbishment work in an aging HPP are [9]:

- Improving output of electrical products and services and hence profitability, by replacement of equipment with more efficient and higher capacity ones.
- Reducing maintenance costs by having more reliable and modern materials and components.
- Reducing operation costs through automation.
- Reducing risks of catastrophic failures, through improved assessment, monitoring and emergency response systems.

2.2 Improving plant value by refurbishment works

Refurbishment is basically the integration of new components and the rework of plant systems with existing structures to maximize overall plant value. Technological advancements made since the initial commissioning of the HPP and economic driving factors of the present market push the plant towards needing to be more efficient, cost effective and perform better. The following categories of refurbishment activities that improve overall plant performance are presented in the Table 1:

Table 1 - Activities that increase overall plant value [9].

Categories of refurbishment activities	
Increasing Plant Output: Actions that increase capacity and/or power output are found throughout the plant; They include increasing operating head by raising the reservoir level or lowering the tailwater levels and uprating or adding capacity through either physical or operational improvements.	Improving operation: Through the usage of computerized models which incorporate plant characteristics, flow forecasts, outage schedules and other operating constraints it is possible to improve the usage of water and optimize generation dispatch.

<u>Reducing Losses:</u> Reducing, or eliminating, losses which have developed over time often restores the capacity and efficiency of hydro plants to their original design levels. In some cases, improvements can be made that effectively increase capacity over the original level. Some typical methods used during plant modernization to reduce energy losses include repairing leaks and reducing seepage in structures, repairing/replacing seals, reducing hydraulic head loss, by optimizing water passage design and installing new, more efficient equipment.	<u>Reducing O&M costs:</u> These costs can be reduced at the plant level in a number of ways. Supervisory control and automated data acquisition (SCADA) reduces many of the manual functions performed at older plants. Improved operational data assists in determining maintenance requirements and reducing forced outages. A move towards condition-based maintenance can be coupled with replacing worn equipment and modern processes for maintenance management systems. Greater automation reduces requirements for operating staff and increases efficient use of equipment. Substantial returns can be identified, when evaluating modernization options, particularly where 24 hour staffed positions can be eliminated or reduced to single shift operation.

2.3 Plant equipment subject to refurbishment

In order to identify which components should be subject to refurbishment works one must use multiple evaluation techniques specific for each kind of component.

The Electric Power Research Institute (EPRI) [10] has put together a very extensive guideline divided into seven volumes that covers most of current HPP equipment. It contains procedures for screening, evaluation of condition and performance, potential improvement assessment, cost estimation techniques, feasibility, and implementation of refurbishment plan. The volumes are divided into discipline specific areas, the complete guideline contains detailed data relevant to the following, and many more, components of HPPs presented in Table 2:

Table 2 - Equipment subject to refurbishment works.

Hydromechanical equipment [11]: • Turbine • Turbine runners • Wicked gates • Pelton nozzle assemblies • Shaft, shaft seal and turbine guide bearings • Governing system • Turbine Inlet Valve (TIV) • Runner	Electromechanical equipment [12]: • Generator • Excitation systems • Bearings • Stator • Exciter • Braking system • Fire protection • Generator cooling
Auxiliary mechanical and electrical systems [13]: • Lubrication • Raw and cooling water • Compressed air • Drainage and dewatering • Fire protection • HVAC • Powerhouse cranes • Tailrace Cranes • Generator transformers • Station Service AC/DC • Cables and cable support • Grouping • Lighting	Protection and Control [14]: • Digital relays • Self-diagnosing • Metering • PLCs • Processors • I/O • Networks • Synchronizers • Machine condition monitoring • Operational information
Civil and other plant components [15]: • Intakes • Spillways • Dams • Powerhouses • Water conveyances • Fish passage • Trash racks and rakes	

2.4 Available BIM uses to be applied to refurbishment works

An important part of the planning process for any BIM project is to clearly define the potential value of BIM for the project and for the team members involved with it. This is done by defining the overall goals for BIM implementation [16].

After defining measurable goals for the project, the possible BIM uses that can contribute to achieving them can be identified. Generally, there are around 25 possible BIM uses for construction projects [16]. Figure 4 shows these uses according to project phase. This section will identify those uses that are compatible with HPP refurbishment projects.

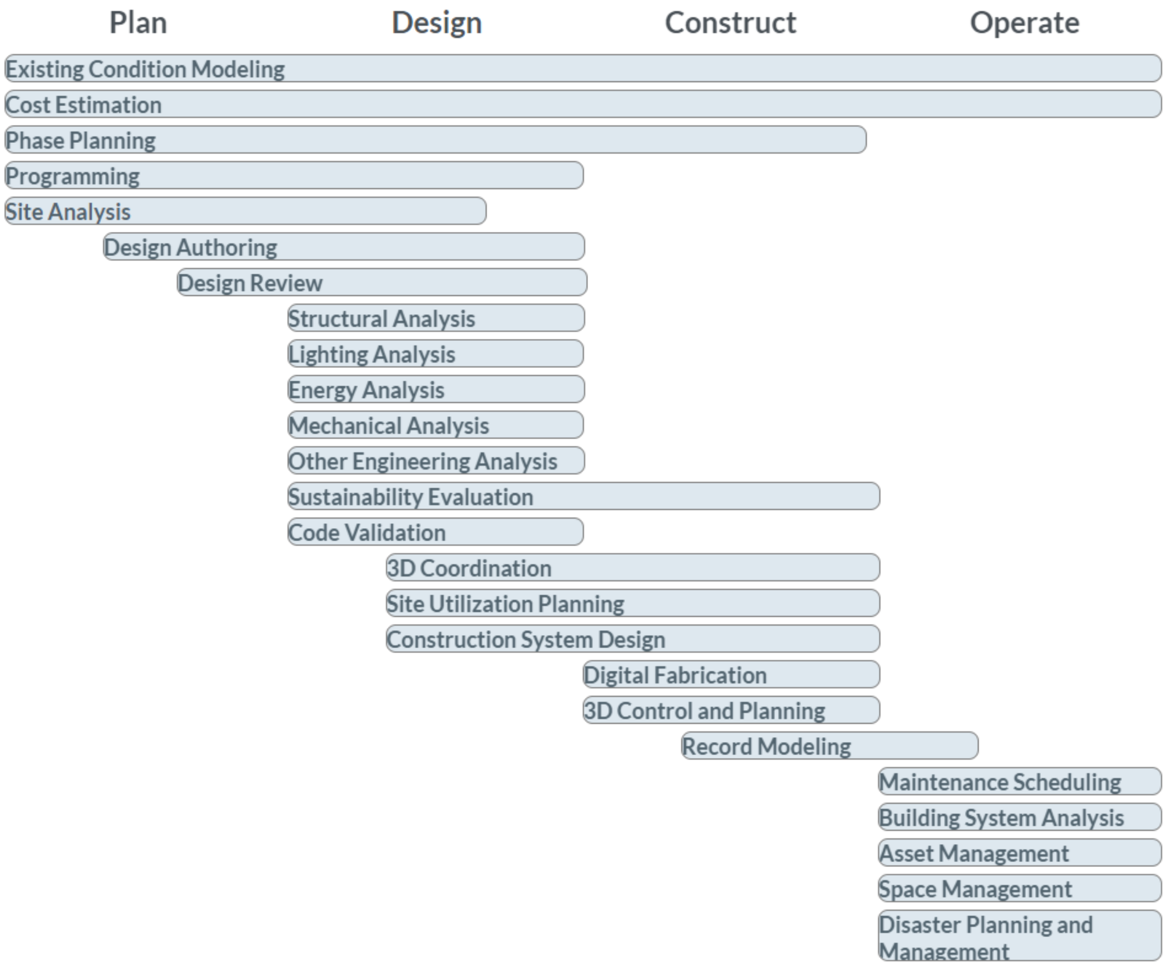


Figure 4 - BIM uses by building project phase [17].

Some BIM uses can be applied to multiple phases of the building lifecycle. According to Messner et. al. there are 4 main phases in a building project [16]:

- Plan
- Design
- Construct

- Operate

Messner et. al. also state that when identifying the BIM uses for a project one should begin with the end in mind [16]. For this reason, they suggest that in order to identify the BIM uses the project team should begin by analyzing the uses that fit into the operate phase, then progress in a reverse chronological order trough the construct and design phases until accessing the uses for the planning phase.

Each project has different goals, but regarding HPP refurbishment projects the actions are usually aimed at achieving what was previously listed at Section 2.2 in Table 1, in general, the ultimate goal is increasing plant value. The role of BIM is to improve the project actions in order to achieve the ultimate goal on a more efficient manner. For this to happen project specific goals need to be defined by the project team. In the case of Formin HPP, an example of project goals could be as shown in Table 3. This table is an example of a tool used to identify the BIM uses for the project team. It is called the BIM goals and uses selection spreadsheet and it helps to list and decide over the possible uses for the project.

Table 3 – Example of possible Formin HPP refurbishment project goals [16].

Priority	Project Goal	Potential BIM Uses
1 = Most Important		
1	Increase overall plant value	Emergency Management, Design Authoring, Structural Analysis, Engineering Analysis, Existing Conditions Modeling.
1	Increase the quality of the delivered project	Record Modeling, 3D Coordination, Design Authoring, Design Review, Existing Conditions Modeling.
1	Predict costs and keep within allocated budget	Asset Management, Design Authoring, Cost Estimation (Quantity Take-Off, 5D Modeling)
2	Accurately predict and track the progress of construction	Site Utilization Planning, Construction System Design, Phase Planning (4D Modeling).
2	Develop a digital twin of the HPP for use in O&M tasks	Building Maintenance (Preventive) Scheduling. Asset Management.
2	Allow data driven decision making by providing design choices	Design Review, Design Authoring.
2	Provide specified equipment requirements to suppliers and subcontractors	Asset Management, Space Managements and Tracking.
3	Increase field productivity and team competence	3D Control and Planning (Digital Layout).
3	Usage of 3D models for equipment fabrication and instalation	Digital Fabrication, Site Utilization Planning.
3	Achieve sustainability goals	Energy Analysis, Lighting Analysis, Sustainability Analisys.

Table 4 – Example of BIM goals and uses selection spreadsheet for Formin HPP refurbishment [16].

BIM Use	Value to Project	Responsible Party	Value to Resp Party	Capability Rating			Additional Resources / Competencies Required to Implement	Notes	Proceed with Use
	High / Med / Low		High / Med / Low	Scale 1-3 (1 = Low)					YES / NO / MAYBE
				Resources	Competency	Experience			
Emergency Management	LOW	Facility Manager	HIGH	2	2	1			**Maybe**
Design Authoring	HIGH	Designer	HIGH	3	2	2			**Yes**
		Subcontractor	MED	1	1	1	Needs training		
Structural Analysis	MED	Designer	MED	2	2	2			**Yes**
		Contractor	MED	1	2	2			
		STR Engineer	HIGH	3	3	3			
Engineering Analysis	MED	Contractor	HIGH	2	2	3			**Yes**
		Plant Owner	LOW	1	1	1	Needs training		
Existing Conditions Modeling	HIGH	Plant Owner	HIGH	1	1	1		Wants the As-Is model	**Yes**
		Subcontractor	HIGH	3	3	3			
Record Modeling	HIGH	Facility Manager	HIGH	2	2	3	Needs to aquire software	Desires to use for O&M	**Maybe**
		Plant Owner	MED	1	2	2			
3D Coordination	HIGH	Designer	MED	2	2	2			**Yes**
		Contractor	MED	1	2	2			
		Plant Owner	HIGH	1	1	1	Needs training		
Design Review	MED	Designer	HIGH	3	3	3			**Yes**
		Contractor	LOW	2	2	2		Should provide design options	
		Plant Owner	MED	2	2	3			
Asset Management	MED	Facility Manager	HIGH	3	3	3	Needs to aquire software	Desires to use for O&M	**Maybe**
		MEC Engineer	HIGH	1	2	3			
Cost Estimation (5D Modeling)	HIGH	Plant Owner	MED	1	1	2			**Yes**
		Contractor	HIGH	2	2	2			
		Designer	HIGH	3	3	3			
Site Utilization Planning	LOW	Contractor	HIGH	2	2	2			**Maybe**
		Subcontractor	LOW	1	2	2			
Construction System Design	LOW	Contractor	MED	2	2	2		Minimal concrete casting needed	**No**
Phase Planning (4D Modeling)	HIGH	Contractor	HIGH	2	2	2			**Yes**
		Subcontractor	MED	2	2	1			
		Plant Ower	MED	1	1	2			
		Designer	LOW	1	2	2			
Building Maitenance	HIGH	Plant Owner	HIGH	2	3	2	Needs to aquire software		**Yes**
Space Management	MED	Designer	MED	2	3	2			**Yes**
		Plant Owner	LOW	1	2	2	Needs to aquire software		
		Facility Manager	HIGH	2	3	2	Needs to aquire software		
3D Control and Planning	MED	Contractor	HIGH	2	3	2			**Maybe**
		Facility Manager	MED	1	2	2			
Digital Fabrication	LOW	Designer	MED	2	2	2			**Maybe**
		Subcontractor	HIGH	3	3	3			
		MEC Engineer	MED	1	3	3	Needs training		
Energy Analysis	LOW	Plant Owner	LOW	1	1	1			**Maybe**
		Subcontractor	HIGH	3	3	3			
		ELE Engineer	HIGH	2	2	3	Needs training		
Lighting Analisys	LOW	Plant Owner	LOW	1	1	1			**Maybe**
		Subcontractor	HIGH	3	3	3			
		Architect	MED	2	2	2			
Sustainability Analisys	MED	Plant Owner	MED	1	1	1			**Maybe**
		Subcontractor	LOW	3	3	3			
		ENV Engineer	HIGH	1	3	2	Needs Training		

On Table 4 the possible BIM uses for the project are listed together with the responsible parties and their value/responsibility toward that specific BIM use for the project. Each party has their capabilities evaluated in terms of resources, competency and experience for each of the BIM uses they are involved with.

The example provided shows that despite being applicable to the project, not all BIM Uses end up being used during the project. This evaluation on each BIM Use is made by the project team and requires it to determine the potential added benefit to the cost of implementation. The team also has to evaluate the risk elements associated with implementing or not each Use, taking into consideration that risks may shift from one party to another depending on the decision [16].

2.5 Requirements, guidelines and industry practices for HPP refurbishment works

One important aspect of any project is how to, as an employer, specify what are your needs, expectations and requirements for that project. To better materialize these needs a document called EIR (Employer Information Requirements) can be developed.

The EIR intends to clearly articulate the information requirements for each involved party and describe the expected information exchanges in terms of documents, model files and data. It should also provide an expectation guideline on how and when information should be exchanged during the project. As each project has its particularities the exact contends of the EIR will depend on the complexity of the project and the experience and capabilities of the employer. Experienced employers may develop highly detailed EIRs, whilst others may only be able to setup high-level requirements or basic rules, leaving the contractors to propose how those requirements can be met [18].

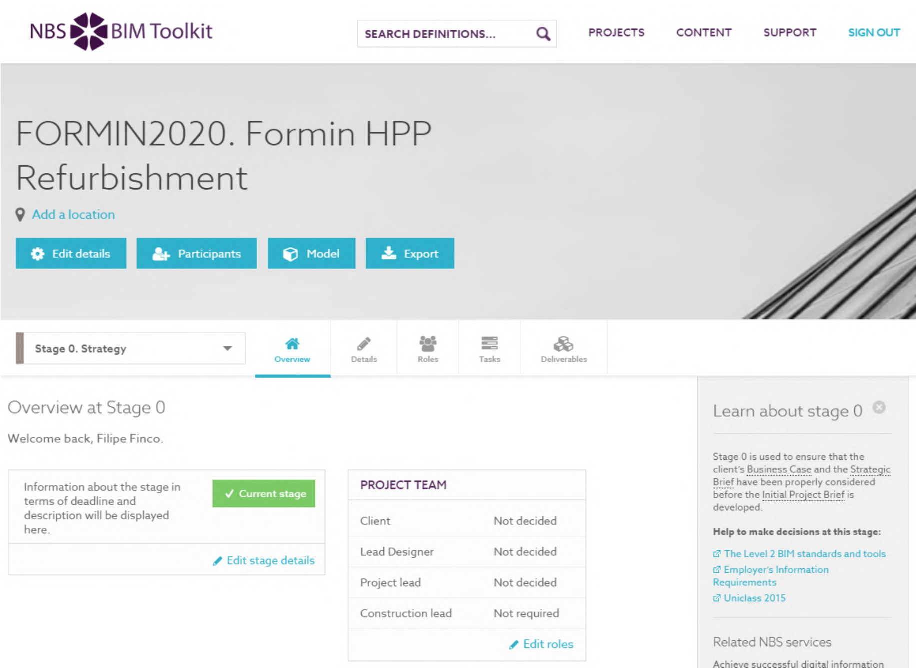


Figure 5 - NBS BIM Toolkit.

There are multiple project management techniques available on the industry. An example of a BIM oriented one is proposed by the NBS BIM Toolkit [19]. An example of the toolkit in shown in Figure 5. The toolkit has a dedicated portion oriented towards the specification requirements and the creating of an EIR for the project. The toolkit uses the RIBA Plan of Work [20], which project phases are shown in Figure 6, as a basis for the project management.

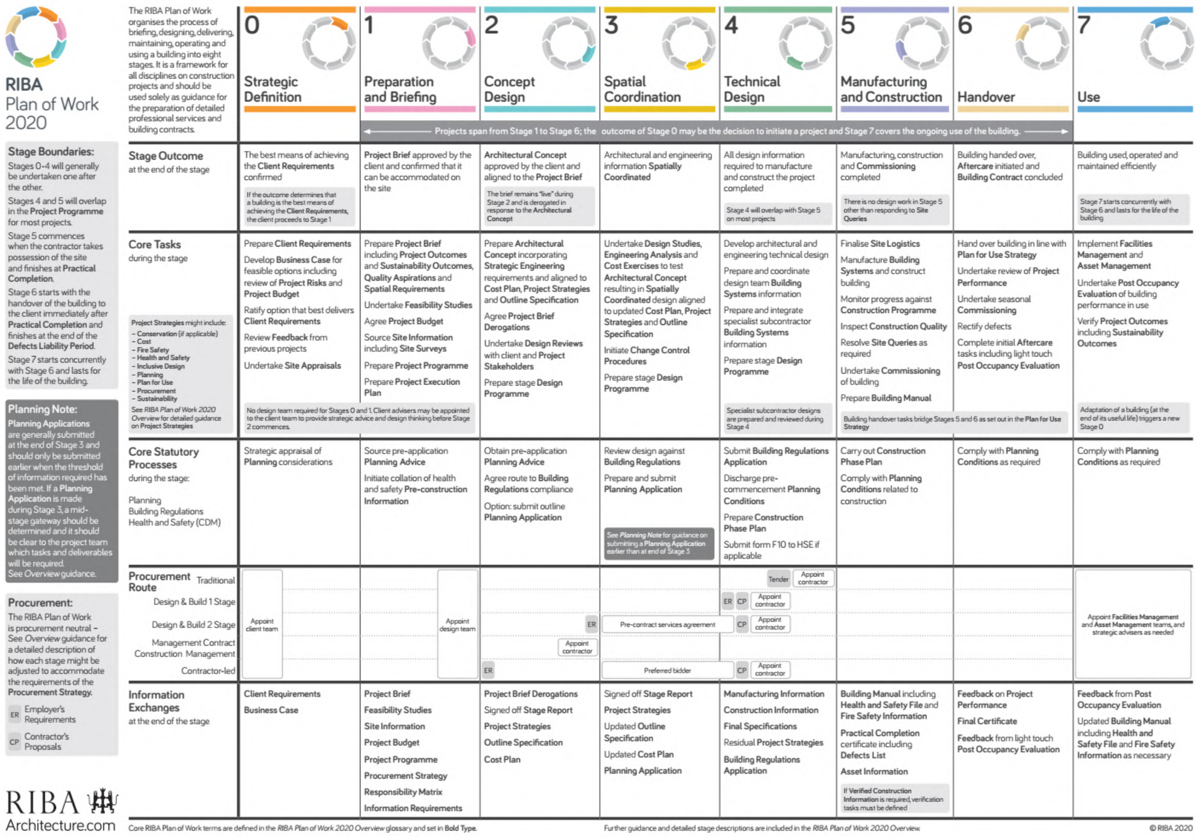


Figure 6 - RIBA Plan of Work project phases definition.

The EIR has to be formulated according to the company's needs and expectations and based upon technical information regarding multiple aspects of the project. For the hydroelectrical sector one of the most comprehensive technical guidelines, previously mentioned in Section 2.3, are entitled Hydro Life Extension Modernization Guide. Formulated by EPRI (Electrical Power Research Institute) [10], it consists of seven volumes of technical specifications regarding HPP refurbishment and modernization details. It covers a wide range of topics from site planning, civil and plant structure and hydromechanical components to protection & control, operation & maintenance and governance.

This thesis paper develops, on Chapter 5, a prototype case study for BIM tools applied into refurbishment projects by using the Stator Frame of Formin HPP as a sample equipment for the development of the BIM workflow. For this reason, the following information is extracted from the EPRI guidelines regarding that equipment as an example of what can be found on those documents.

Condition Assessment of equipment: Stator Frame [12]

The stator frame mounting system should be examined from both the coupling room and behind the stator frame (if practical). Particular attention should be given to expansion provisions (if any) and to concrete spalling/cracking. Benchmark status will be important if any upgrade or capacity increase is contemplated. The stator frame key bars and split joints should be examined for distress. Also, at this time, the stator core dovetails should be inspected for fractures, missing tabs, and fretting; and on a sectionalized frame, the frame splits should be examined for possible distortion, displacement, and retting.

Criteria: New cracks in the frame structure or concrete are unacceptable. If uneven expansion is suspected, the stator frame should be rated as unacceptable until further researched (check of negative sequence stator current variation from cold to full load, additional runout, and displacement tests as a function of temperature). Some keybar and split joints fretting corrosion is acceptable, but excessive and localized fretting or broken bars are unacceptable. Any dirt should be examined for magnetic material, which is unacceptable.

Condition Assessment of equipment: Generator Cooling [12]

There are three main designs for generator cooling:

- The most common design consists of surface air coolers on the stator frame; cooling water is usually taken off the penstock, and rotor fins recirculate the air.
- Normal air ventilation is a design that does not provide any coolers. Cold air from the tailrace is pumped through the unit by the rotor fins (non-recirculating). These systems expose the units to considerable dirt, and maintenance issues can arise.
- For large, modern machines, sometimes the cooling water tubes are embedded in the stator coil. Cooling water is usually taken from the penstock.

If water-cooled, the generator is the largest consumer of cooling water. Cooling water systems for generators are usually unchanged from the OEM’s specifications when the station was commissioned. These systems are often conservative with flow capacities that greatly exceed the cooling requirements of the unit. Condition assessment of the system consists basically of evaluation of the condition of valves, piping, and the generator coolers. Age and water quality are the two significant factors that affect cooling water equipment. Certain water qualities can lead to aggressive corrosion of the pipes and valves, especially if microbial activity is involved.

Assessment of the cooling water system should begin with a review of the auxiliary cooling water system’s maintenance history. The type and frequency of failures will identify those areas that may require attention. The valves, strainers, intake, intake screen, and piping should be visually inspected for blockage, leaks, and excessive rust or corrosion. When the system is inspected, the appropriateness of material selection should be an important factor.

All valves and strainers within the system should be checked for condition and proper performance. All water filtering systems should be inspected to ensure that the system is removing the necessary debris from the water. Automatic backwash systems should be checked for proper valve operation and backwashing of debris from the filters. Proper setting of the differential pressure control for initiating automatic backwash should be verified. The generator air coolers should be checked for leaks, corrosion and mineral buildup. The maximum pressure differential across any of the coolers should be approximately 10 psi (68.9 kPa) to ensure satisfactory cooling.

Cooling water piping should be also checked for leak-tightness, corrosion, and mineral buildup.

If constant blockage of pressure-reducing valves and radiators is a problem, further studies should be conducted to assist in the formulation of a solution. Some cooler valves should allow throttling to avoid or reduce condensation occurring on the outside of coolers and dripping into the generator housing.

Additional description of cooling water systems are provided in Volumes 4 and 5, “Auxiliary Mechanical Systems” and “Auxiliary Electrical Systems” of the EPRI guidelines.

Life Extension activities: Stator Frame [12]

Life extension activities include:

- Repair any weld fractures, including keybars;
- Retorque frame and anchor bolts;
- For expanding frames, recenter and relubricate sliding surfaces;
- Clean and paint ferrous surfaces.

Life Extension activities: Generator Cooling [12]

The life extension activities include:

- Repair generator coolers (re-tubing);
- Install new generator coolers;
- Repair supply piping and accessories;
- Install new generator supply piping, pressure reducing valves, and strainers.

Primary life extension activities for the cooling water supply consist of replacement or rebuilding of pumps, strainers, and other equipment.

Strainer rebuilding typically includes replacement of the straining media. Brass straining media can be replaced with stronger stainless steel materials. Self-cleaning filters should be considered when replacement is required.

Large valves may be rebuilt, including replacement of seats, seals, and stems. Replacement of smaller valves is usually more cost-effective. Gate valves larger than approximately 12 inches (30.48 cm) are quite costly; and when replacement is necessary, it might be possible to substitute a butterfly valve or a knife gate valve. Piping should be replaced if it is badly corroded. New stainless steel piping can be considered for corrosive environments. Plastic and high-density polyethylene pipe has also been used for some applications, although care must be taken to ensure that the softer and less rigid polyethylene pipe is protected from external damage and that it is well supported to prevent sagging sections between supports. If water contamination is severe and has resulted in plugging or erosion of coolers or load limitations, it may be necessary to modify the cooling water system. Proven remedies are closed-cycle systems with heat exchanger coils in the turbine intake or forebay and double-circuit systems.

Heat exchangers should be flushed/cleaned and retubed if leaking. If only a few tubes leak, then these tubes can be plugged. Anti-sweat insulation should be replaced if deteriorated; however, replacement of asbestos insulation can be costly. Nevertheless, deteriorated asbestos insulation must be removed for health reasons. Application of a new protective coating to piping, valves, and equipment will also aid in life extension.

Control devices are either rebuilt or replaced if they do not function satisfactorily. Automation requires that hand-operated valves be replaced by power (electric or pneumatic) operated valves if the open and close operations of the valve are a part of the unit start/stop sequence. One temperature sensor and one pressure sensor should be installed at the cooling water intake, after the pumps, and at the cooling water discharge. For larger, water-cooled generators, temperature and pressure sensors should also be installed at both ends of each generator cooling water loop.

Advances in Technology for Electromechanical Equipment

Table 5 - Advancements in technology for the relevant equipment of the Formin prototype Case Study.

Equipment	Advances in technology
Stator Frame	• Welding/stress relieving for site fabrication/assembly; • Finite element analysis; • Expansion/contraction provisions.
Generator Cooling	• Modulated flow of cooling water using control valves

These parts of information extracted from the guidelines demonstrate what sort of practices should be taken by the design team when planning the refurbishment actions of the HPP, subsequently this information will make their way into the project through the EIR document, which in turn is used to create the BEP (BIM execution plan), more information about this process is shown on Section 4.1.

As mentioned previously the guidelines are very extensive, the development of the EIR can make full use of its information which can be transformed into actual model requirements. The tools suggested for implementation of model requirements are demonstrated in Section 4.4 and the case study utilization is shown in Section 5.3.

3 FORMIN HPP REFURBSHMENT PROJECT

This chapter introduces Formin HPP and discusses information relevant to the refurbishment project under the light of BIM implementation for usage in a prototype case study on the subsequent chapters.

3.1 About Formin HPP

Completed in 1978, Formin is the last HPP in the chain of Drava river power plants, the second in terms of electricity production in the country and has the largest reservoir in the Slovenian part of the Drava river. Figure 7 shows the location of Formin HPP on the Slovenian map. Due to natural conditions it is designed as a derivation hydro power plant. It exploits a 29-meter head between Ptuj and the state border with Croatia and has an annual production of 548 GWh of electricity at 116 MW [21].

Figure 7 - Location of Formin HPP in the Slovenian country [22].

The dam located upriver in Markovci has six, seventeen meters wide, overflow sections. It is equipped with radial gates and top flap gates. The maximum design discharge at the dam is 4,200 m^3/s. A submersible wall is installed above the inflow into the inlet channel, which prevents the inflow of float into the inlet channel with the bridge part of the dam. Table 6 shows the technical specifications for Formin HPP. Figure 8 show a picture of Formin HPP powerhouse from downriver perspective.

Table 6 - Data about Formin HPP [21].

Formin technical specifications			
Annual production:	548 GWh	Reservoir size:	17.1 million m^3
Threshold power:	116.0 MW	Usable volume:	4.5 million m^3
Number of aggregates:	2	Commissioning:	1978 (Both units)
Nominal flow of turbines:	500 m^3/s	Renovations:	Planned for mid 2020s
Length of reservoir:	7 km (Lake Ptuj)	Coordinates:	46°24'09.8"N 16°02'01.2"E

Figure 8 - Formin HPP powerhouse from downriver [21].

3.2 Currently available and provided data

To have a better understanding of the plant a filed visit was made for collecting data and getting to know the staff of Formin HPP. Pictures and 360 images of the plant we taken. Later, after discussing the project with the plant owner the point-cloud scan model, together with 3D models of the HPP were provided. Figure 9 shows a picture of the entrance to Formin HPP powerhouse.

Figure 9 - Entrance to Formin HPP powerhouse.

A .zip file was delivered via DropBox transfer. This file contains the 3D revit models and and the point clouds made available by the plant owner. Data was divided into 7 different .zip files due to its size (27Gb). After unpacking the files total 47Gb.

The files were divided into revit models and point clouds. The point clouds were given in Recap files as well as in Scene2GO. The Recap one was treated previously to be used as a reference on the modeling of the 3D Revit files. The Scene2GO is a useful tool to quickly navigate and visualize the scan. The provided Revit files were all together in a folder organized as shown in Figure 10.

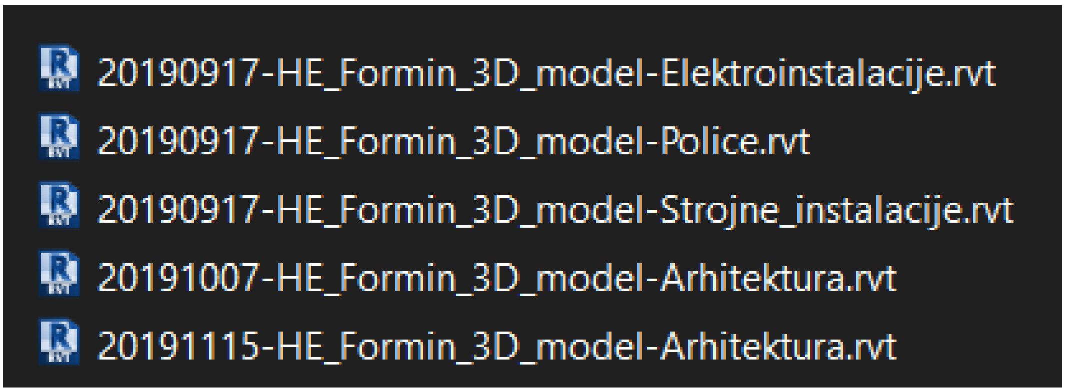


Figure 10 - Provided Revit models.

By inspecting the models, it was retrieved that they were organized as shown in the diagram at Figure 11. The architectural model, which was made having the linked Recap point clouds as a guide, had the other models linked to it. The diagram shows the relation between the files and a general list of each file's contents.

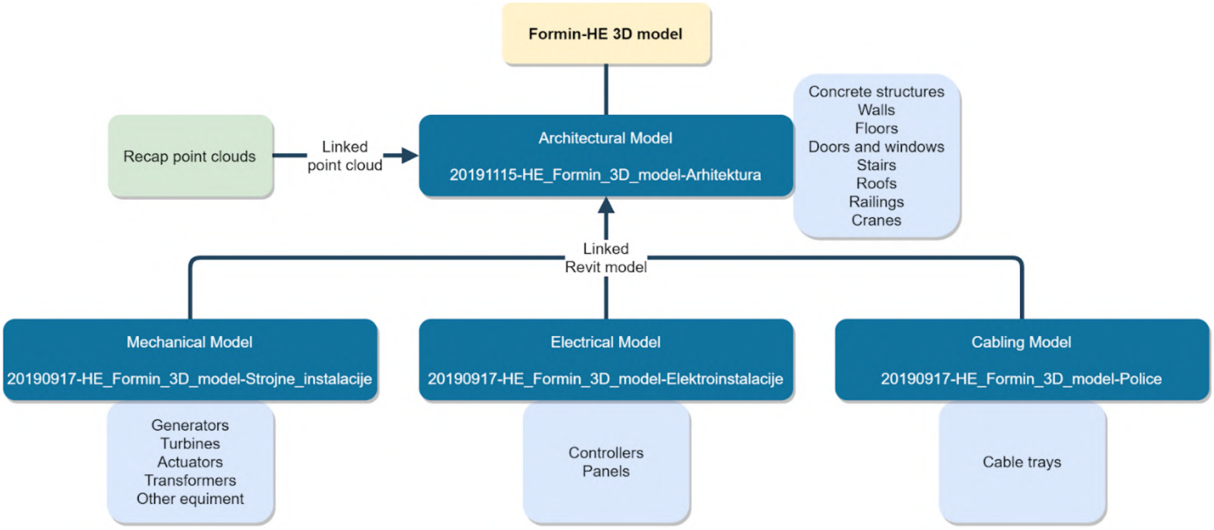


Figure 11 - Provided model breakdown structure.

In order to improve the file structure, the provided files were reorganized. But first all Revit files were converted to the 2020 version. The original files were saved on a backup. After conversion, they were organized into a CDE (common data environment) like structure on OneDrive.

The files have been reorganized into the CDE by dividing the archives into different folders as shown on the left of Figure 12. On the right it is shown how the files are divided into each folder, for example, the WIP folder. The files are now separated by discipline.

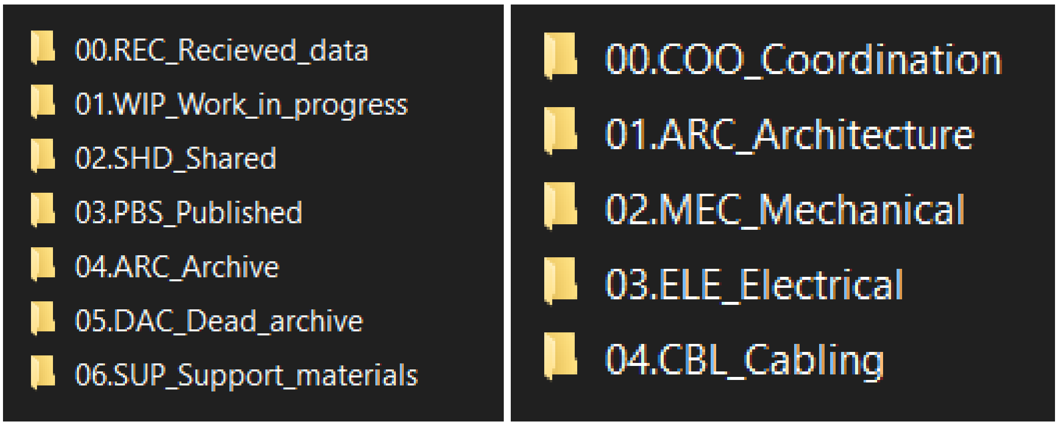


Figure 12 - New file structure.

- REC_Received_data contains the backups of the original .zip files and Revit files.
- WIP_Work_in_progress is for the files being actively worked on.
- SHD_Shared are for files sent for approval.

- PBS_Published are for evaluated and approved files.
- ARC_Archive are for valid files not used anymore.
- DAC_Dead_archive is for outdated or invalid files.
- SUP_Support_materials are for pictures, documents and other files like point cloud data.

To have more control over the overall modeling work, a federated model was created and the model breakdown structure was updated. Now all disciplines are linked into a federated model that contains only positional data, like elevations for example. The files have also been renamed to a more standardized manner. The new model breakdown structure is shown in Figure 13.

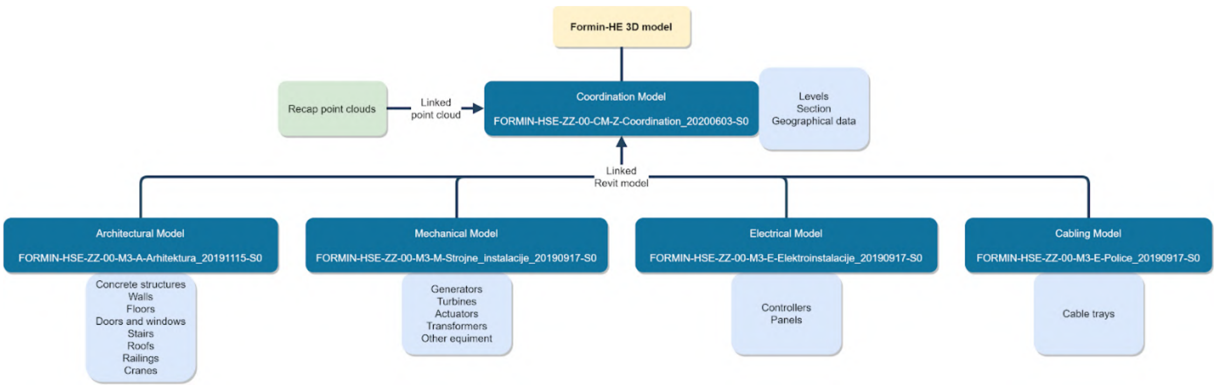


Figure 13 - New model breakdown structure.

The main difference between the previous structure and the new one is the inclusion of the Coordination model which has all the other models linked to it. This allows for better control over coordination work. The individual disciplines can work separately by linking whichever models are needed and then saving the changes to update the coordinated model. The coordinated model can then be checked for interferences and used for exporting into IFC or NWD.

To better understand what is currently represented in the 3D model an evaluation was done comparing the point cloud on Scene2GO and the Revit model. Following are some key locations and the individual evaluations. The goal is to determine what components would have to be modeled for a more detailed as-is model of the power plant, and also acquire more information about what systems are to be modeled on the to-be model.

Elevation 196,00 unit 1 oil systems:

Figure 14 - 3D scan of unit 1 oil systems.

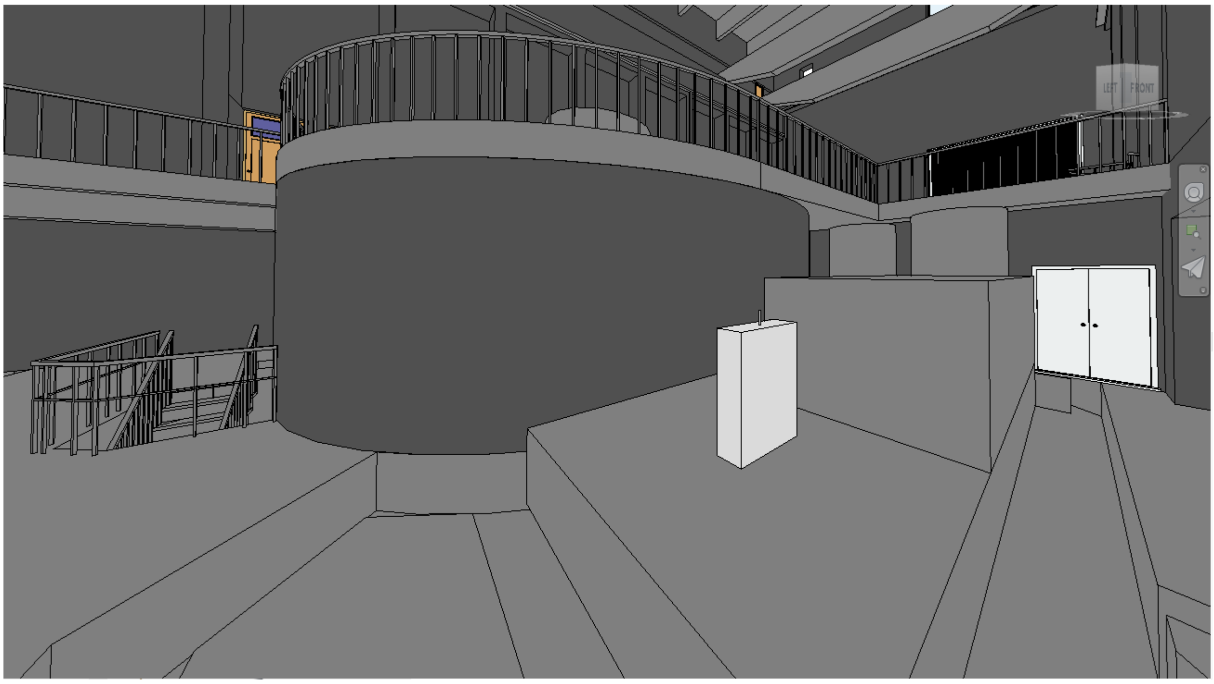


Figure 15 - Revit Model of unit 1 oil systems

The architectural model at Figure 15 contains the concrete structures like walls stairs and floors. Railings and doors are also present. The cabling channels on the floor are also present without the top walkover panels but the cables itself are not.

The controller box for the oil system actuators is modeled and in place, by comparing it with Figure 14, but the actuators, pipes, fittings and other small equipment are not present. Larger equipment like the tanks and pumps are represented only by simple geometry, like boxes and cylinders. By looking at an overlay of the 3D model and the point cloud scan at Figure 16 it is possible to realize better the missing components at this location. It also becomes clear that each model is correctly referenced and positioned, as the 3D geometry and the scan match with good accuracy.

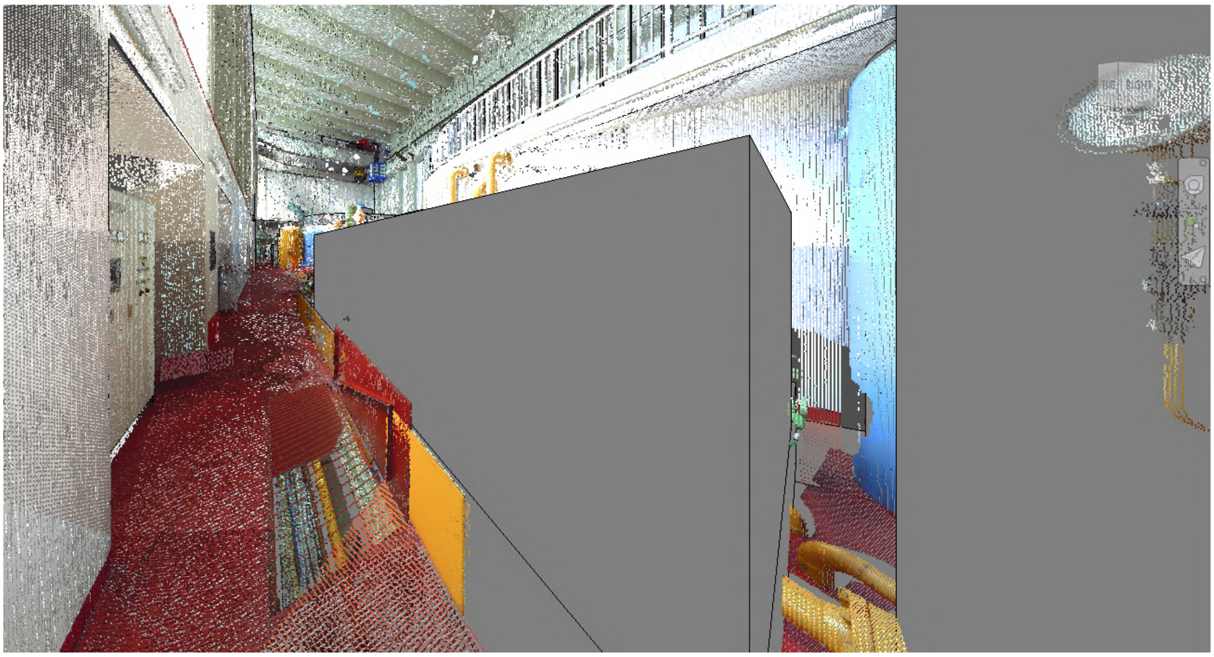


Figure 16 - Overlay of the provided Revit model with the point cloud data.

For the to-be model of the refurbished plant the finer components of the systems have to be present with a higher level of detail: Pipes, actuators, controllers, tanks. All should be present for a detailed model so that all the relevant metadata associated with these components can be used for the construction, operation, maintenance and decommission works.

Elevation 193,99 unit 1 upper bearings:

The architectural model at Figure 18 contains the concrete structures like the circular wall. But the grilled segmented floor does not contain any openings nor it is segmented as seen in Figure 17, there is also no representation of the access stairs.

The cabling arrays and the controller panels are present but currently not connected to each other. The main mechanical components like the bearing array are represented with a low level of detail, by just 2 cylindrical solids. The bearing cooling system is absent in the model and the piping and fittings for the pressurized oil system are represented only by a cylindrical arc section.

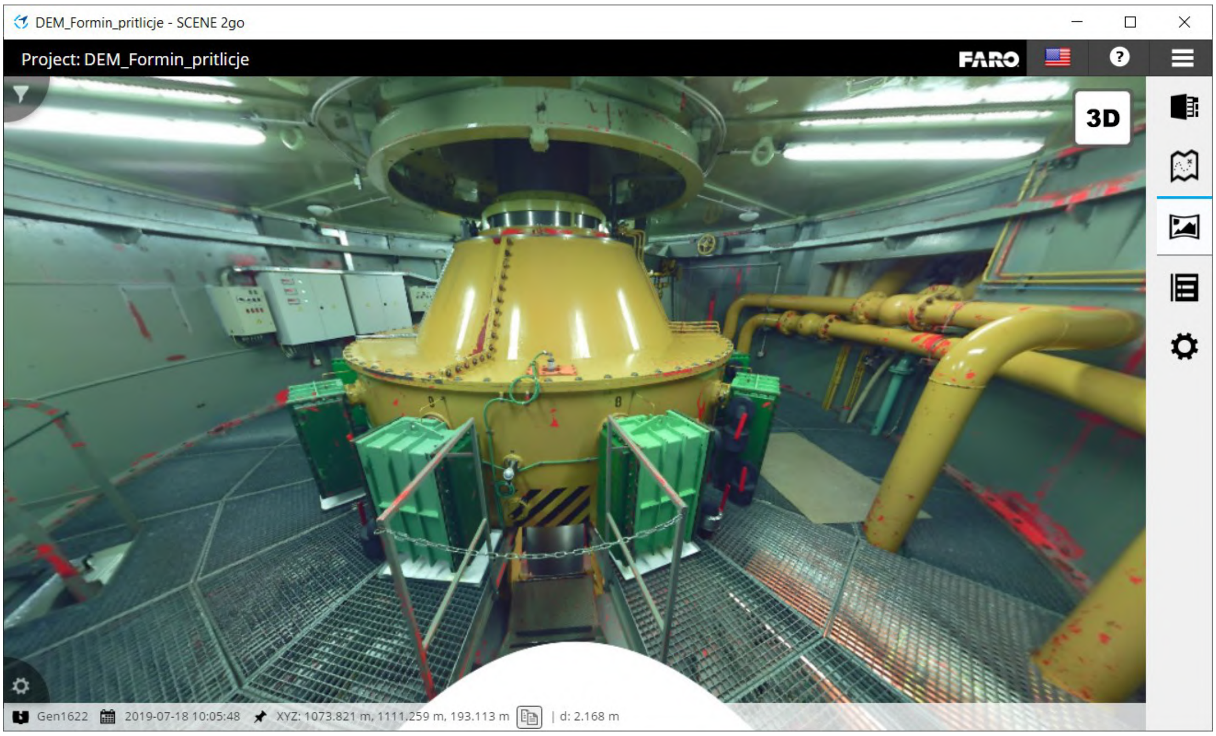


Figure 17 - 3D scan of unit 1 upper bearings.

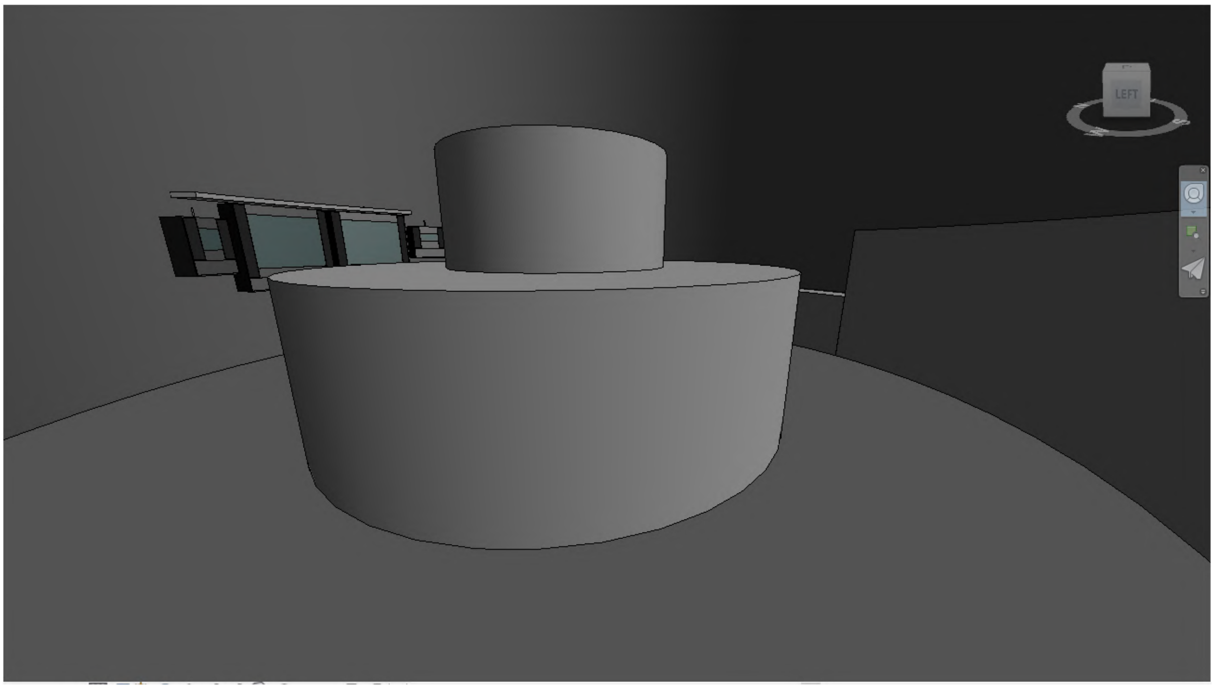


Figure 18 - Revit model of unit 1 upper bearings.

The overlay view at Figure 19 once again shows accurate positioning of the existing geometry with the point cloud.

For the to-be model of the refurbished plant the mechanical components have to be present with a higher level of detail: Bearing array, coolers, axis, caps, valves, controllers and piping. The monitoring and actuator equipment should also be modeled to details so the all the relevant metadata associated with these components can be used for the construction, operation, maintenance and decommission works.

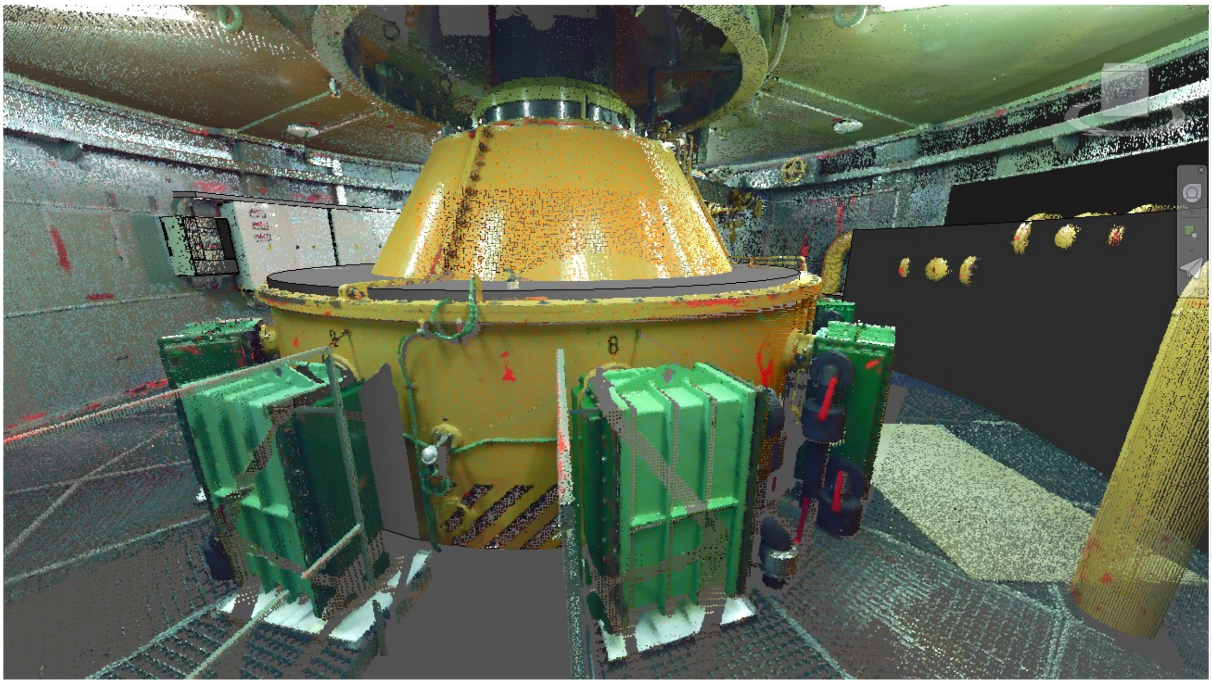


Figure 19 - Overlay of the point cloud data and the Revit model.

The openings have the potential to be a big issue for the design team around the unit area. Multiple piping and cabling systems need to cross floors and walls and interact with other systems. At the current LOD of the model elements the necessary information for this level of interaction between the disciplines is not provided. Having an as-is architectural model with a higher LOD and that contains more information about the openings can be beneficial for the designers.

Elevation 196,00 unit 1 generator:

The architectural model at Figure 21 contains the concrete structures like walls and floors. Doors are also present, but their opening direction is reversed. The metallic ceiling above the generator in not separated from the surrounding concrete ceiling. The cabling arrays and the controller panels are present but currently not connected to each other as seen in Figure 20.

The main mechanical components like the generator pressure chamber walls and cooling pipe array are represented with a low level of detail, by just 2 cylindrical solids. The coolers are absent in the model and the piping and fittings for the rest of the system are currently not represented.

Figure 20 - Unit 1 generator (stator housing) 3D scan.

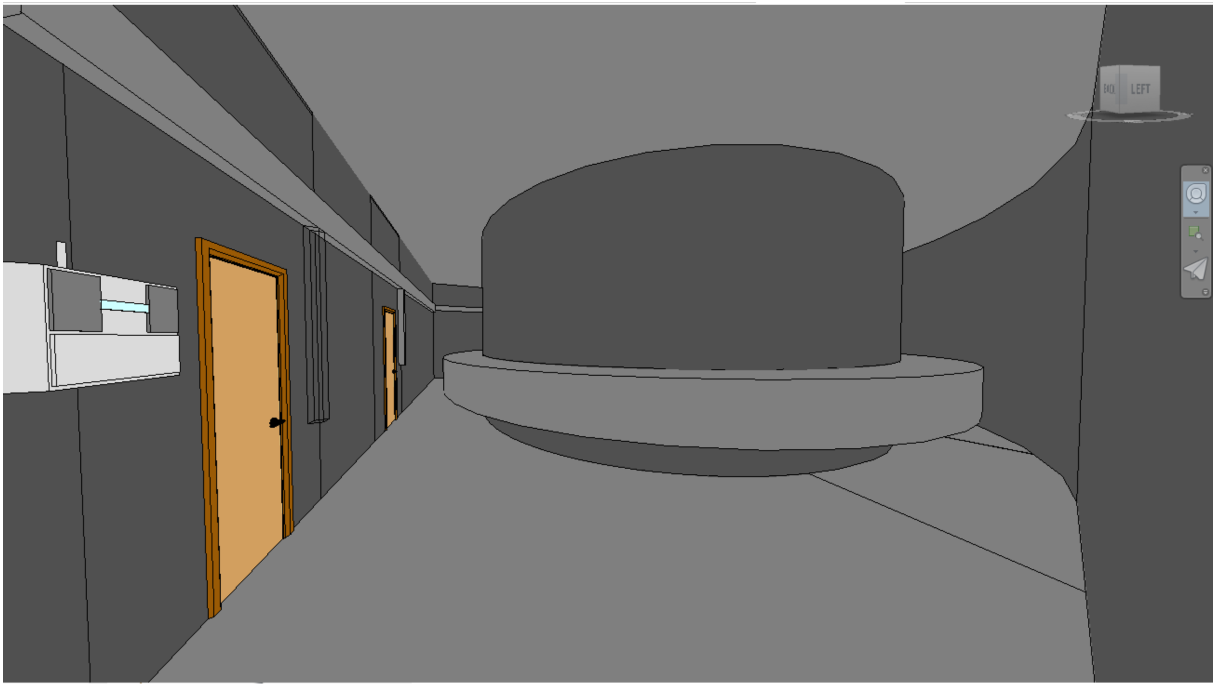


Figure 21 - Unit 1 generator (stator housing) provided Revit model.

The overlay view at Figure 22 once again shows accurate positioning of the existing geometry with the point cloud. But also shows that the important interactions the mechanical components of this location have with the surrounding structures are currently not represented at this level of detail. The generator pressure chamber has a structural importance to the ceiling above, but this cannot be seen from the model.

For the to-be model of the refurbished plant the mechanical components have to be present with a higher level of detail: Generator pressure chamber, coolers, piping, metallic structures, valves and controllers. The monitoring equipment should also be modeled with higher level of detail so that all the relevant metadata associated with these components can be used for the construction, operation, maintenance and decommission works.

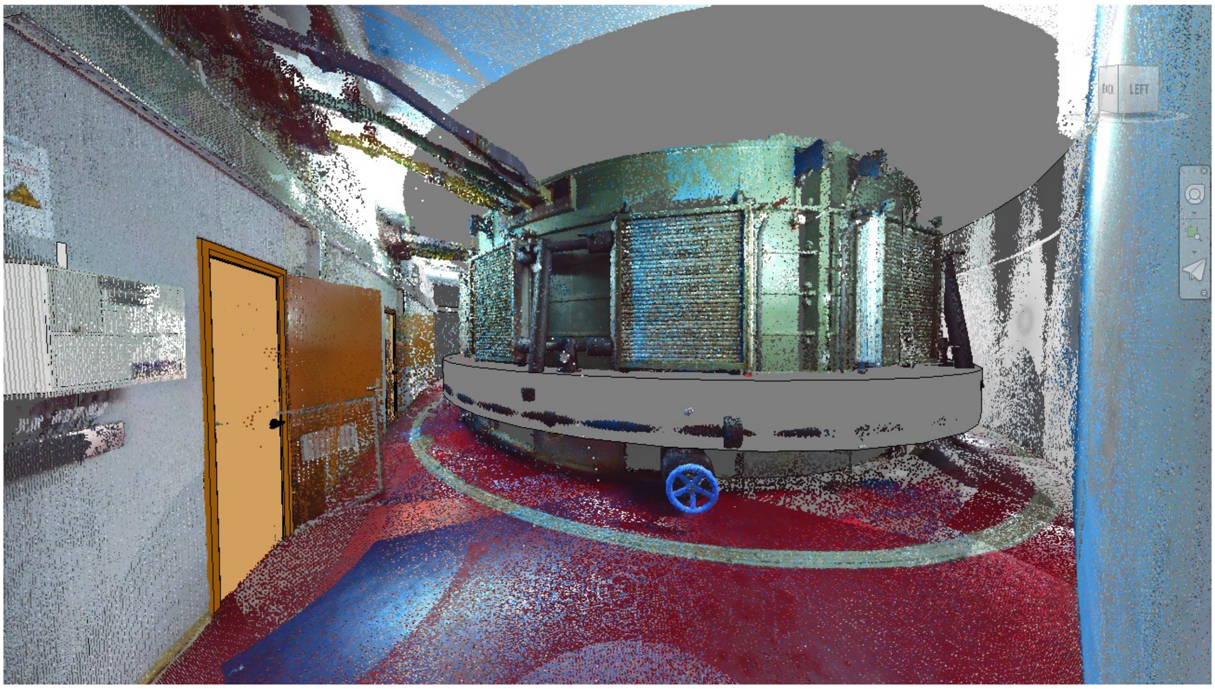


Figure 22 - Overlay view of the point cloud with the Revit model.

The interactions between mechanical and structural disciplines have the potential to be a big issue for the design team around the generator area. The generator has to be accessible for assembly and disassembly through the ceiling. At the current level of detail, the model elements cannot provide the necessary information for this level of interaction between the disciplines. Having an as-is architectural model with higher level of detail elements containing more information about unit assembly procedures can be beneficial for the designers.

3.3 Planned refurbishment actions on Formin

Formin HPP is the only power plant operated by Drava power generation company (DEM) that has not yet undergone a complete renovation. It is planned to start in the middle 2020s decade [21]. The goal is to replace all main plant components with new equipment and also increase the power generation capacity by enlarging the water intake to the turbines. The entire power units will be replaced along with all secondary systems. For this reason, the as-is mechanical and electrical model has a lower level of development compared to the architectural model, as structural changes are expected to be minimal during this project.

The observed pattern on the provided models around the entire power plant is that the architectural model elements have the highest level of detail of the provided disciplines. This is in accordance with expectations as the refurbishment works will focus on equipment. The current architectural model can be used as a solid base for design work. For the inclusion of more detailed metadata and geometry the to-be architectural model elements will need to have a higher level of detail then they currently have in the as-is model in order to accommodate the expected BIM uses for the project.

Adding information about existing openings and getting a higher level of detail on some areas where there are interactions between structures, mechanical equipment and other disciplines will be important for the maximum usability of the model.

The mechanical, electrical and cabling system elements currently, as planned, have a low level of detail. They are correctly positioned according to the point cloud data, but these system's model elements do not contain enough information on its current level of detail to fulfill the expected BIM uses of the to-be model. This means their level of detail and information need to be higher on the to-be model. The current low level of detail on these systems is understandable as it is expected that the vast majority of them will be completely substituted by the new ones, which means the current level of detail of the as-is model elements are, for most expected BIM uses, adequate for its purpose.

After the inspection of the provided data discussed in Section 3.2 the prototype workflow case study subject is set to be the generator's stator frame and it's cooling system as these structures regard multiple aspects of the expected BIM uses to be explored.

The requirement expected definition from the designers and having an input on the range of possibilities for the generator allow the exchange of data between requirement specification and design options.

The cooling system of the generator allow for the development of libraries of components to be used with the proposed tools for drawing piping systems.

The interactions between structural architectural model and mechanical model are particularly important on this location, allowing for the development of coordination activities that should improve the refurbishment workflow.

The provided point cloud is very detailed on that location and the overall complexity of the system is not too overwhelming, making it more feasible for this case study.

4 USING BIM TO IMPROVE THE REFURBSHMENT WORKFLOW

This chapter presents main BIM techniques that can be used into the Formin HPP refurbishment project as a first step into implementing a BIM culture in the plant owner and consultant companies with the intention of increasing their BIM maturity levels.

4.1 BIM implementation - BEP

To effectively integrate BIM into the project one of the most important steps is to develop a document called BIM execution plan (BEP). The BEP is a collection of implementation details that outlines the overall vision for team to follow throughout the project lifecycle regarding how BIM will be applied to each aspect of the project. The BEP must be developed during the early stages of the project, it can be continuously updated as additional participants join the project and must be revised as needed throughout the implementation phase of the project [23].

The BEP should determine the scope of BIM implementation for the project, identify the workflow process for each BIM task, define the information exchanges between the involved parties, and describe the technical infrastructure and company capabilities required to support the BIM implementation. By implementing a BEP the following values are added to the project and project team [23]:

- Clear understanding and improved communication of each party's strategic goals for BIM implementation on the project.
- Organizations will understand their roles and responsibilities in the BIM implementation.
- The designed execution process will be well suited for each team member's typical business practices and organizational workflows.
- The BEP will identify required additional resources, training or other competencies that need to be acquired to successfully implement BIM for the intended uses.
- It provides a benchmark as reference describing the process for other parties who may join the project in the future.
- Contract languages will be defined by the purchase division to ensure all project parties fulfill their obligations.
- The BEP provides a baseline for measuring goals and progress through the project lifecycle.

The development of a BEP can be divided into 5 steps as shown in Figure 23. The first two steps, define project goals and select BIM (Model) uses, have been discussed previously on Section 2.4. There are multiple available templates for the actual BEP document that can be used as a starting point for developing it. This work recommends the template provided on the publication by MESSER, J. et al "BIM Project Execution Planning Guide, Version 3.0 [23]".

The 3rd step is to design the BIM execution process. Starting from a high-level map showing an overall view of the interaction between the project's primary BIM uses and progressing all the way to each individual subtasks the entire project map is developed. All teams work together on developing the high-level maps. After that, the individual teams develop the more detailed maps for the process they are responsible for.

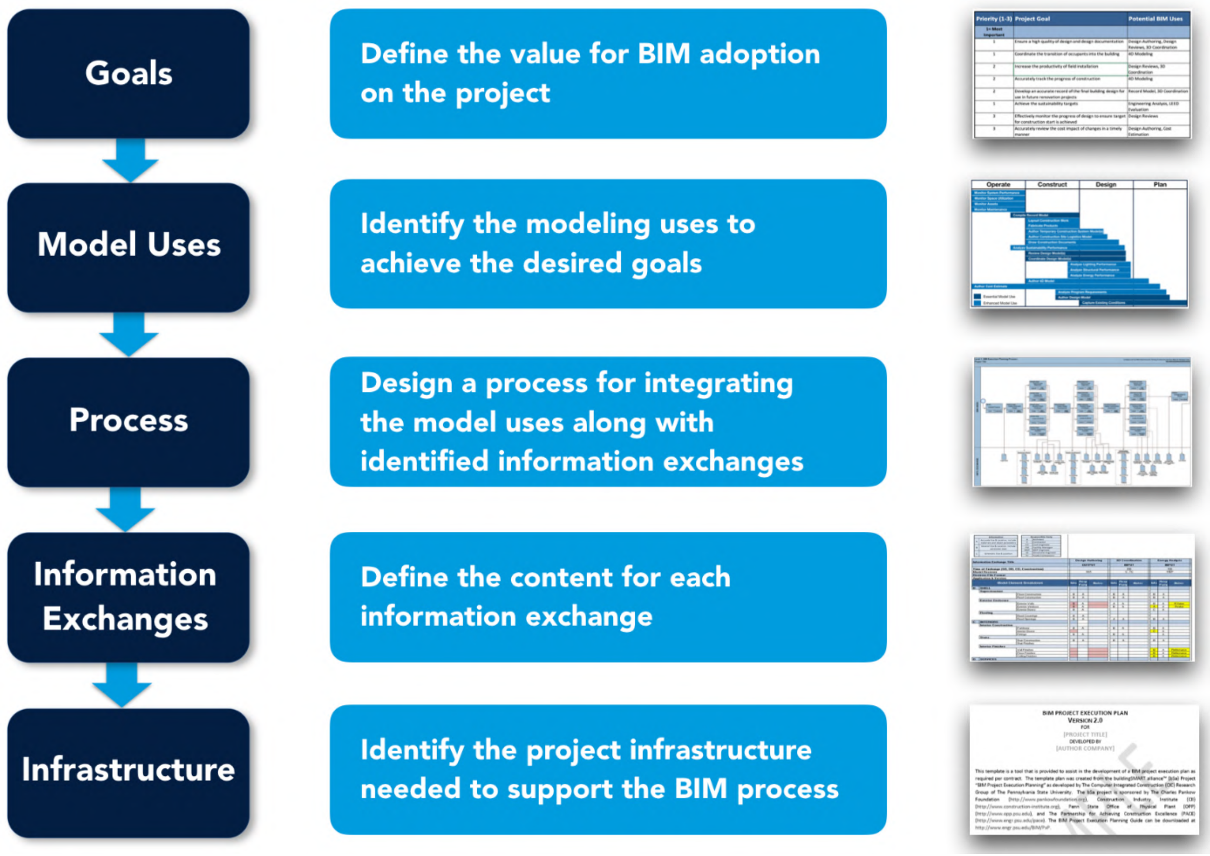


Figure 23 - Steps to develop a BIM Execution Plan [23].

<u>Level 1: BIM Overview Map</u>

The Overview Map shows the relationship of BIM Uses on the project. This process map also contains the high-level information exchanges that occur throughout the project lifecycle [23]. The example shown on Figure 24 is a template for a level 1 BIM process map. All the primary BIM uses and the relations between they are shown on a global high-level scale together with the main information exchanges of the project.

<u>Level 2: Detailed BIM Use Process Maps</u>

Detailed BIM Use Process Maps are created for each identified BIM Use on the project to clearly define the sequence of various processes to be performed. These maps also identify the responsible parties for each process, reference information content, and the information exchanges which will be created and shared with other processes [23]. Figure 25 shows the template for a level 2 BIM process map for the

Cost Estimation 4D analysis BIM Use. The sequencing of the individual tasks is complemented by the required input shown as reference information. There are also decision-making gateways that influence the progress of the process according to the specified logical test to be performed. The information exchanges for the subtasks are also displayed.

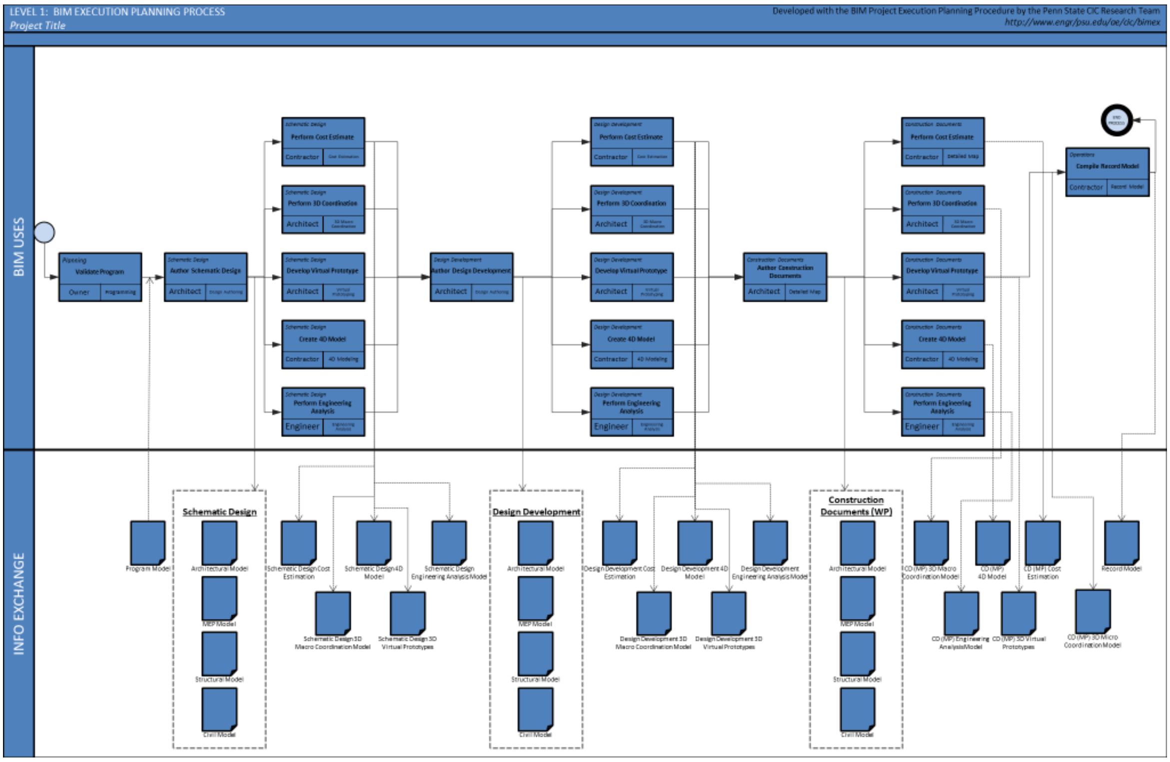


Figure 24 - Level 1 BIM process map template [23].

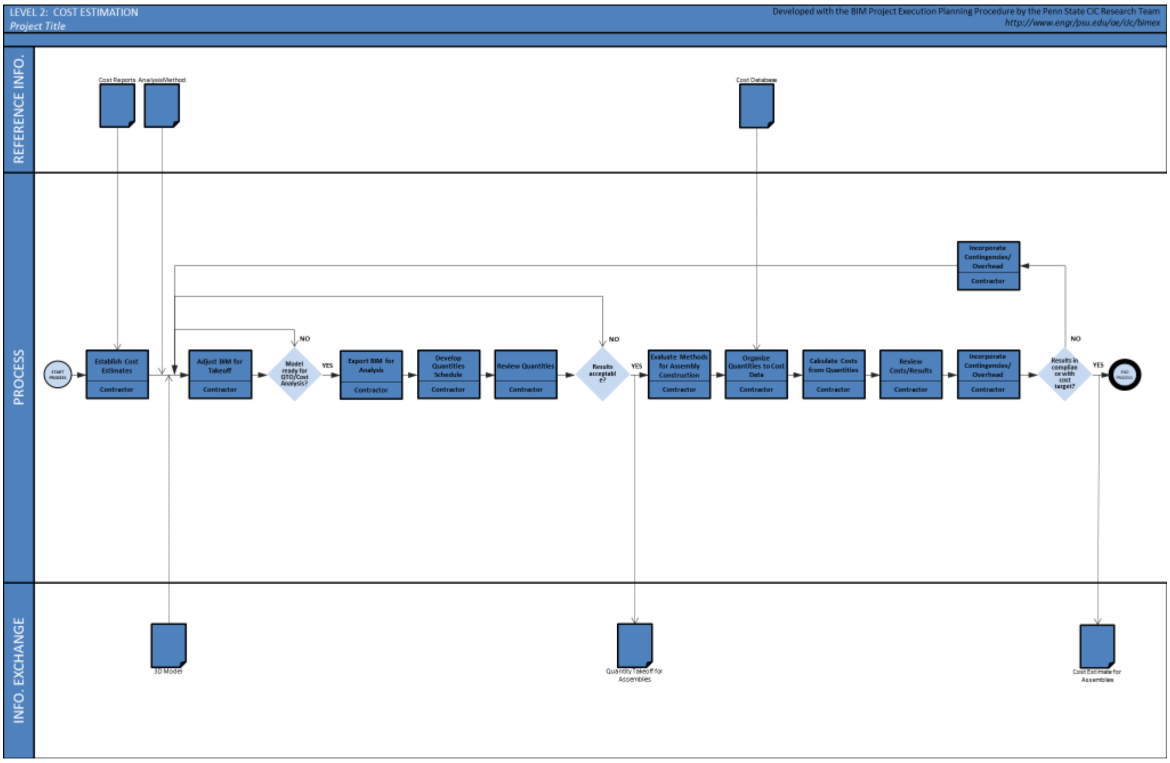


Figure 25 - Level 2 BIM process map template for Cost Estimation 4D analysis [23].

There is widely available literature with extensive in-depth information regarding the design, optimization and creation of process maps for BIM implementation. Most of them rely on Business Process Modeling Notation (BPMN) for the development of the process maps and more information about how to create them can be found on the literature. On this paper, instead of explaining all the details regarding these maps, the focus will be on using them to design a prototype workflow for HPP refurbishment projects.

The 4th step of developing a BEP, define information exchanges, is discussed in Section 4.3. The 5th step, define infrastructure needs, generally speaking, is very dependent on the capabilities of the involved parties and can only be fully assessed by having each party perform a self-evaluation of their conditions. Nevertheless, some of the more technical requirements for the explored BIM Uses for HPP refurbishment projects are presented in Sections 4.4 and 4.5.

4.2 Overall HPP refurbishment BIM process map

For the development of a BEP process map for an HPP refurbishment project the entire project team must participate in the decision-making process to establish the relations between the selected BIM uses. This project wide discussions cannot be fully accurately substituted by a single individual estimate whose primary objective is to just provide a guideline for BIM implementation. For this reason, the following overall process map shown in Figure 26 serves only as an example to be followed as a guide for the actual BEP process map development for the Formin HPP refurbishment project. A larger version of this image can be found on Appendix 7.1.

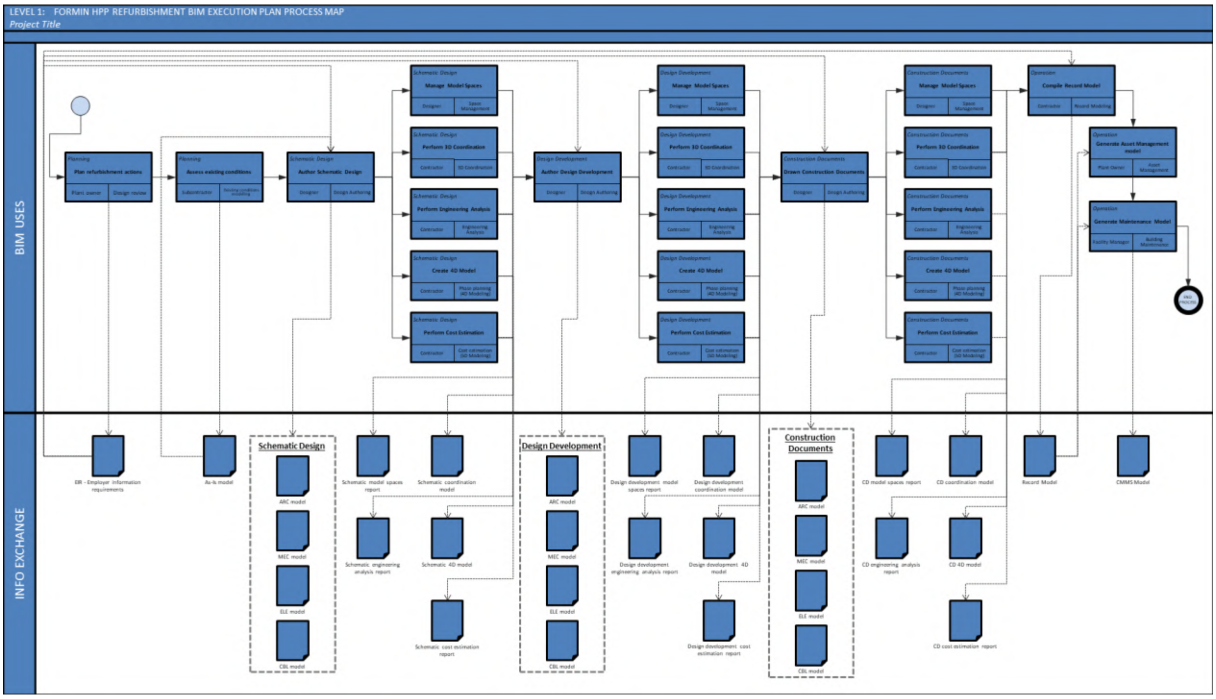


Figure 26 - Formin HPP refurbishment overall BEP process map.

The process maps for the individual BIM uses also must be developed following the same guidelines. Figure 27 shows an example of what Formin HPP refurbishment project's design authoring BIM use process map could be, applying the tools to be discussed in Sections 4.4 and 4.5, dRofus and MagiCAD. A larger version of this process map can be seen on Appendix 7.2.

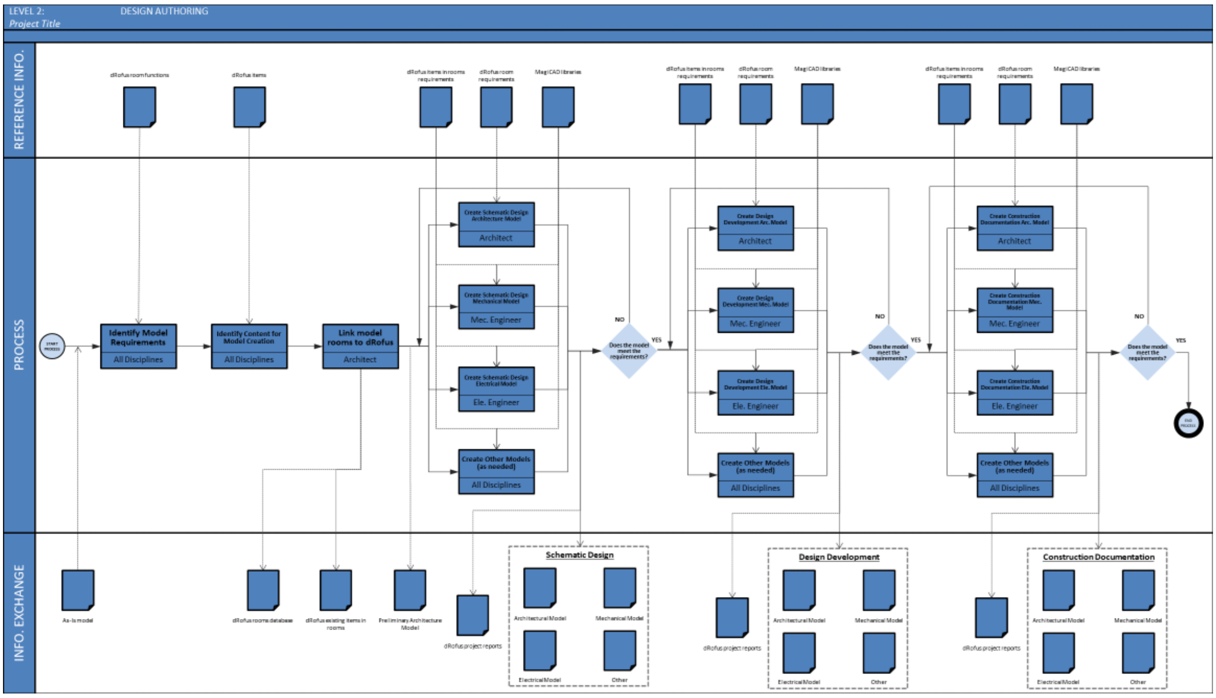


Figure 27 - Design Authoring BIM use process map for Formin HPP refurbishment project.

4.3 Information exchanges and interoperability adjustments

After developing process and subprocess maps for the project BIM Uses, as discussed in Section 4.2, the information exchanges between project participants must be identified. It is important that the project team goes through the process maps to find each information inputs and outputs, to define the responsible authors and receivers. The transactions can be clearly presented in a table know as Information Exchange Worksheet. This table is constructed by going through the following steps [23]:

<u>1) Identify each potential information exchange from the process maps:</u>

From the process maps seek the information exchanges and note what are the involved BIM uses, the project phase when they must happen and the responsible parties involved. This identification phase requires all involved parties to search the process maps as each one knows what the actual requirements are to perform their roles in the project.

<u>2) Choose a Model Element Breakdown structure for the project:</u>

The Model Element Breakdown Structure is a classification method to identify model elements according to predetermined criteria. There are different classification systems. A commonly used one is the "OmniClass Table 21 – Elements [24]" which classifies model elements for building projects. Unfortunately, most industrial or HPP specific equipment, like turbine, generator, bearings and such, are not classified by this standard. Currently there is no unified classification system widely used in BIM applications that contains HPP specific equipment, for that reason the model element breakdown structure in the Information Exchange Worksheet has to be customized according to the project needs by adding the equipment and elements that are not classified. One alternative is implementing the KKS systems, commonly used in HPP, into the model breakdown structure. For Formin HPP refurbishment project the category 00 – HPP SPECIFC COMPONENTS has been added as an example of what sorts of elements the project team would want to identify after their discussions while creating the BEP.

3) Identify the Information Requirements for each Exchange:

To achieve this, data must be input into the Information Exchange Worksheet. On the IE (Information Exchange) tab, there are fields that should be filled in with the following information for each BIM use:

A) Input/Output: Identifies if this BIM Use generates model data that is used by other BIM Uses or if it requires model data. Only BIM Uses that require exchange of model data need to be listed on the worksheet.

B) Project State: The project milestone at which the current BIM Use is applied to. There are different ways to divide the project according to its progression on the timeline and it can be different for each project. One of the proposed ways is to use "OmniClass Table 31 –Phases [25]" which is shown in a simplified manner on Table 7.

Table 7 - Project Phases according to OmniClass table 31 [25].

Stages (OmniClass Table 31)	
10	Conception Stage
15	Project Delivery Selection Stage
20	Design Stage
25	Construction Documents Stage
30	Procurement Stage
40	Execution Stage
50	Utilization Stage
60	Closure Stage

C) Time of exchange: When the information is exchanged (Can be different from actual project stage for that BIM Use).

D) Model Receiver/Sender: This is the party that will be receiving (Input) or sending (Output) the model elements of for that BIM Use.

E) Model file type: What type of file is expected to be sent/received by the responsible party for that BIM Use.

F) Application Version: Lists the infrastructure requirements for that particular exchange in terms of software needs.

G) LOD: Determines the required Level of Development of that particular model element to satisfy the requirements for that specific BIM Use. There are different ways of classifying the LOD of model elements. For this example, the chosen standard is the one proposed by the BIM Forum group on their publication “Level of Development (LOD) Specification [26]” that divides the LOD into 6 categories according to the amount and accuracy of geometrical and non-geometrical (meta)data. This publication contains detailed LOD requirements for individual model elements as well as a general overview of each LOD. A general short description of each LOD level in shown on Table 8.

Table 8 - General description of BIM Forum LOD specification levels [26].

LOD (Level of Development) BIM Forum LOD Specification document	
100	Non geometrical representation
200	Generic placeholders
300	Accurate size and location
350	Contains coordination elements
400	Fabrication sufficient details

H) Responsible Party: The party responsible for the creation of that particular model element. An example of project participants is shown in Table 9.

Table 9 - Example of responsible parties for the Information Exchange Worksheet.

Responsible Party	
PO	Plant owner
SC	Subcontractor
DE	Designer
CO	Contractor
FM	Facility Manager
ARC	Architect
MEC	Mechanical Engineer
STR	Structural Engineer
ELE	Electrical Engineer

I) Notes: Space for addition information and coordination purposes between parties.

4) Assign the Responsible Parties to Author the Information Required:

Filling in the data presented on the previous step by coordinating with the project team so that the information exchanges are discussed and cleared in terms of requirements and responsibilities. This step is the filling in of items G and H and must be in accordance with the expected needs of each BIM Use.

5) Compare Input/output contend:

Check if model information generated by an output has the correct LOD required by an input on that same project stage. For example, if a model element is needed for Cost Estimation with an LOD of 350 but Design Authoring has that model element as an output with LOD 300 there is a discrepancy on that exchange that needs to be fixed by either raising the LOD of the Design Authoring use or lowering the requirement for the Cost Estimation for that project stage. It is also important that the responsible party listed at an output BIM Use is consistent with the responsible party listed for that element on an input BIM Use. This allows for better coordination during the exchanges making it easier to identify the party correctly in case updates are needed to the elements.

For better referencing the MOD (Model Definition) Tab shown in Figure 28 can be filled with the required LOD for each element across project stages. This information can be derived from the EI tab and used to control model elements progress throughout the project.

MODEL DEFINITION (MOD)

LOD (Level of Development) BIM Forum LOD Specification document	
100	Non geometrical representation
200	Generic placeholders
300	Accurate size and location
350	Contains coordination elements
400	Fabrication sufficient details

Responsible Party	
PO	Plant owner
SC	Subcontractor
DE	Designer
CO	Contractor
FM	Facility Manager
ARC	Architect
MEC	Mechanichal Engineer
STR	Structural Engineer
ELE	Electrical Engineer

Project Stage Deliverable		10 Conception Stage			15 Project Delivery Selection Stage			20 Design Stage			25 Construction Document Stage		
Author File Format (if varies, specify in notes)													
Application & Version													
Model Element Breakdown		LOD	Resp Party	Notes	LOD	Resp Party	Notes	LOD	Resp Party	Notes	LOD	Resp Party	Notes
21 00	HPP SPECIFIC COMPONENTS												
21 00 10	Civil Structures												
21 00 10 10	Dam												
21 00 10 20	Collector												
21 00 10 30	Scroll Case												
21 00 10 40	Stay Vane Ring												
21 00 20	Mechanical Equipment												
21 00 20 10	Wicket Gates												
21 00 20 20	Bull Ring Mechanism												
21 00 20 30	Gate Servomotor												
21 00 20 40	Kaplan Turbine												
21 00 20 50	Main Shaft												
21 00 20 60	Spider Cube												
21 00 20 70	Stator Housing												
21 00 20 80	Slip Rings												
21 00 20 90	Thrust Bearings												

Figure 28 - MOD (Model Definition) tab template.

The Disciplines tab lists all responsible parties of the project. They can be classified according to the project needs but for this example the classification is based on "OmniClass Table 33 – Disciplines [27]". A portion of the Discipline tab is shown at Figure 29 as an example of possible responsible parties for Formin HPP refurbishment project

Code	Disciplines (OmniClass Table 33)	Responsible Party
11	**Planning**	
11	Regional Planning	Plant Owner
21	Development Planning	Contractor
44	Transportation Planning	Subcontractor
51	Enviromental Planning	Plant Owner
61	Facility Conservation Planning	Facility Manager
99	Other Planning	Contractor
21	**Design**	
11	Architecture	Contractor
19	Drafting	Designer
21	Landscape Architecture	Contractor
23	Interior Design	Contractor
25	Specifying	Plant Owner
31	Engineering	Contractor
11	Civil Engineering	Contractor
14	Sructural Engineering	Contractor
17	Mechanical Engineering	Designer
21	Electrical Engineering	Contractor
23	Communications Engineering	Subcontractor
24	Process Engineering	Contractor
99	Other Engineering	Contractor

Figure 29 - Example of Responsible parties by discipline.

After filling in the Information Exchange Worksheet the project team should have an overview of the interaction each model element is going to be having across the project. An example of this worksheet filled in for Formin HPP refurbishment project is shown in Figure 30.

INFORMATION EXCHANGE (IE)

LOD (Level of Development) BIM Forum LOD Specification document	
100	Non geometrical representation
200	Generic placeholders
300	Accurate size and location
350	Contains coordination elements
400	Fabrication sufficient details

Responsible Party	
PO	Plant owner
SC	Subcontractor
DE	Designer
CO	Contractor
FM	Facility Manager
ARC	Architect
MEC	Mechanichal Engineer
STR	Structural Engineer
ELE	Electrical Engineer

BIM Use Title		Existing conditions modeling			Design Authoring			Space Management			3D Coordination		
Input/Output		Output			Output			Input			Input		
Project Stage		Planning			Schematic Design			Schematic Design			Schematic Design		
Time of Exchange (SD, DD, CD, Construction)		SD			SD			SD			SD		
Model Reciever/Sender		Subcontractor			Designer			Designer			Contractor		
Model File Type		Recap point Cloud			Revit Model			Revit Model			Revit Model		
Application & Version		Recap			Revit			dRofus			Revit		
Model Element Breakdown Based on OmniClass Table 21 Elements (2011-02-11)		LOD	Resp Party	Notes	LOD	Resp Party	Notes	LOD	Resp Party	Notes	LOD	Resp Party	Notes
00	HPP SPECIFIC COMPONENTS												
10	Civil Structures												
10	Dam	200	SC		200	DE					200	DE	
20	Collector				200	DE					200	DE	
30	Scroll Case				200	DE					200	DE	
40	Stay Vane Ring				200	DE					200	DE	
20	Mechanical Equipment												
10	Wicket Gates				200	DE					200	DE	
20	Bull Ring Mechanism				200	DE		200	DE		200	DE	
30	Gate Servomotor				200	DE		200	DE		200	DE	
40	Kaplan Turbine				200	DE		200	DE		200	DE	
50	Main Shaft				200	DE		200	DE		200	DE	
60	Spider Cube				200	DE		200	DE		200	DE	
70	Stator Housing	200	SC		200	DE		200	DE		200	DE	
80	Slip Rings				200	DE		200	DE		200	DE	
90	Thrust Bearings	200	SC		200	DE		200	DE		200	DE	
30	Electrical Equipment												
10	Rotor Poles				200	DE		200	DE		200	DE	

Figure 30 - Example of the IE (Information Exchange) tab for Formin HPP refurbishment project.

The next step on BIM implementation planning is to define the infrastructure needs for the project. As mentioned previously on Section 4.1, this is very dependent on the capabilities of the involved parties and can only be fully assessed by having each party perform a self-evaluation of their conditions. There are guidelines that can be found on how to assess the needed infrastructure, the one recommended in accordance to this project is the "BIM Project Execution Planning Guide, Version 3.0 [23]" by MESSER, J. et al. The next sections will explore some of the more technical solutions having in mind the specific Formin HPP refurbishment project for some of the proposed BIM Uses.

4.4 dRofus as a requirement specification tool

dRofus is a planning, data management and BIM collaboration tool that provides project stakeholders with extensive workflow support and access to building information throughout the building lifecycle. Core features of the software are capturing client requirements (EIR), validating design solutions (BIM) against client requirements, management of public standards and equipment planning.

dRofus has strong ArchiCAD, Revit and IFC integration with bi-directional data sync capabilities. Model data from each discipline is captured, together with planning data, non-geometric data and documents in a centralized database accessible to all project stakeholders via the dRofus desktop client and dRofus Web.

dRofus is a program aimed at flexibility and can be utilized for all types of buildings. The software allows major adaptations to an individual project, the program's functionality and appearance can be tailored from project to project. The program also adapts to the permission levels of individuals within a project and will therefore vary in appearance for different users (for example, an equipment consultant vs a room data sheet technician). Because dRofus is a client-server based application where users work towards a central database server over the internet, several users can work on the same database at the same time, irrespective of geographical location, thereby providing a highly flexible choice of workplace. Figure 31 shows the main modules of the dRofus software and a brief explanation of them.

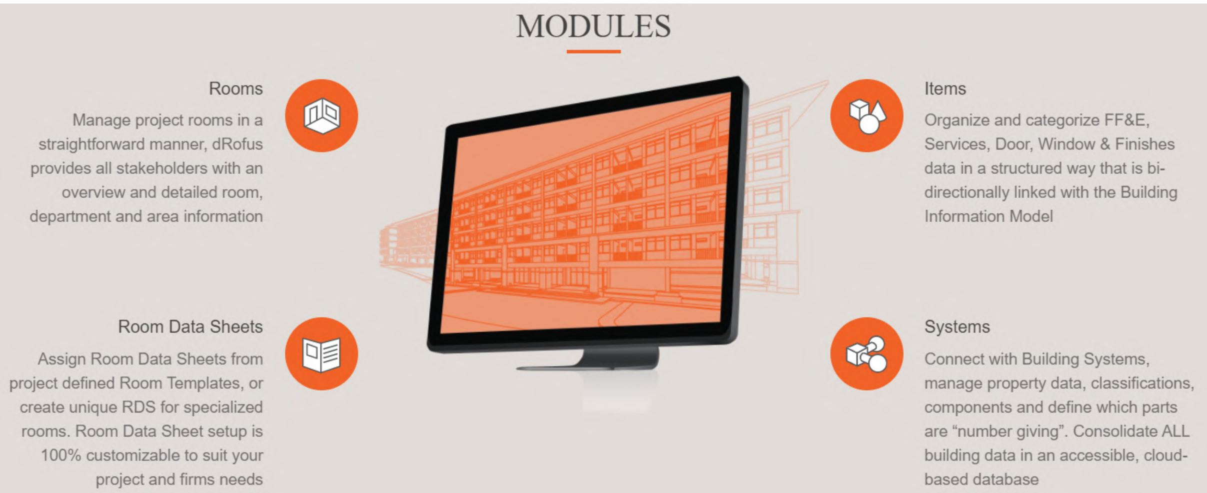


Figure 31 - dRofus main modules [28].

The most central concept in the program is a room. The rooms are placed within a functional structure, that classifies the rooms withing them according to the designed criteria. This structure most often has two or three levels. The functional position of the room is not directly linked to the room's geographical position and location but to its purpose withing the project. The room is identified using a unique room function number. This number stays with the room throughout the building project. The room function number is composed of the room's position within the functional structure in addition to a serial number, for example, as shown in Figure 32, room no. 01.01.001 will be positioned as follows [29]:

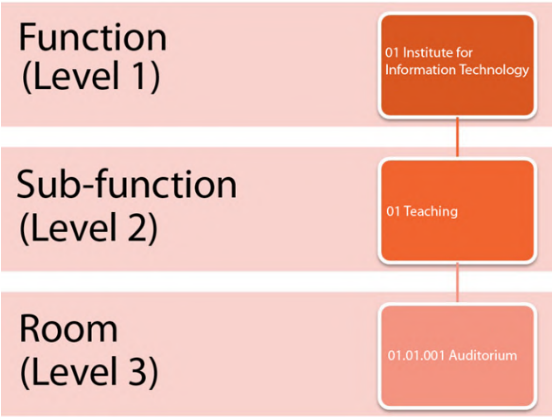


Figure 32 - dRofus Rooms and functions structure logic [29].

The room has a number of central qualities which are described in the room properties information. This is information such as: Room function number, name of room, description of room, other room numbers (drawing number, designed/geographical room number and use room number), the programmed area (the planned size of the room) and the designed area (the final size of the room as drawn by the architect). The room is linked to other information, such as room data sheet (Room Data) and Item lists. This is information not normally assigned to a room, but which has to be created for each room [29]. Figure 33 show an example of the room module and its components:

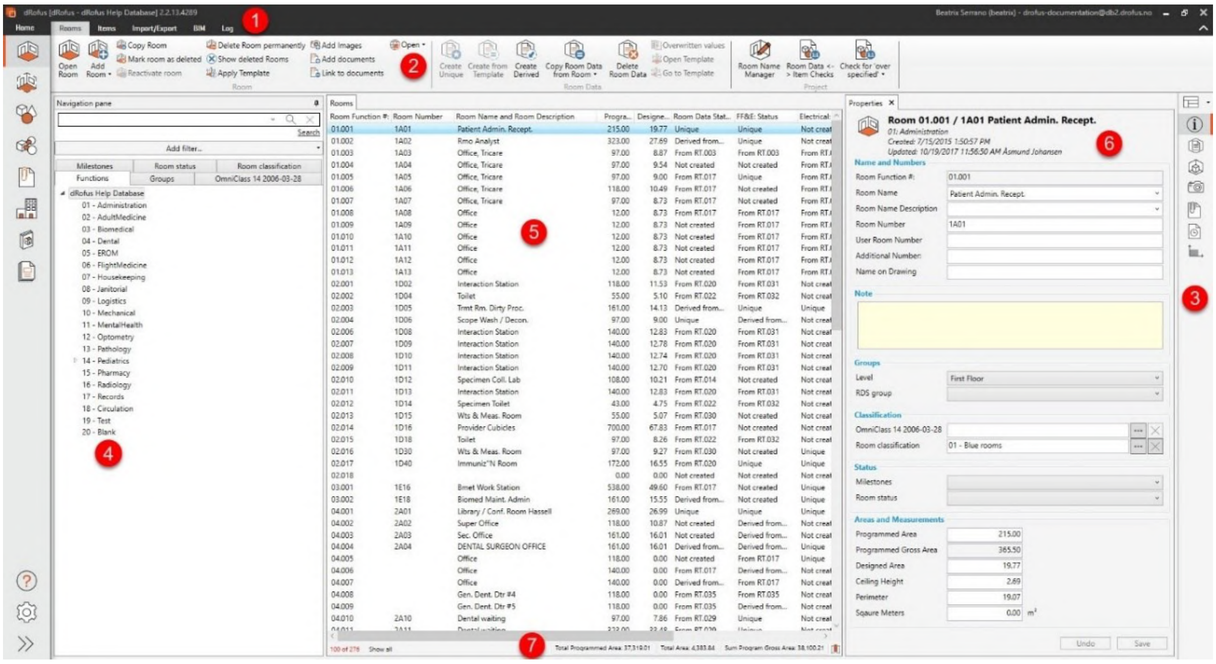


Figure 33 - Example of the Room module in dRofus [29].

1. Tabs: The Rooms Module have several tabs that contain different options. By toggling between them it is possible see the additional options that are available for rooms. The tabs are contextual and will automatically update depending on what is selected.
2. Ribbon menu: The ribbon will automatically activate and deactivate available options depending on what is selected in the interface. When a room has been selected, all options available for the room will be activated, whereas all non-applicable options will be greyed out.
3. Panels: These can be turned on and off depending on what is intended to be displayed at the time. The information within these panels will be contextual to the room(s) selected.
4. Navigation panel: This is the primary tool for navigation within the Rooms Module. Navigation can be based on Functions, Groups, Status or Classification.
5. Rooms panel: This panel will list the room(s) depending on the selected function/sub-function/group. It can also display any search results.
6. Properties panel: This panel will display properties depending on the selected entity (function, sub-function, group, room, occurrence etc.), and is therefore contextual.
7. Room Summaries: Shows Total Programmed Area, Total Area, and Sum Program Gross Area.

To create a room, Figure 34, the function under which the room will be created has to be selected. A level can be created in the function structure by right-click on the project name in the room overview and select New department or by navigating to Room → Functions → New in the ribbon menu. This selection may have different names depending on the project. This can also be done to create sub-levels. The depth (how many levels on top of each other) of the structure and the names of the different levels (function, department, section etc.) are set by the project administrator [29].

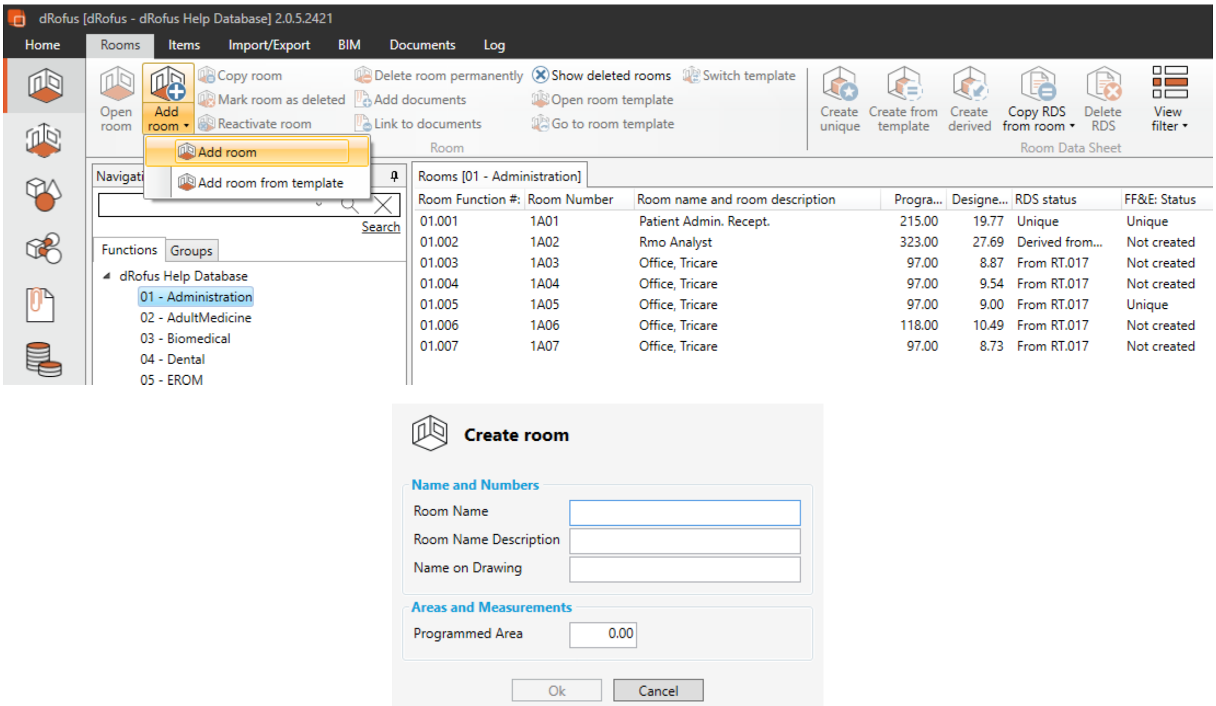


Figure 34 - Creating a room in dRofus [29].

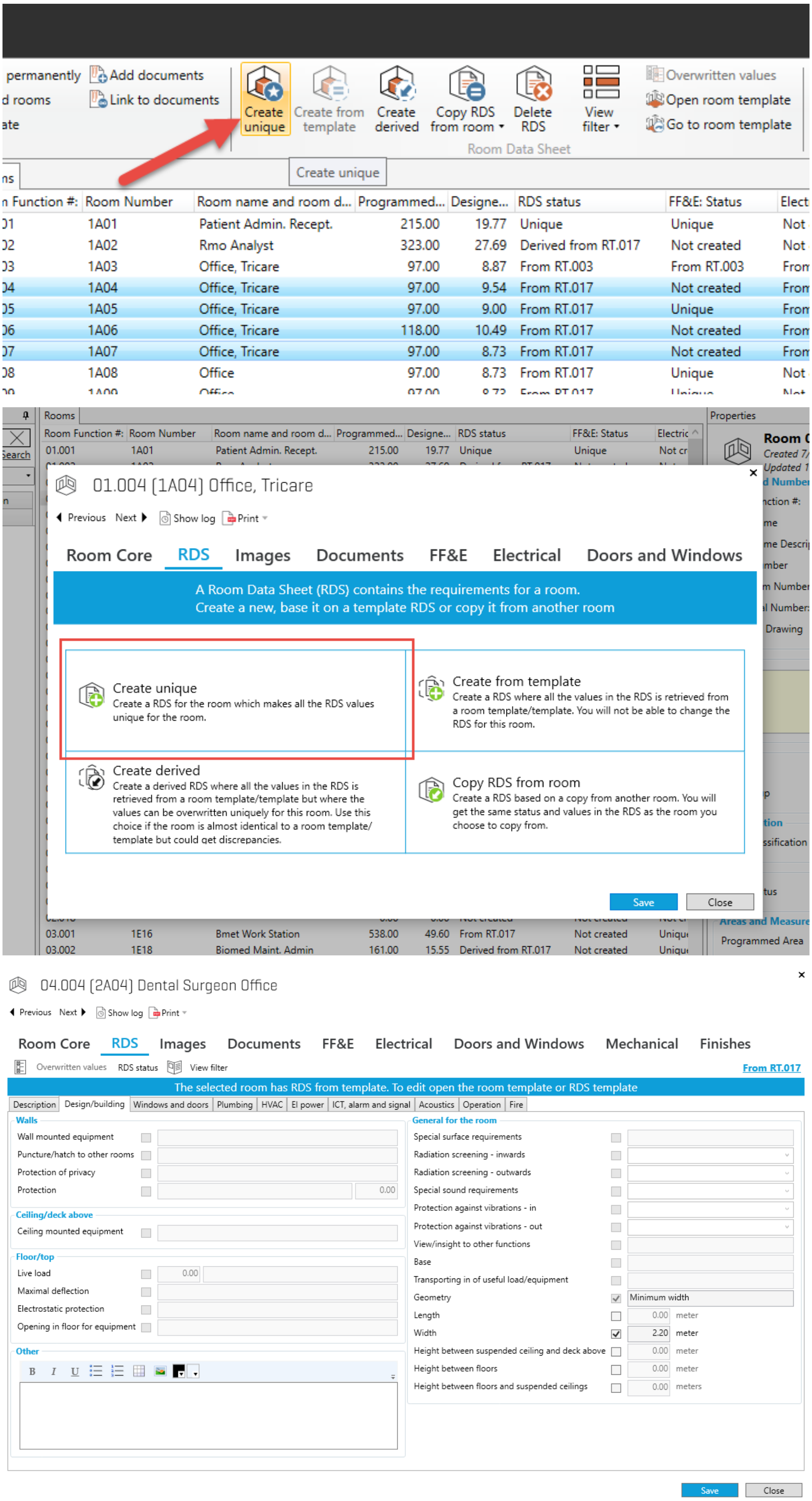


Figure 35 - Creating room data in dRofus [29].

After creating the rooms data can be assigned to them in order to define the requirements according to the project design. Room Data information describes functional and constructional engineering requirements for a room. This can be done by using predefined or customized data templates or by creating unique room data sheets. Adding data to a room is done according to Figure 35. There are multiple aspects of the room that can be defined as requirements on the room data, including openings, door and windows, electrical, ventilation, temperature and many others. It is possible to attach additional documents for more detailed specifications.

Another useful module of dRofus is the Items module. An Item is anything that needs to be tracked in a room, such as equipment, furniture, finishes or doors. An Item is specified as a type and can be used for several rooms and for other projects. Items are stored in the Items Module within a database that can be shared among several projects. Items are organized within a function structure, similar to how the rooms are organized in functions. The location within the function structure also forms the foundations for the Item number assigned to Items when created. Items can be moved to new locations within the function structure, forming a new item number based on the new location [29].

Items include built in fields for storing basic information including item name, BIM ID, budget price, budget price date, budget price description, responsibility, and tender group. The budget price forms the basis for cost estimates, with the date for when price was obtained or stipulated and a price comment for where the price was obtained. The tender group is applied to an item when it has been identified to be purchased. Each Item can be managed using a responsibility group to control the permissions for viewing and editing items. The portion of an item that can be customized is the item specification used to describe more details regarding the size, function and use of the item [29].

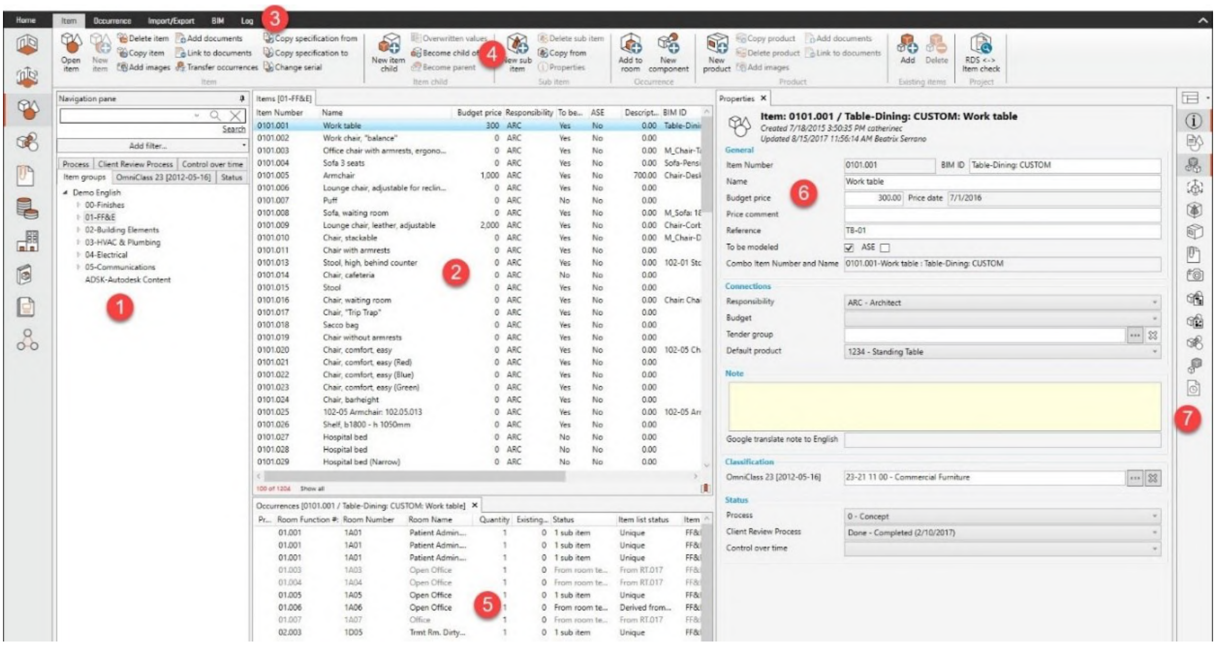


Figure 36 - Items overview in dRofus.

The Item Overview contains the entire Item register. The Item Overview has different windows with different information pertaining to an item. Figure 36 shows an example of the items overview.

1. Navigation pane: Navigate the Item function structure created in the database. By selecting a level in the structure, the Item pane (2) will list all items in all its child levels. The Occurrence pane (5) will also update and show occurrences for all items in selected item function structure location.
2. Items window: The Items window will list all items in the function level selected in the navigation pane. All items from the selected function level in the function child levels will be listed.
3. Tabs: contextual menu that displays more options according to the selection made.
4. Ribbon menu: The ribbon will automatically activate and deactivate available tools dependent on what entity (Item group, Item, Occurrence, product, document etc.) are selected. If an occurrence is selected the program you will automatically be transferred to the Occurrence tab and show available options. The Item tab is divided into different sections for Item, Item child, Sub item, Occurrences, Product and Report. Hoovering the cursor over the options will display a short explanation of what the options do.
5. Occurrences: Displays lists of occurrences for the selected item or items sharing the same function level. Editable occurrences are shown in black (occurrences placed in unique or derived item lists) while non editable occurrences are shown in grey (occurrences in item list from room template of item template.
6. Properties: The properties window will update dependent on what is selected in the item overview.
7. Panels: It is possible to show or hide different panels like occurrences, sub-items, documents, images etc. The layout can also be modified (default / Simple) by dragging the desired panels over the interface.

On the prototype case study developed in this thesis work dRofus is used to manage the design of a specific portion of Formin HPP refurbishment project, the interoperability aspect of dRofus with Revit by means of an application is demonstrated in more detail on Section 5.3.

4.5 MagiCAD as a design, analysis and evaluation tool

MagiCAD is a BIM solution application, available to Revit and AutoCAD, for Mechanical, Electrical and Plumbing (MEP) design. Fully integrated software enables powerful modelling capabilities and produces a more streamlined working environment. It offers frequently updated localized content, standards and engineering calculations. MagiCAD promises to make the design of accurate BIM models easier, more flexible and less time-consuming. MagiCAD application grants access to over a million data-rich intelligent manufacturer-verified real MEP BIM objects from leading globally renowned international manufacturers [30].

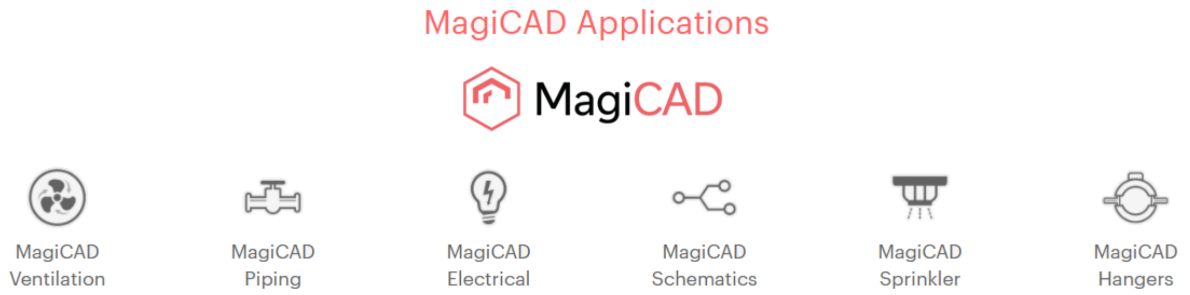


Figure 37 - MagiCAD main applications [30].

MagiCAD for Revit (MCREV) is an application that is built on top of AutoDesk's Revit system. MCREV provides extended functionality to standard Revit operations and supplies thousands of real products to be used on Revit platform. These products, called families in Revit, contain both the graphical representation of the product as well as all the required technical information. Together they enable easy tools for designing a real product model of HVAC and electrical systems as well as to perform reliable technical calculations of the systems [31].

Advantages of MAGICAD [30]:

- BIM workflow – Supports IFC export and BIM Collaboration Format (BCF);
- Accurate design – Access to over 1,000,000 manufacturer-verified MEP BIM objects;
- Automated routine work – Streamlined modelling tools to reduce repetitive routine work;
- Integrated calculations – Design and calculate within the Revit and AutoCAD environments;
- Improved quality – Remain within the Revit environment to deliver higher quality with less revisions.

MagiCAD works based on the principle of having libraries of elements and products used for modeling, these libraries are called datasets. The purpose of the MagiCAD dataset is to act as a template, where products (for example air devices, duct components, radiators, valves etc.), sizing methods and insulation series can be collected. Various datasets can be created for different types of projects like hospitals, office buildings, residential buildings and etc. The same datasets can be used in several Revit projects without the need to recreate a unique dataset for each project from scratch [31].

When a Revit project is started, the products and other information which are used in the project should be collected to the dataset from where they can be used in the project. MagiCAD data can be imported from different dataset files into one Revit project [31].

MagiCAD encourages the creation of company specific dataset templates that contain products that are usually used in different types of projects. When a Revit project is created, it is possible to use the template as a base for the project specific information. To avoid overwriting the company template it is recommended to use the "Create dataset" method for each project. Figure 38 shows the dataset management window.

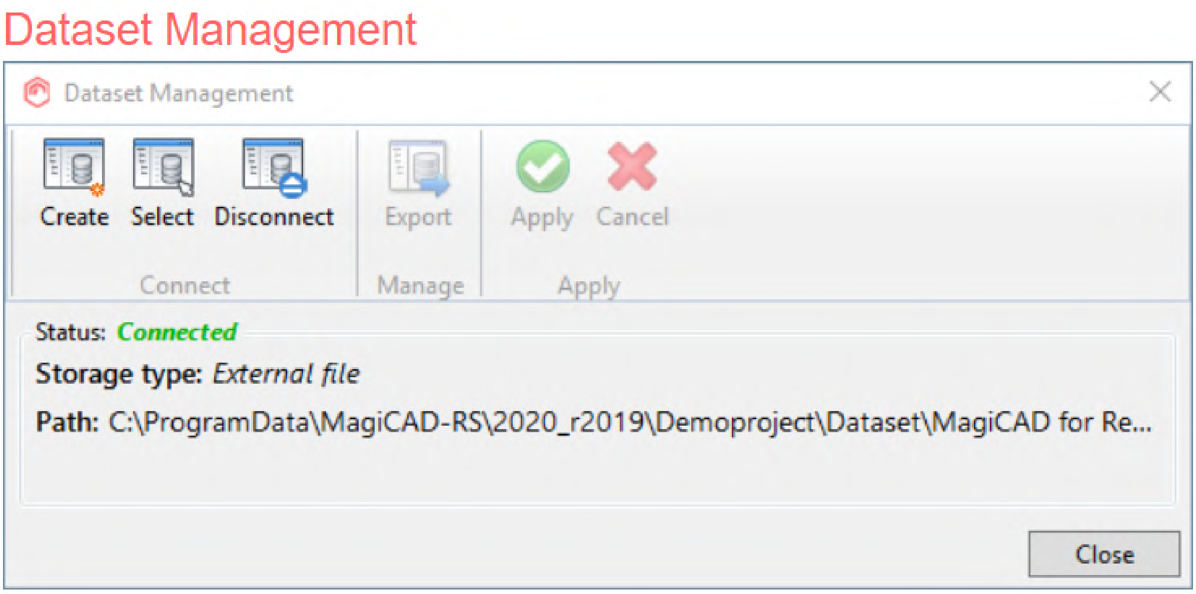


Figure 38 - MagiCAD dataset management window [31].

While performing the Design Authoring BIM Use MagiCAD data sets can be used to quickly insert project components into the model. The datasets are structured according to the template, and the components present on the dataset can be modified. When selecting a product for placement in the model the designer can navigate the dataset to find the desired component. Figure 39 shown an example of a dataset element structure.

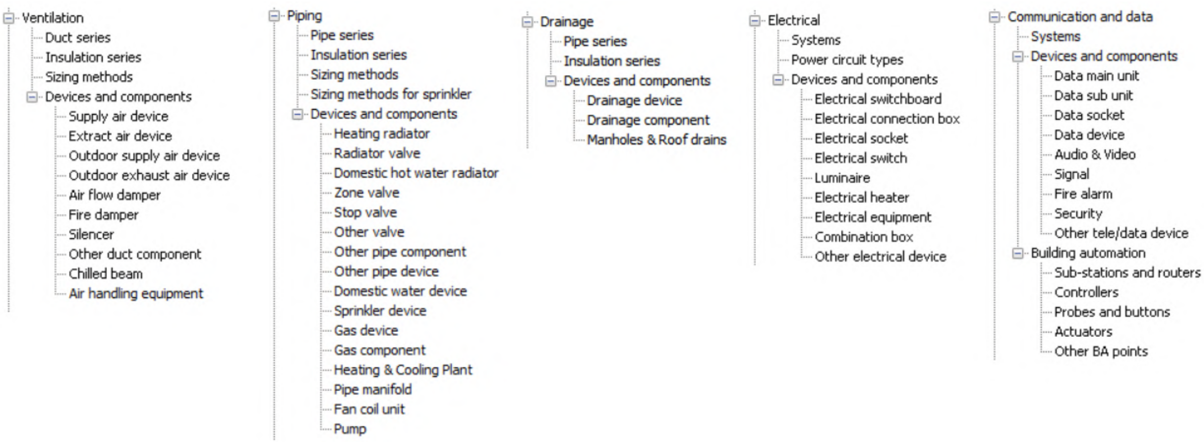


Figure 39 - Example of a dataset structure showing the categories of different components [31].

Figure 40 shows the functionalities of the dataset editor window, where all the elements of the dataset can be edited, or new elements can be added.

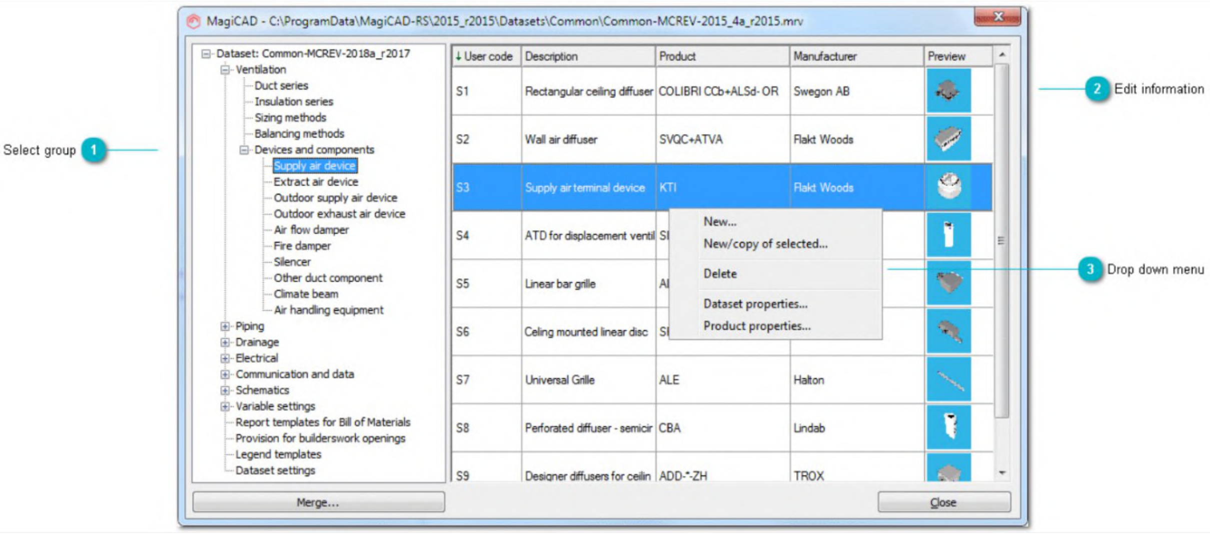


Figure 40 - Dataset product browser window functionalities [31].

1-Select group: Display the available categories for browsing products on the dataset.

2-Edit information: Displays and allows the management of available elements on the selected category.

3-Drop down menu: Right-clicking displays the available options to modify or create the new components.

When modeling a system using one of MagiCAD applications and selecting the insert component option the product browser windows displays the available elements by system according to the dataset definition. Figure 41 shows an example of the product selection window for mechanical equipment.

The application has a dedicated systems manager functionality for mechanical and electrical systems. When a project is created in Revit, there are no real ventilation or piping systems. Instead there are system types. Actual systems will be instances of the system types and a system instance cannot exist without the equipment or other objects like ducts and pipes. All the systems that belong to the same system type share the properties of the system type. The properties are for example line colors, line types, system temperatures etc [31].

When an equipment is installed with Revit's own functionality, the user cannot select the system where it belongs to. After the installation, Revit systems must be manually created and the devices are transferred to the correct systems. When an equipment is installed in the project with MagiCAD, it is possible to select the system among existing Revit systems or create a new system. The systems are selectable from the combo boxes in all the installation dialogs. If the system does not already exist, MagiCAD automatically creates the system specified [31]. This is particularly interesting for mechanically oriented projects like the HPP refurbishment, as MagiCAD greatly improves the system management of the model, making they easier to create, edit and reassign components to different systems. Figure 42 shows an example to the interface for systems management when modeling air duct systems.

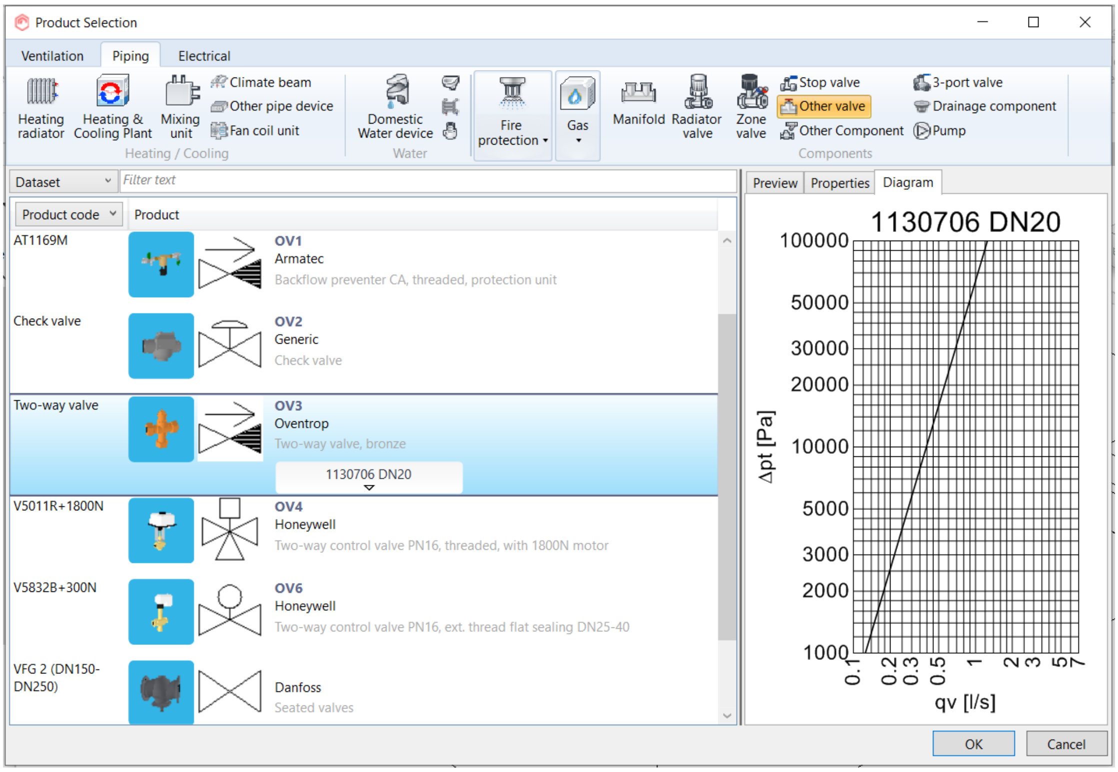


Figure 41 - Product selection window displaying the available elements by category, manufacturer, application and available sizes along with their properties.

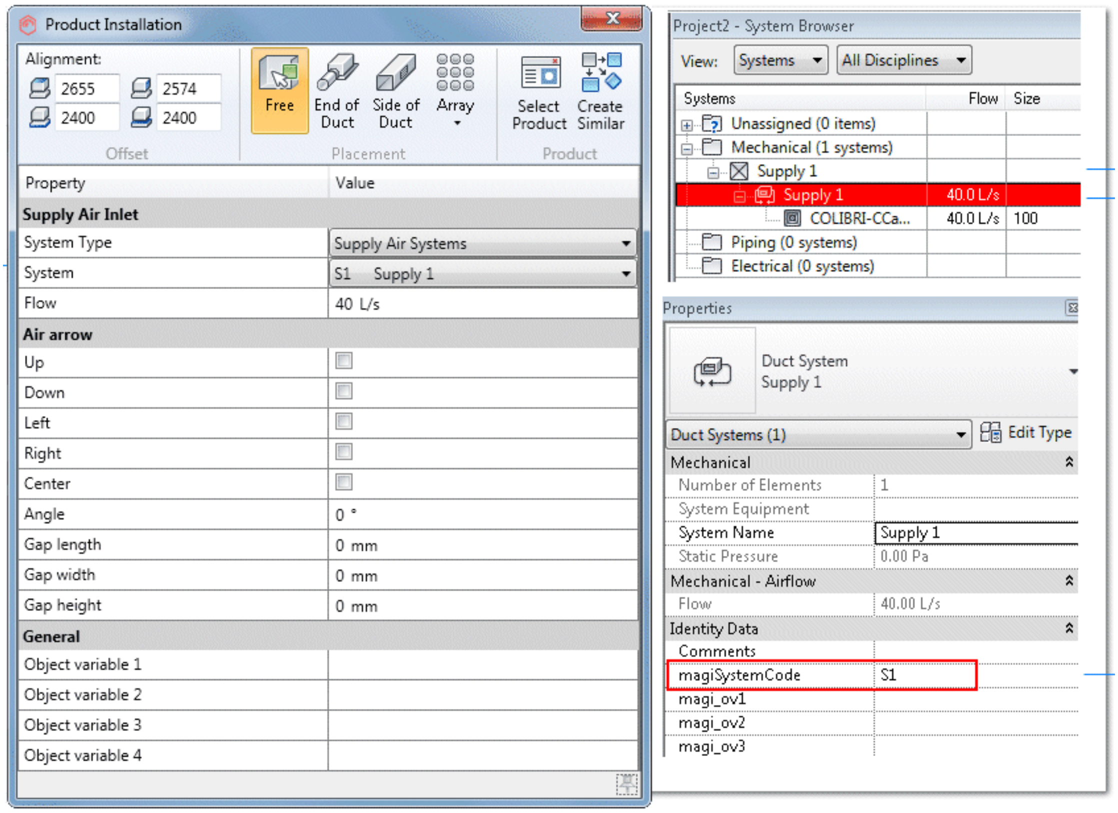


Figure 42 - Example of the systems functionalities of MagiCAD [31].

Regarding the creation of the actual duct and piping systems the application has additive features that expand upon Revit's capabilities streamlining the design process. It contains its own duct and pipe drawing tools, shown in Figure 43, as well as calculation and sizing methods to aid with on Design Authoring BIM use, show on Figure 44.

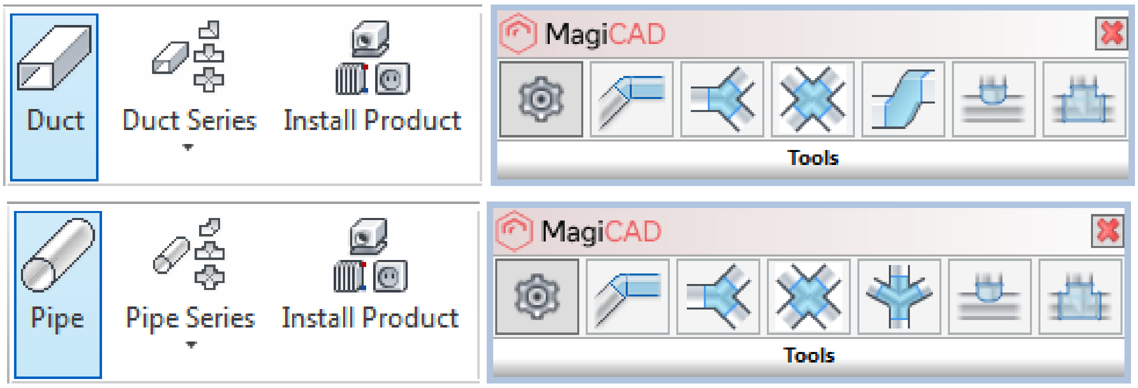


Figure 43 - Duct and Pipe drawing tools from MagiCAD [31].

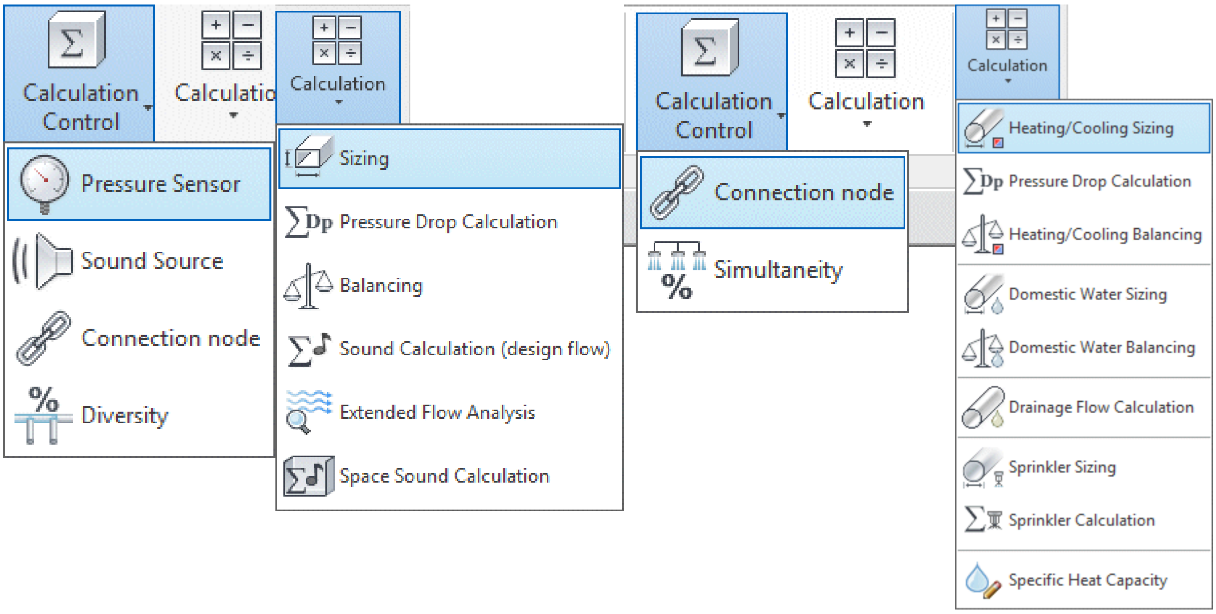


Figure 44 - Sizing and calculation options for ducts and pipes in MagiCAD [31].

There are also tools with similar functionalities for cabling and sprinkler design. Including automated routing options, cable tray modeling assistant, sprinkler distribution planning and more. The MagiCAD Online Help for Revit [31] contains detailed information about the usage of all these functionalities.

5 PROTOTYPING WITH FORMIN CASE STUDY

In this chapter some of the previously discussed BIM Uses and workflow improvement opportunities are used into a prototype model for Formin HPP refurbishment project, with the main goal of testing out some of the proposed possibilities.

5.1 Refurbishment of the stator housing

The chosen subject for the modeling prototype was the Stator frame of Unit 1, shown in Figure 45. This component serves as the support for all the stator systems which are held in place withing the internal cylindrical face of the metal structure. The subject of the modeling is the outside of the equipment which has cooling heat exchangers attached along its perimeter. The coolers are fed by a piping system that flows water into the exchangers into a circular piping system around the stator frame.

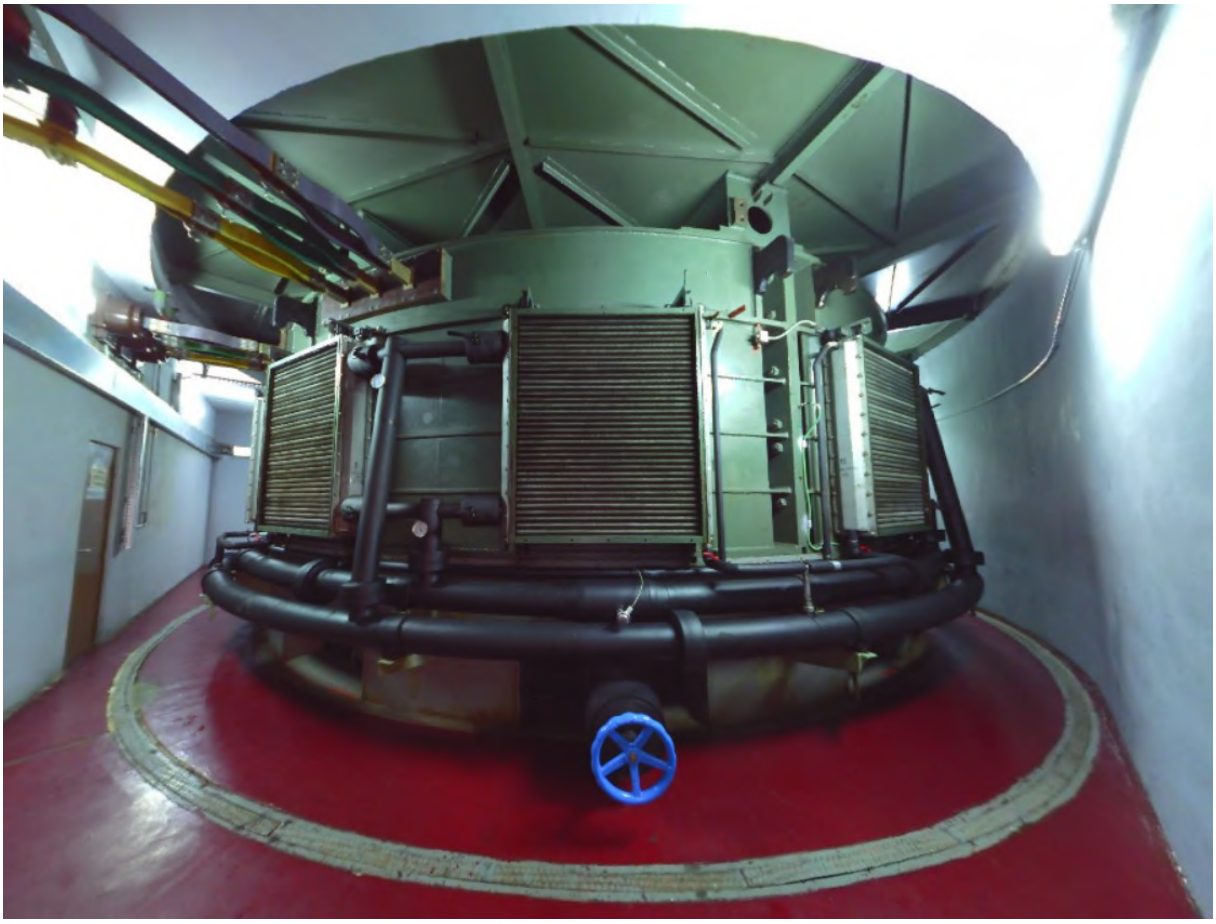


Figure 45 - Unit 1 Stator frame housing.

To assist with the modeling the original drawings of this equipment were provided, one of them is shown in Figure 46, some useful information was extracted from the drawings and helped fulfill the eventual blind spots that the point cloud data scan had. Nevertheless, the highly detailed and very well executed point cloud scan was the primary source of information for the modeling of this equipment.

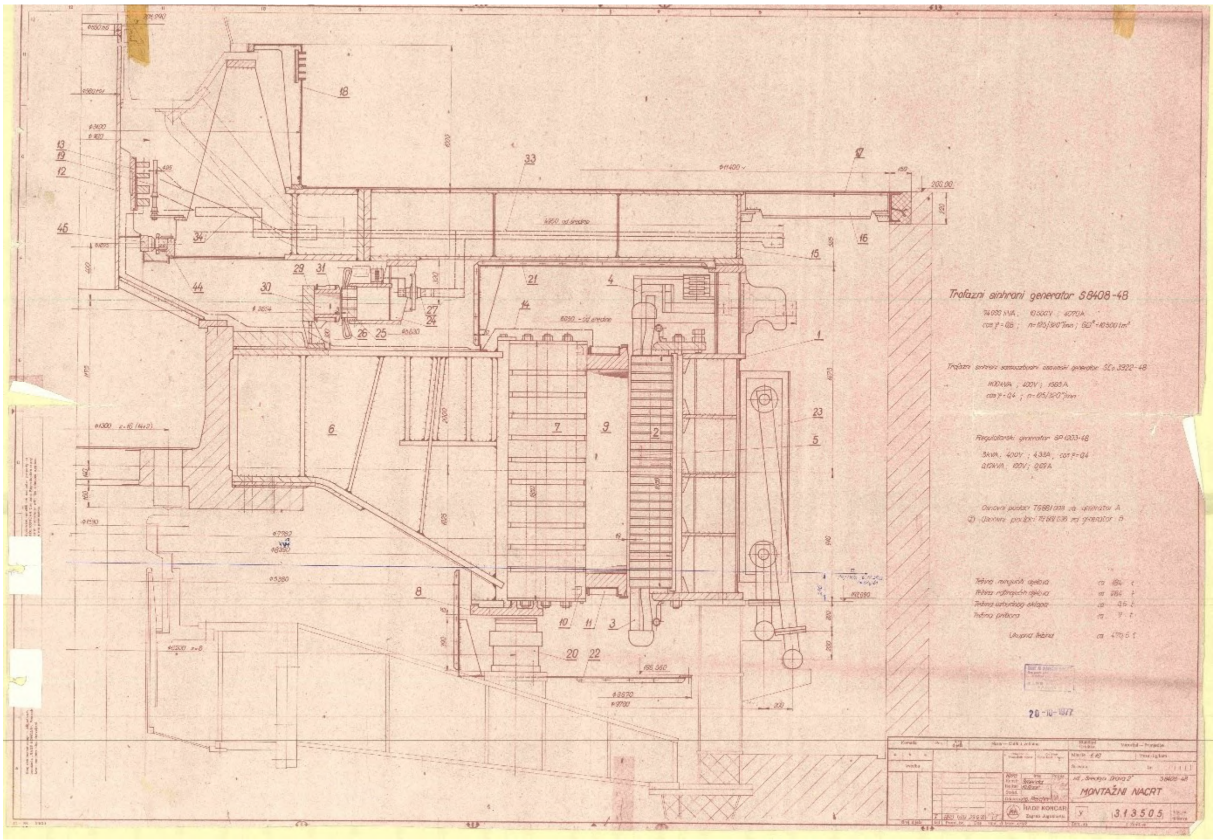


Figure 46 - Original drawing of a cross section of the stator frame.

By checking the available data, discussed in Section 3.2, the decision was made that working on the generator stator frame and it's cooling system made a good option for the prototype case study specially because the provided point cloud is very detailed on this location and the overall complexity of the system is not too overwhelming, making it more feasible. This equipment also touches multiple aspects of the expected BIM uses to be explored, such as:

The requirement expected definition from the designers and having an input on the range of possibilities for the generator allow the exchange of data between requirement specification and design options. The cooling system of the generator allow for the development of libraries of components to be used with the proposed tools for drawing piping systems. The interactions between structural, architectural and mechanical model are especially important on this location, allowing for the development of coordination activities that should improve the refurbishment workflow.

As the refurbishment project is still in its early stages there are currently no available preliminary designs for this equipment. Because of that this case study will focus on developing an AS-IS model of the current installed equipment making use of the provided point cloud data and using the tools discussed in Chapter 4 to prototype them.

5.2 Prosed modeling workflow

This case study will explore the BIM tools described in Chapter 4 by applying them into a modeling workflow for the stator frame described in Section 5.1. This workflow can be extended for use at the other equipment and disciplines of Formin HPP refurbishment project.

As the main focus of this thesis is in requirements specifications and library management for design authoring, the project phase at which the proposed actions mostly apply to are planning and designing, nevertheless, the models and the data can be used during construction and operation & maintenance phases as prescribed on the expected BIM Uses for the project.

On Section 2.5 it is presented how to use available resources to aid the project team on specifying requirements. This would be the first step: Determining, by documenting the specifications on the EIR document discussed in Section 4.1, what the model should contain and what level of information each model element has to have during each project phase. This management of information is made by using dRofus, presented in Section 4.4.

Once the requirements are defined and documented, the dRofus project manager software can be fed the information by setting up the functions and rooms, defining the items and creating the relevant room and item data. This process is exemplified by the case study on Section 5.3.

The next step is preparing the Revit Model to comply with the room requirements defined. Using the dRofus Revit plugin shown on Section 5.3 and Revit's rooms tools, the rooms of the model must be linked to dRofus in order for the software to be able to manage the model components. After linking the model rooms to dRofus it is possible to assess what components are missing, incomplete, outdated or finished. For the components that still need work, Section 5.4 exemplifies the modeling actions that were needed in this case study.

As the modeling work progresses the model can be assessed on dRofus and the progress checked, reports can be generated showing the number of items existing or missing in a room and the number of items that contain data. The process of linking the model elements to dRofus for this management actions is shown in Section 5.3.

In order to better illustrate the overall workflow of proposed for the modeling actions of this project the following diagram, shown in Figure, was developed. A larger version of this image is available at Appendix 7.3.

More details on each individual task are provided as examples in sections 5.3 and 5.4.

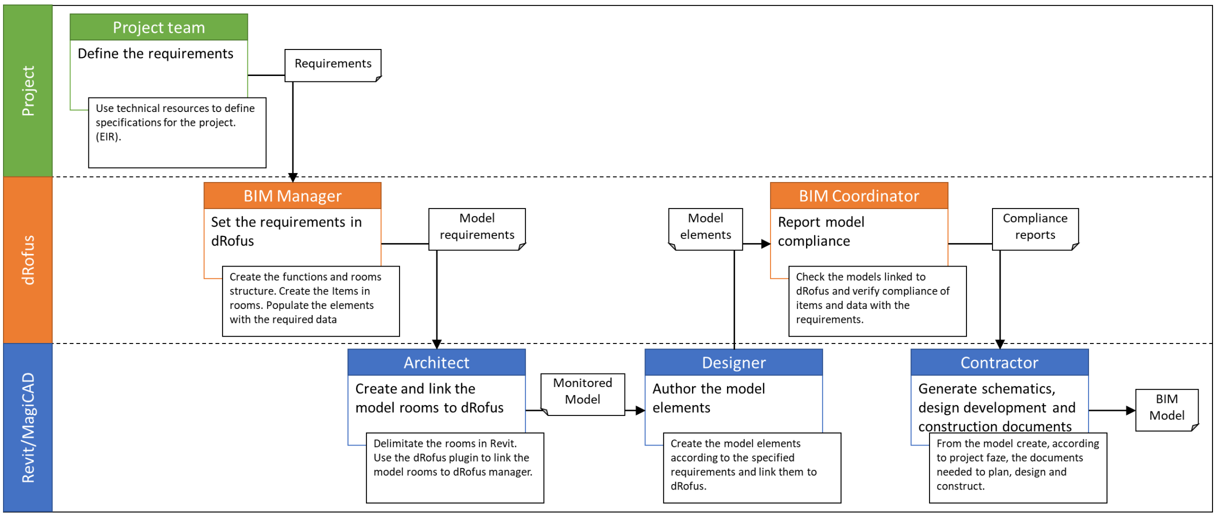


Figure 47 - Proposed workflow for BIM model authoring for Formin HPP refurbishment project.

The workflow is divided into 3 environments:

- Project: Regards the decision making level of the involved business organizations.
- dRofus: Is the project management software used to coordinate requirement specification across all disciplines.
- Revit/MagiCAD: Is the design authoring software and tool. It is used for 3D modeling and library management.

The party responsible for each step is presented generally, as shown on the subsequent Sections of this paper, there are multiple sub-steps to each step. Those can be performed by a team or individuals, but in general the goal is to have the following roles performing the modeling actions:

- Project team: Composed by the multiple disciplines involved in the project and fundamental for the requirements specification development.
- BIM Manager: Will rely the information presented at the project documents, like the BEP and the EIR, into dRofus software as model requirements.
- Architect: Will manage the architectural model so that it complies with the requirements set on dRofus. Linking the model to the software will allow the management of the requirements for equipment.
- Designer: Is responsible for the authoring of the model elements and components according to the requirements defined by working in tandem with the dRofus platform.
- BIM Coordinator: Will check the authored models in dRofus by using the available tools and report generation. Is responsible for checking the model compliance and providing evaluation on needed iterations.
- Contractor: Responsible for generating the needed documentation for construction using the authored models.

5.3 Requirements specification linked to the model

For this case study dRofus was the software used to manage model requirements by using some of the features described in Section 4.4. The first step was to create the rooms in the Revit architectural model, FORMIN-HSE-ZZ-00-M3-A-Arhitektura_20200630-S0, using Revit room tools as shown in Figure 48.

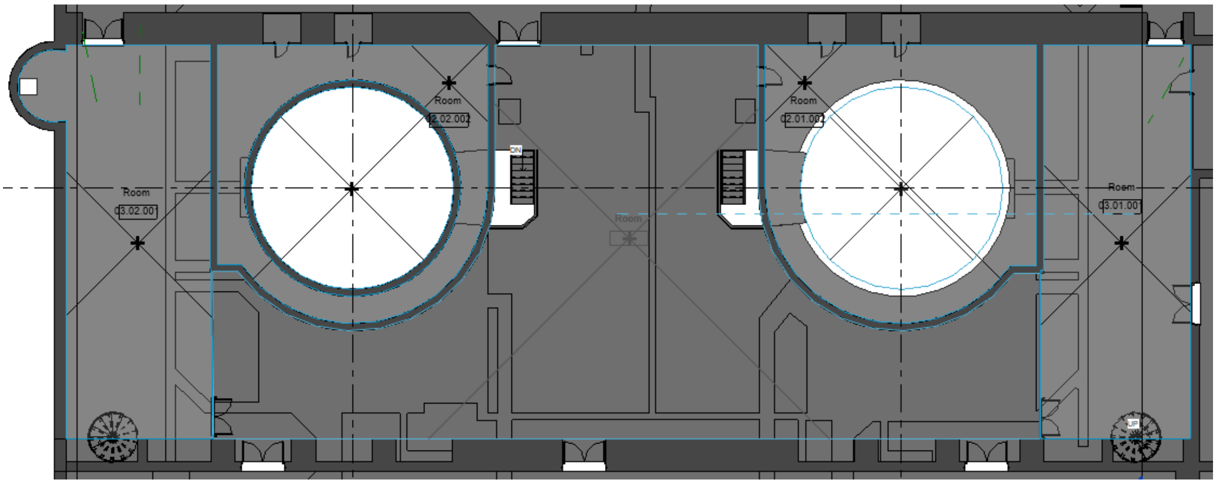


Figure 48 - Inserting rooms on the architectural model, at elevation 196,00 using Revit.

The architectural model with the rooms defined can then be linked into the coordination model, FORMIN-HSE-ZZ-00-CM-Z-Coordination_20200603-S0. The next step is to the create the so-called functions, sub-functions and rooms in dRofus according to the expected design for the building. For this project, the existing room structure will be kept, as there are no major architectural changes planned. Using the provided as-is model as a guide the function and rooms structure, shown on the left side of Figure 49, was created in dRofus.

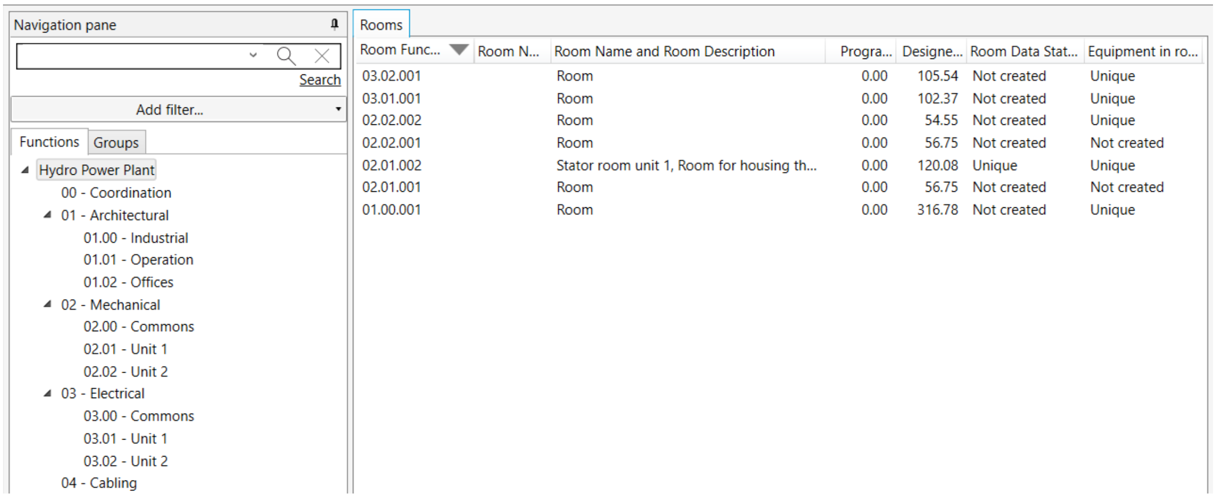


Figure 49 - Function structure (left) and currently linked rooms (right) on dRofus rooms panel.

The next step was to assign the created rooms in dRofus to the Revit model so that the requirements and progress of each room can be checked. This is done by first using the “linked model rooms → rooms” function on dRofus Revit plug-in to import the rooms from the linked model into the coordination model.

This particular option is required for this project as the rooms are not created on the coordination model itself but on the linked architectural model. This process is shown on Figure 50, the architectural model is selected as the source of data and a notice will show the results.

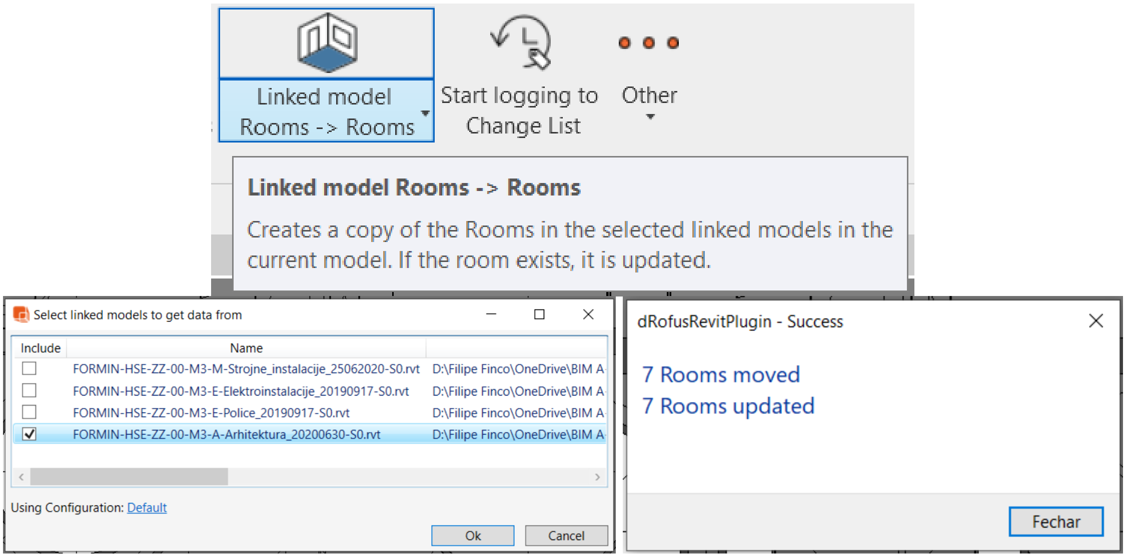


Figure 50 - Creating the room instances in dRofus from the linked model.

Now that the rooms are assigned to the coordination mode the "Link to dRofus" option, Figure 51, was used. This option will link the rooms in the Revit model to the dRofus functions and rooms structure created previously and allows tracking of project progress and requirements monitoring.

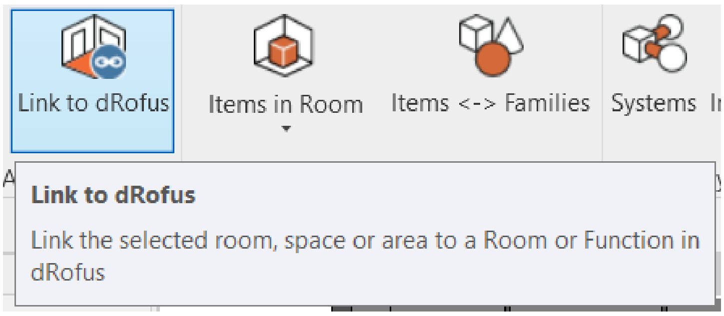


Figure 51 - Link to dRofus option.

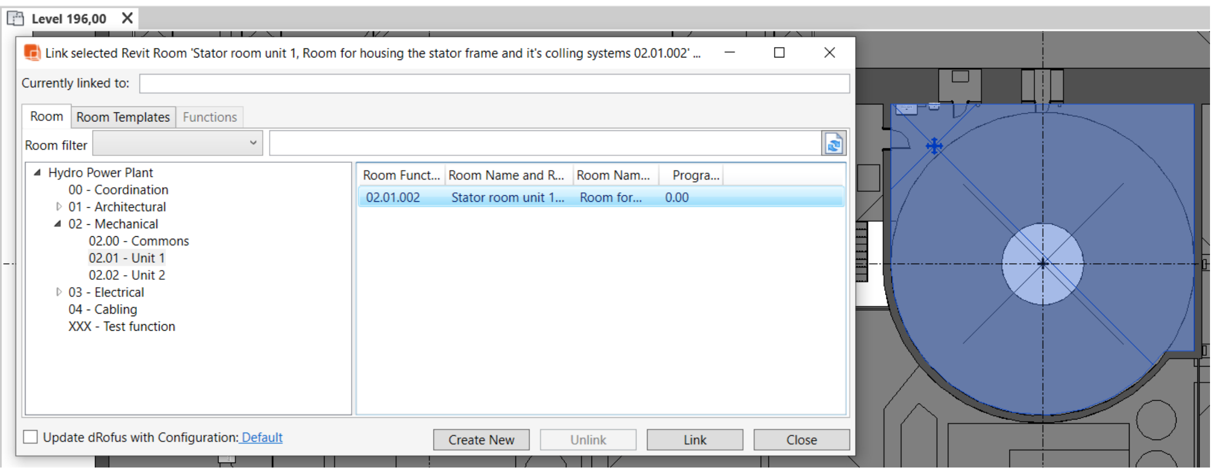


Figure 52 - Linking a Revit room to a dRofus room.

After selecting "link to dRofus" option, a window will appear displaying the current functions and rooms structure. By using the select tool on Revit the room to be linked needs to be selected. After being selected the available dRofus rooms at which the selected room can be linked to will be shown and the option to link the rooms will be available as shown on Figure 52. Now that the Revit model and the dRofus project manager are linked, the parameters and installed equipment on the room can be monitored on dRofus. The next step was to define the requirements for each room and monitor the progress of the Revit model.

After linking the rooms to dRofus, navigating the functions and rooms structure allows to inspect the data for each room. Each room can be assigned to the so-called "room data" that will contain the requirements specified for that particular room. Figure 53 shows how the room window looks like when creating the data for a room.

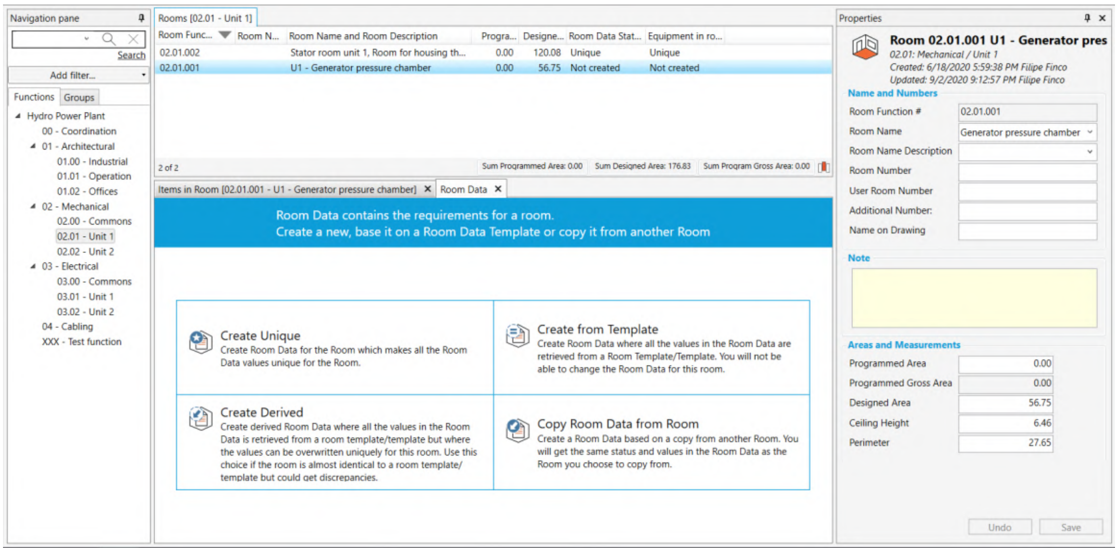


Figure 53 - Room data panel displaying the available options for room data creation.

These requirements can be of multiple disciplines, Figure 54, such as architectural (number of openings, doors, windows), plumbing (number of toilets, basins, sinks), HVAC (minimum temperature, ventilation specs), electrical (available power outlets, lighting specs) and many others.

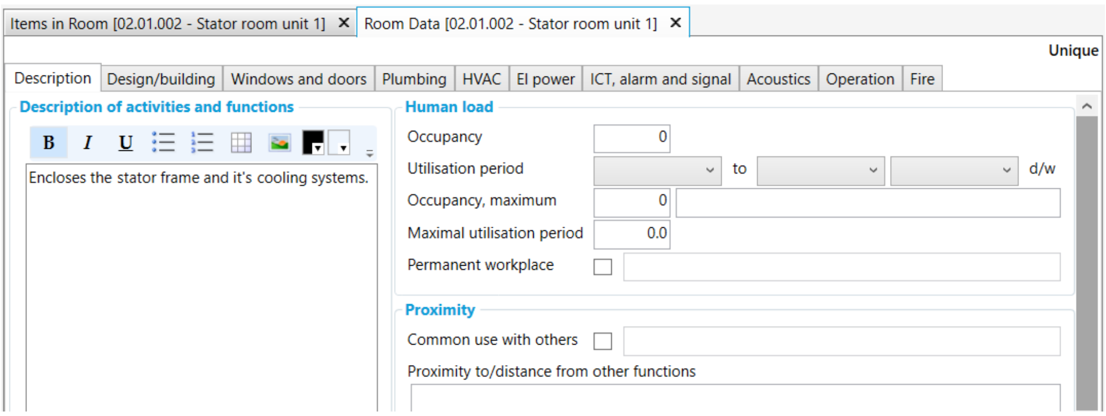


Figure 54 - Available tabs for room data requirements definition.

This room data information must then be filled in according to the desired design for the project and its rooms. dRofus will check the model and monitor the changes, it is able to provide reports to see if the requirements are being met with model elements.

After setting up the rooms the "Items", as called by dRofus, can be configured. This is the most valuable feature of dRofus for this kind of industrial projects, it allows the requirements definition and monitoring of the model to check if the required equipment is already present in the model. The first step is to create the item group structure that will classify the items. The structure created for this case study is shown on the left in Figure 55. After the groups are created the individual items can be created in dRofus.

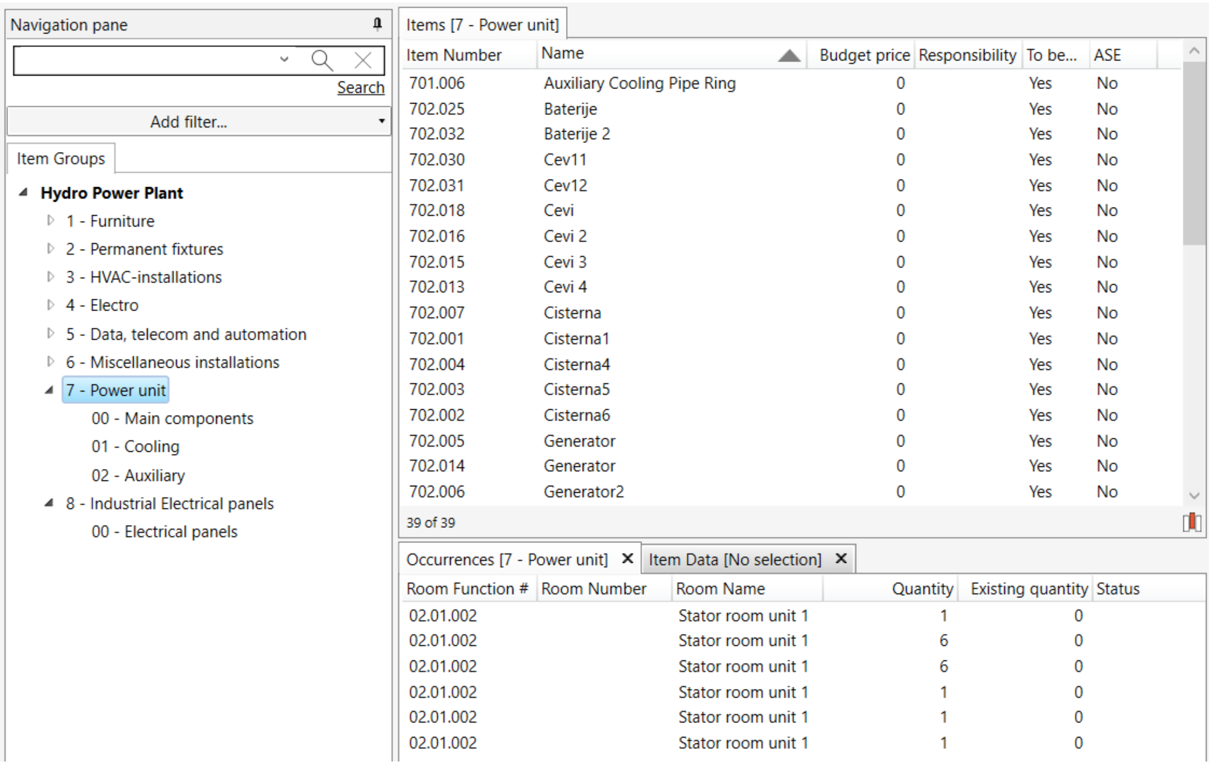


Figure 55 - Items dRofus window showing the items groups on the left and the currently monitored items on the right. On the bottom the occurrences window.

The next step is to start modeling the entities on the Revit model and placing the equipment according to the requirements set in dRofus. The modeling part of this case study is discussed in Section 5.4.

In order for dRofus to keep track of the equipment placed in the room the model components need to be identified by dRofus. The option that enables this is "Items ↔ Families", Figure 56. This option will link the families present in a project to their dRofus counterparts. On the top left the tool displays the current item groups, on the right the Revit families present in the project according to the categories to be displayed, selected on the Family categories window on the right. On the bottom the currently linked families are displayed.

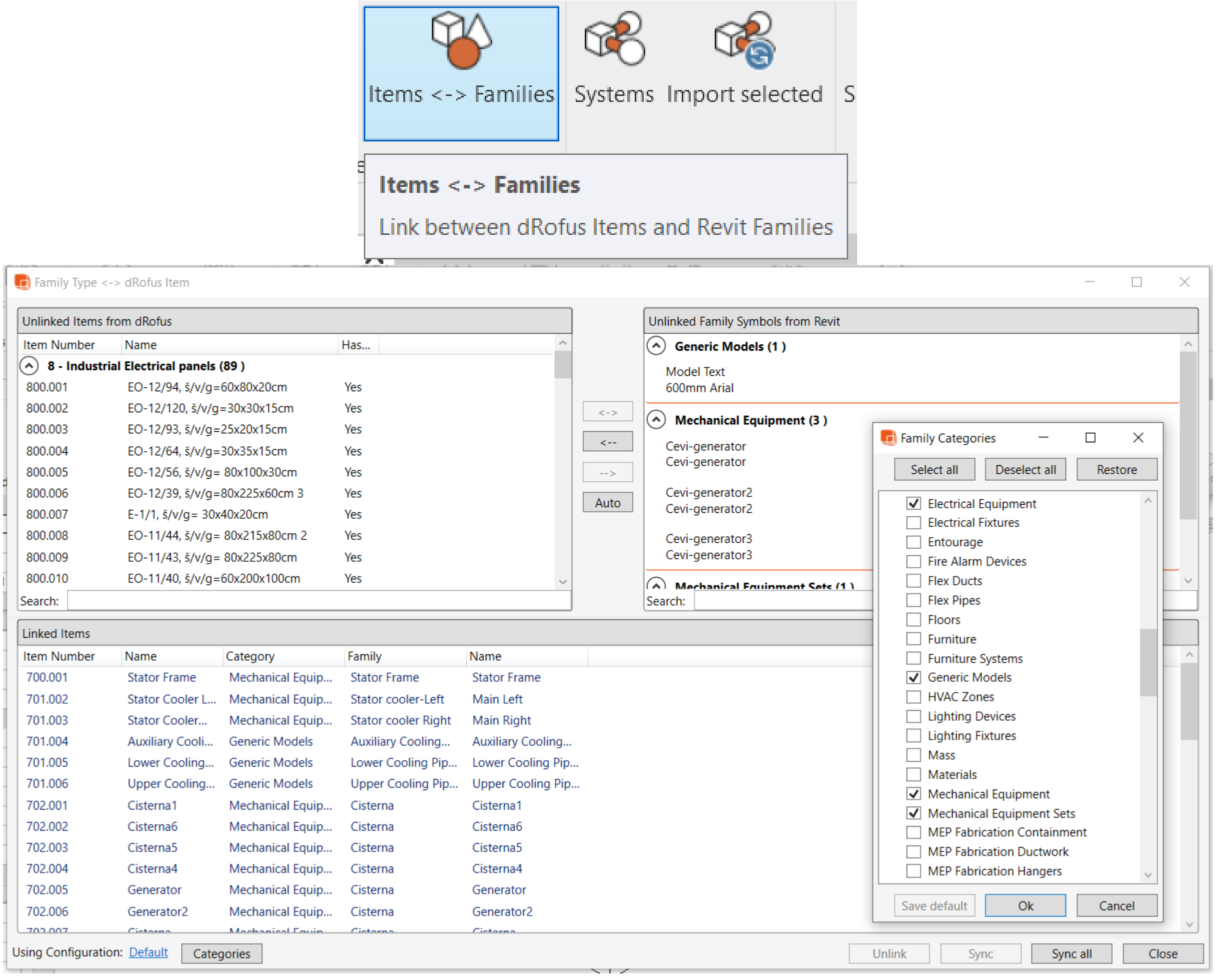


Figure 56 - Mapping Revit Families to dRofus Items.

There are three options for linking the Revit Families to dRofus items, it involves using the arrows on the middle of this window. If the item already exists in dRofus but not in Revit, the item in the left side can be selected and using → (arrow to the right) in the middle create the item in Revit. If the family exists only in Revit a dRofus item can be created by selecting the family on the right and using ← (arrow to the left). If the item has already been created in dRofus and there is already a Revit family in the model they can be linked by selecting both the item and the family and using ↔ (two way arrow) as shown in Figure 57.

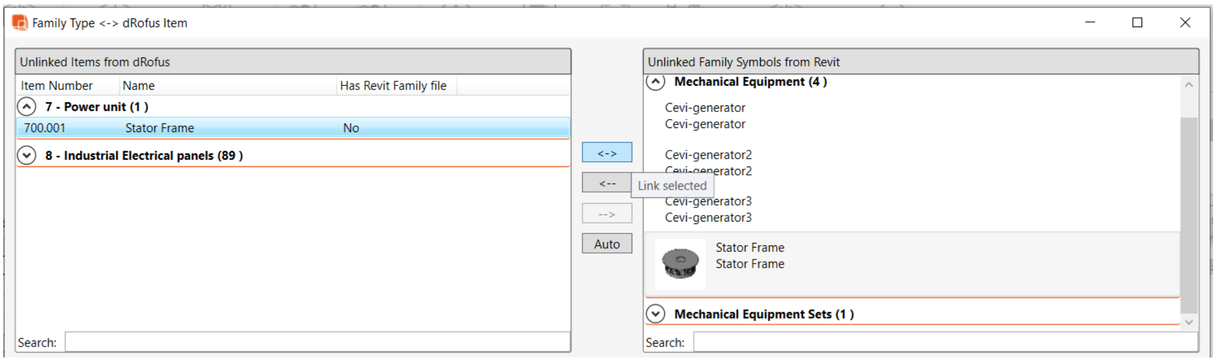
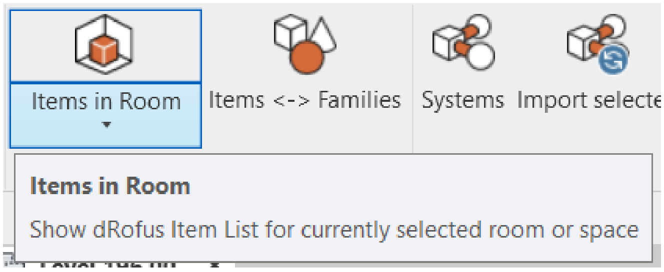


Figure 57 - Linking the stator frame Revit family to the Stator Frame dRofus item.

This operation has to be done in the lowest project level of discipline for the model, this means this mapping process cannot be done on the coordination model as the families used in the linked models are not really loaded in the coordination model, but only loaded on the architectural or mechanical model. The next step is to make the dRofus verify the presence of these items and families in the coordination model.

This is done using the "Items in room" option and selecting the room to be checked on the coordination model in Revit. If the families were correctly linked to dRofus on the linked models, like on the mechanical one, the equipment will appear on the list on the left of Figure 58, but for these linked items to properly appear the option "look for items in linked models" need to be checked as shown in Figure 59, the categories of equipment being searched also need to be checked under the "Categories…" option.



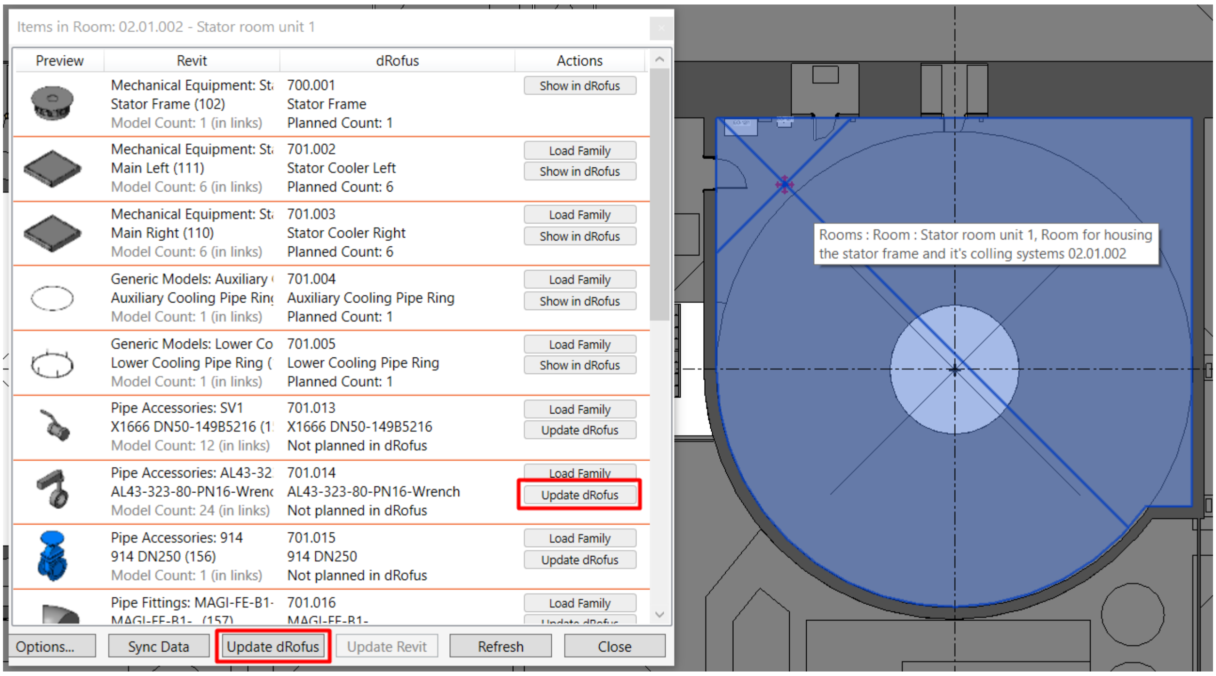


Figure 58 - List of model entities liked to dRofus and present in the room while evaluating the coordination model.

If new equipment are added to the linked model and linked to dRofus there, then they will appear on the list with the option "Update dRofus" as shown in Figure 58. This will create or update the item on dRofus based on the Revit Family in the model.

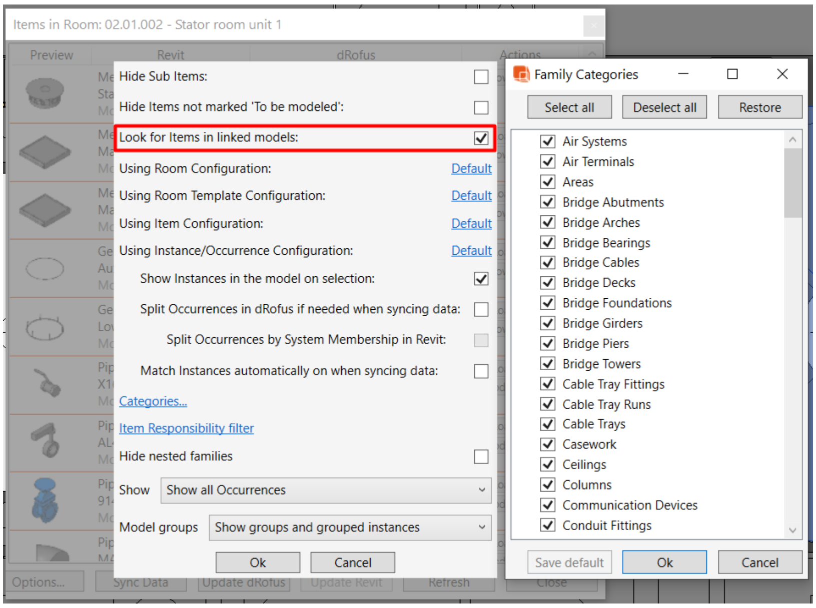


Figure 59 - Set dRofus "Items in Room" option to search for items in liked models.

The systems defined in Revit were also imported into dRofus using the “Systems” tool to create or link the Revit system information to dRofus project. Similarly, to the “Items” tool, the “Systems” tool window, shown on Figure 60, allows to select the dRofus systems on the left, the Revit systems on the right and then use the buttons on the middle to either link the systems or create new ones. The currently linked systems are shown on the bottom.

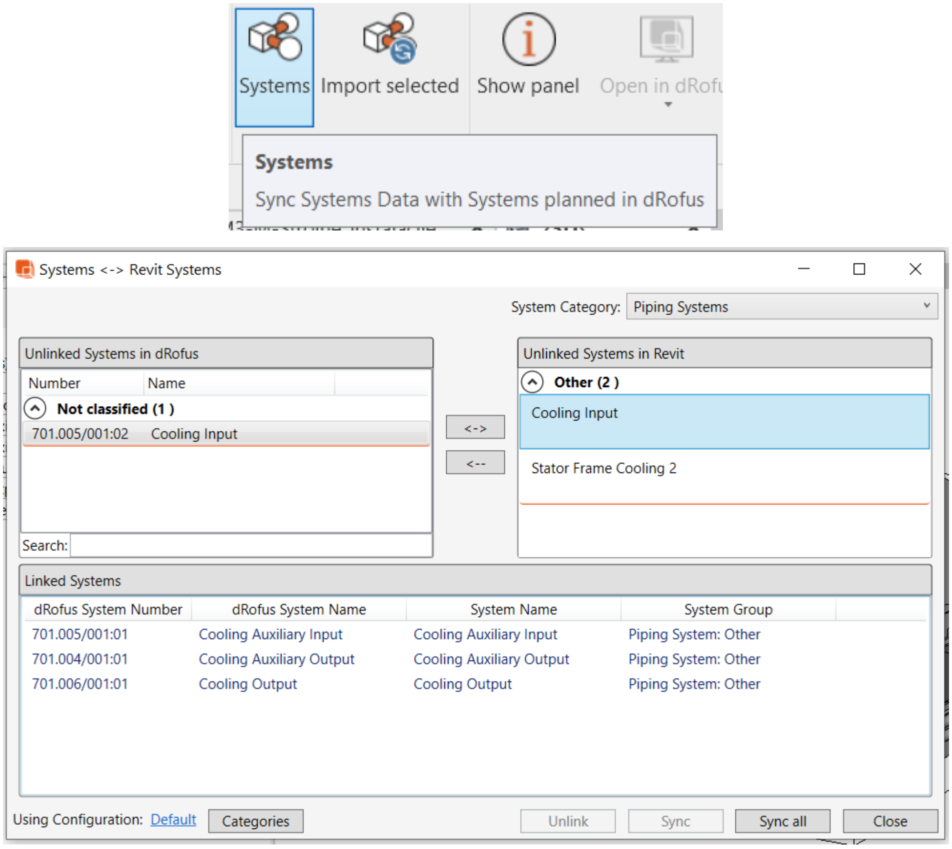


Figure 60 - System tool in dRofus showing how to link a Revit system to dRofus project manager.

After creating the systems, the next step was to assign the components that make that system. This is done using the “Import selected” tool.

Using the systems browser in Revit to select all the desired systems and then choosing the “Import selected” option will open the “Choose systems to be imported” window, shown in Figure 61, on this window the guiding or defining component of each system needs to be selected. After the components are correctly selected the import button will link the Revit systems to the dRofus systems.

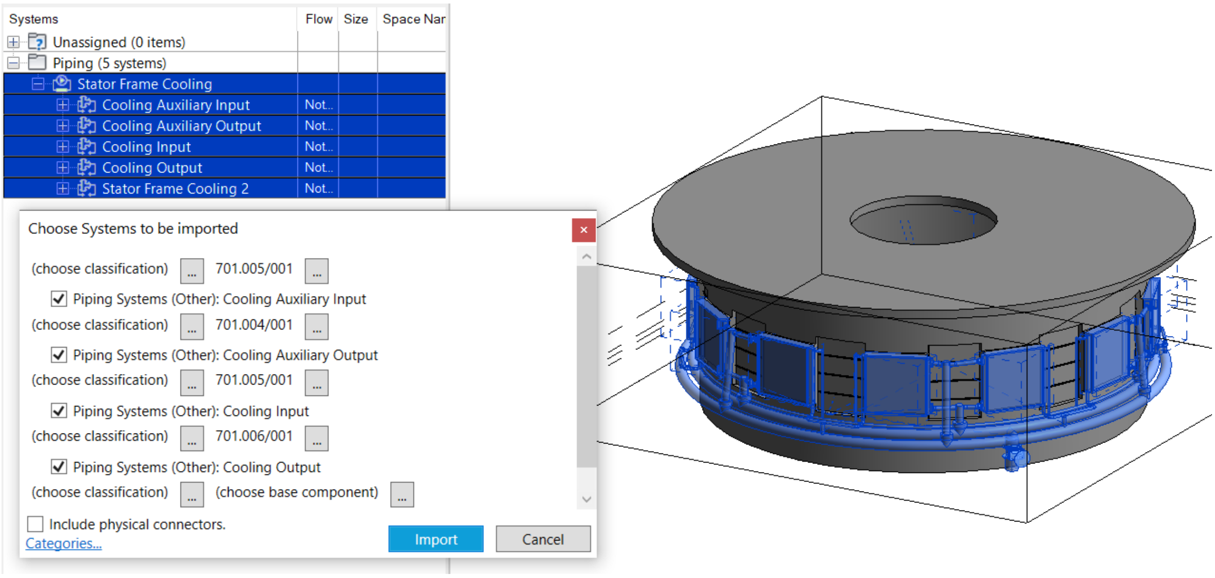


Figure 61 - Importing selected system components to dRofus.

After the importing process the systems tab in dRofus will contain the information according to the Revit model. It even has an interesting feature, the “system graph” shown on the middle of Figure 62, that automatically creates a diagram of the selected system for visualization and evaluation purposes.

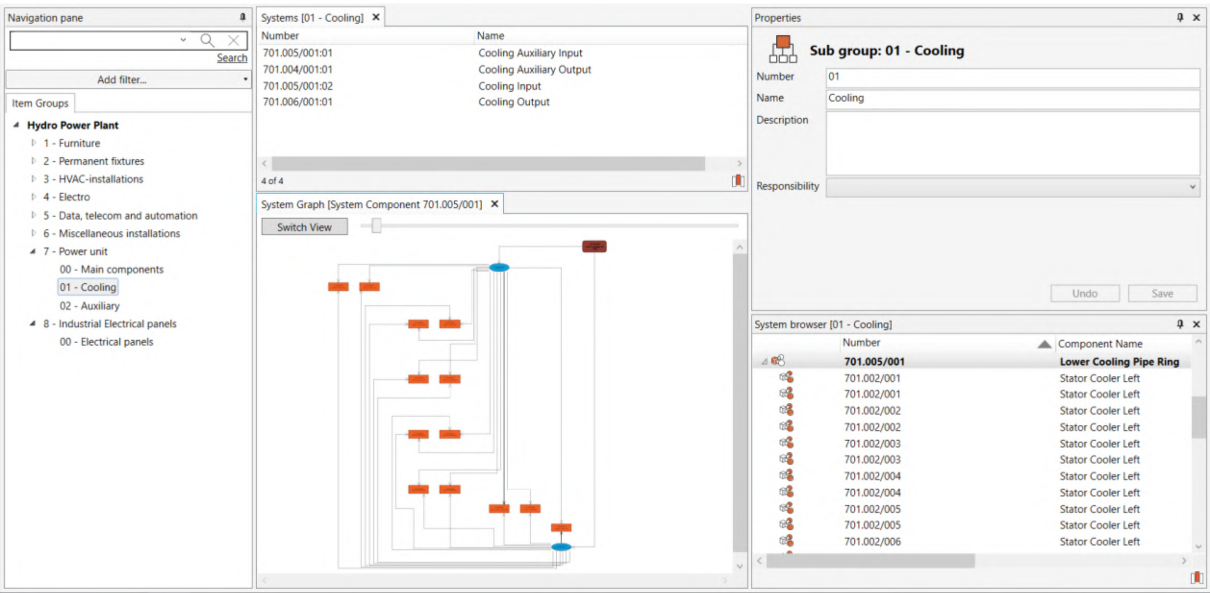


Figure 62 - Systems tab in dRofus showing the linked systems from Revit.

After all these steps the progress of the Revit model and its compliance with the requirements specified can be checked in dRofus, as all the information from the model is made available for the designed rooms. This allows designers to have a reference for their Design Authoring BIM Use while modeling and allows the coordination team to keep track and monitor model compliance to the specifications. The resulting dRofus environment for this case study is shown in Figure 63.

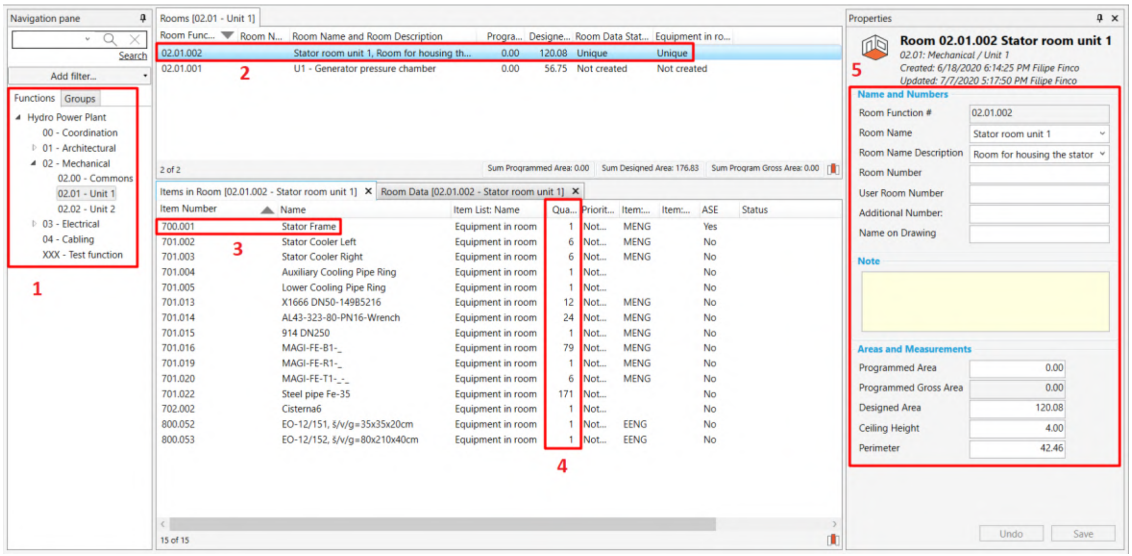


Figure 63 - dRofus manager for Formin HPP refurbishment case study.

1. Rooms and functions structure.
2. Rooms under the selected function.
3. Items present in the selected room.
4. Occurrence of the items present in selected the room.
5. Information about the selected room.

Another feature that can be explored during the project is the Company and products tab.

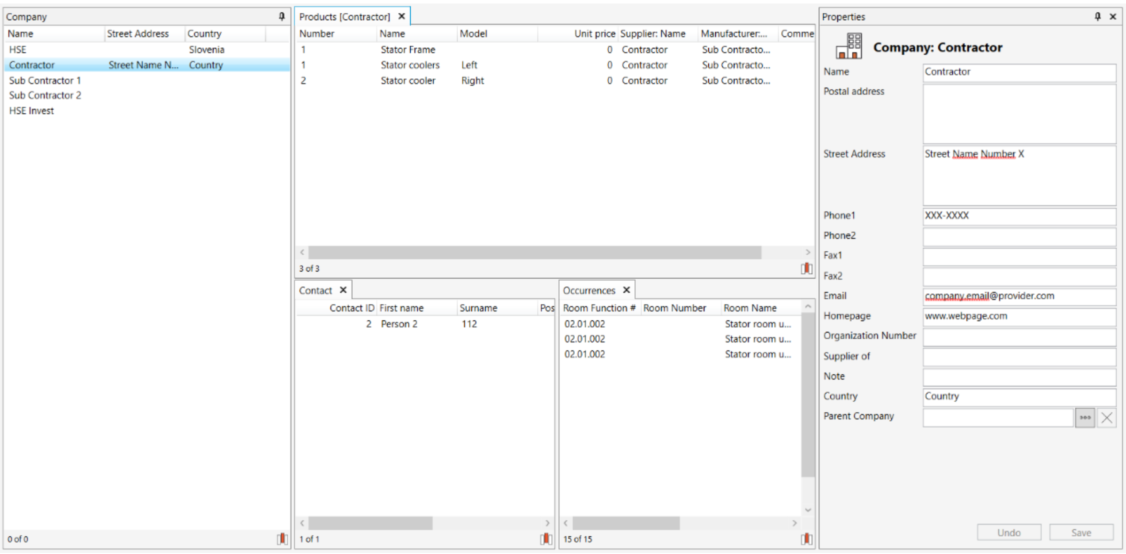


Figure 64 - Example of the company tab in dRofus.

It is possible to create in dRofus entities for all the participating companies of the project and by assign products to them, which are representatives of project assets like equipment being purchased for example. Figure 64 shows the company tab, on the left panel all the created companies for the project are shown. When a company is selected, the products they are responsible for are shown on the upper middle part of the window, the items associated with those products are shown in the occurrences tab. It is also possible to input the data of responsible people for each company with contact information. The company data, like address and phone number, is shown on the right side.

Another useful feature of dRofus is the automated report generation tool. Basically, all sorts of reports can be generated based on the selected report template and by using the relevant filters. Figure 65 Shows an example of the setup for a report, Figure 66, that will list all the items in the selected room.

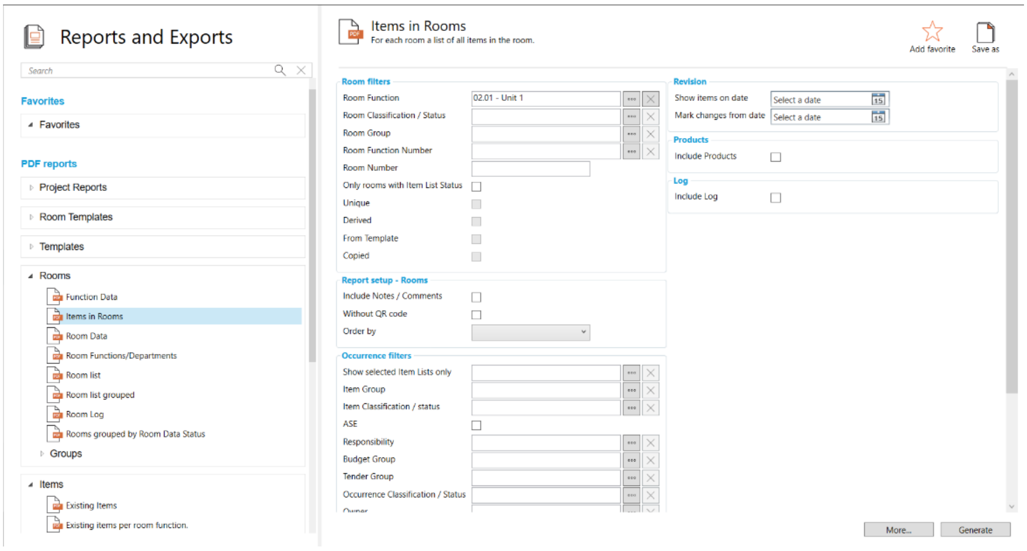
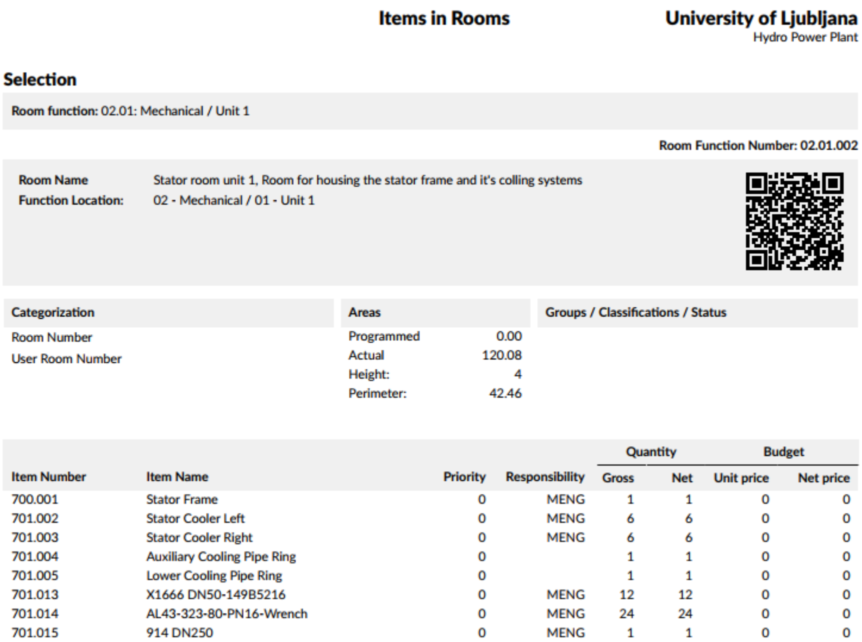


Figure 65 - Report generation in dRofus.



Items in Rooms

University of Ljubljana
Hydro Power Plant

Selection

Room function: 02.01: Mechanical / Unit 1

Room Function Number: 02.01.002

Room Name Stator room unit 1, Room for housing the stator frame and it's colling systems
Function Location: 02 - Mechanical / 01 - Unit 1

Categorization	Areas		Groups / Classifications / Status
Room Number	Programmed	0.00	
User Room Number	Actual	120.08	
	Height:	4	
	Perimeter:	42.46	

				Quantity		Budget	
Item Number	**Item Name**	**Priority**	**Responsibility**	**Gross**	**Net**	**Unit price**	**Net price**
700.001	Stator Frame	0	MENG	1	1	0	0
701.002	Stator Cooler Left	0	MENG	6	6	0	0
701.003	Stator Cooler Right	0	MENG	6	6	0	0
701.004	Auxiliary Cooling Pipe Ring	0		1	1	0	0
701.005	Lower Cooling Pipe Ring	0		1	1	0	0
701.013	X1666 DN50-149B5216	0	MENG	12	12	0	0
701.014	AL43-323-80-PN16-Wrench	0	MENG	24	24	0	0
701.015	914 DN250	0	MENG	1	1	0	0

Figure 66 - Example of a generated report for items in a room.

5.4 Modeling using BIM tools

Starting by modeling the individual families for the whole equipment in Revit according to the specification requirements defined in dRofus, the first component to be modeled was the Stator Frame. This component was modeled based on the point cloud scan data with the assist of the original drawings. The LOD of the model elements is generally 300 [26] according to the BIM Forum specifications because, as stated previously, all of this equipment will be removed from the plant and exchanged for new machines. Meaning there is no need to have a higher LOD for AS-IS model elements within the expected BIM Uses for the project.

As discussed previously in section 4.3 the classification systems currently widely available on BIM applications are incomplete in terms of mechanical equipment, they do not include HPP equipment into their taxonomy. For this reason, the usability of the OmniClass plugins for Revit is limited when applied to this sort of families, the result is having to classify the family as a Mechanical Equipment with no classification in the OmniClass Number Identity Data parameter, as shown in Figure 67. The KKS classification system can be implemented into Revit given the proper allocation of resources to it, as a matter of fact, it would be a very useful development for future studies.

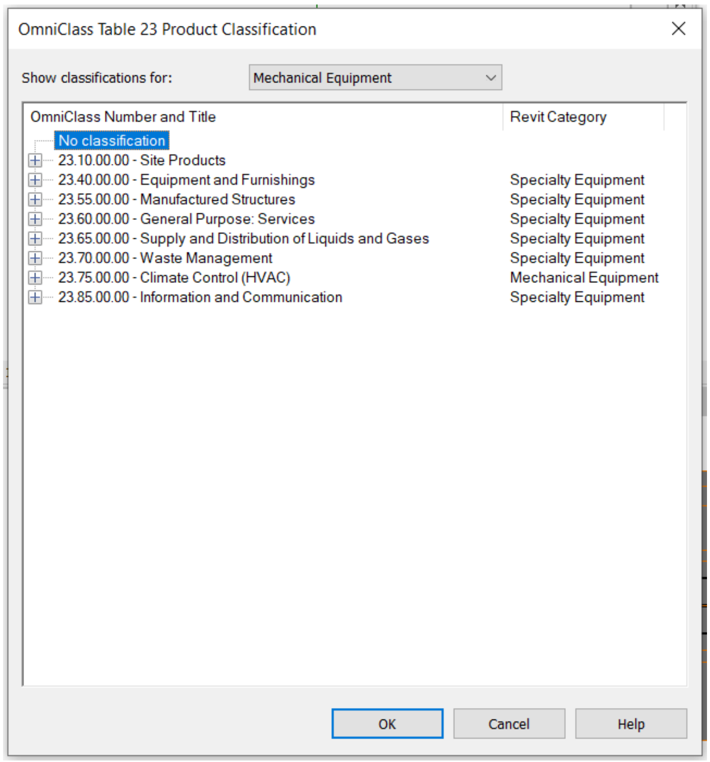


Figure 67 - OmniClass Classification Number parameter list, there are no compatible categories for most of the mechanical equipment present in HPPs.

For modeling the geometry reference planes are drawn from the center of the equipment with angles for positioning the surfaces where the heat exchangers are installed, as shown in Figure 68.

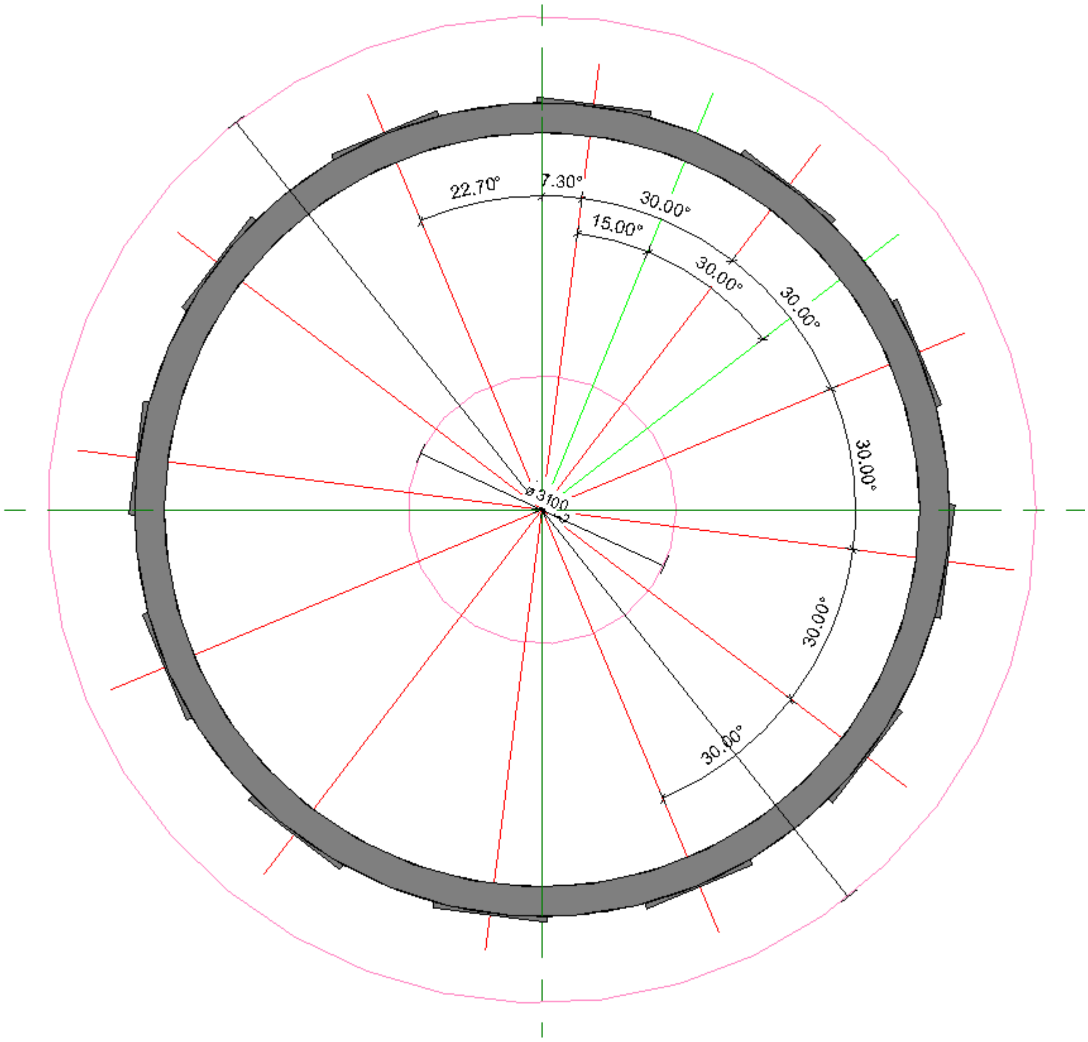


Figure 68 - Top view of the stator frame showing the reference planes.

The next step is creating the cylindrical extrusion that composes the main sides of the frame. The horizontal reference planes that will dictate the sizing of the attachment planes for the coolers are created, as shown in Figure 69. Using these planes as references other extrusions are created to provide the surface for the coolers. Shown in Figure 71.

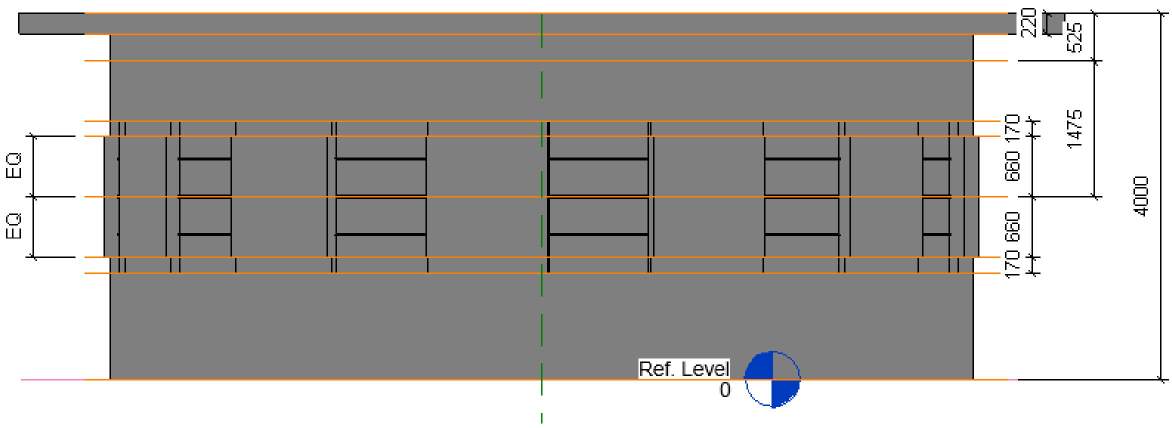


Figure 69 - Front view of the stator frame showing the reference planes for the cooler surfaces.

The extrusions and voids for the cooler surface and railings are added as shown in Figure 70.

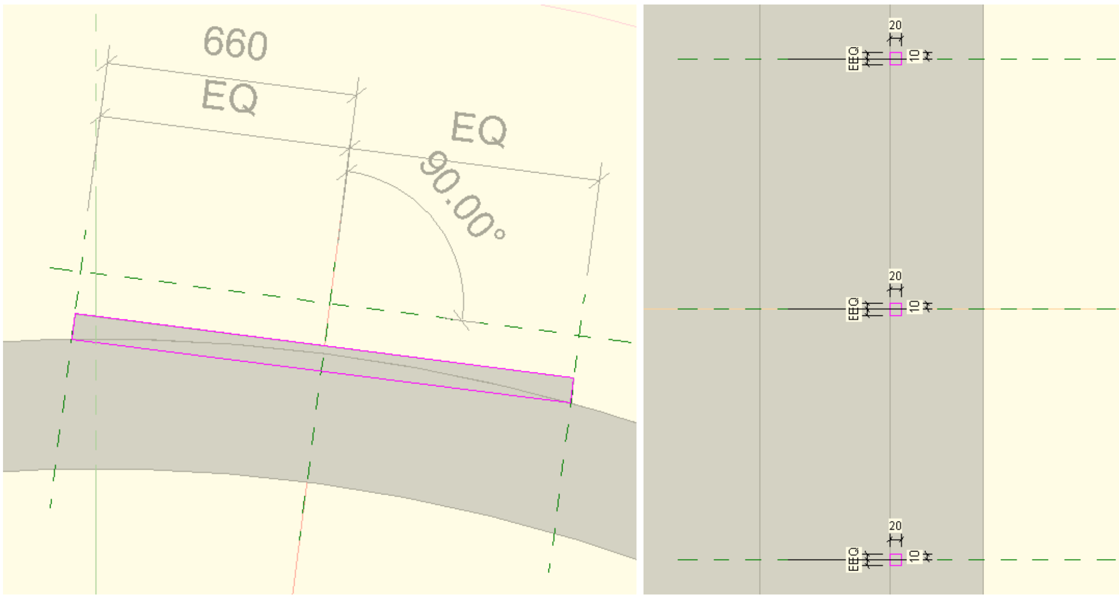


Figure 70 - Details of the cooler installation surface. The yellow tone signifies these resources are part of group of resources.

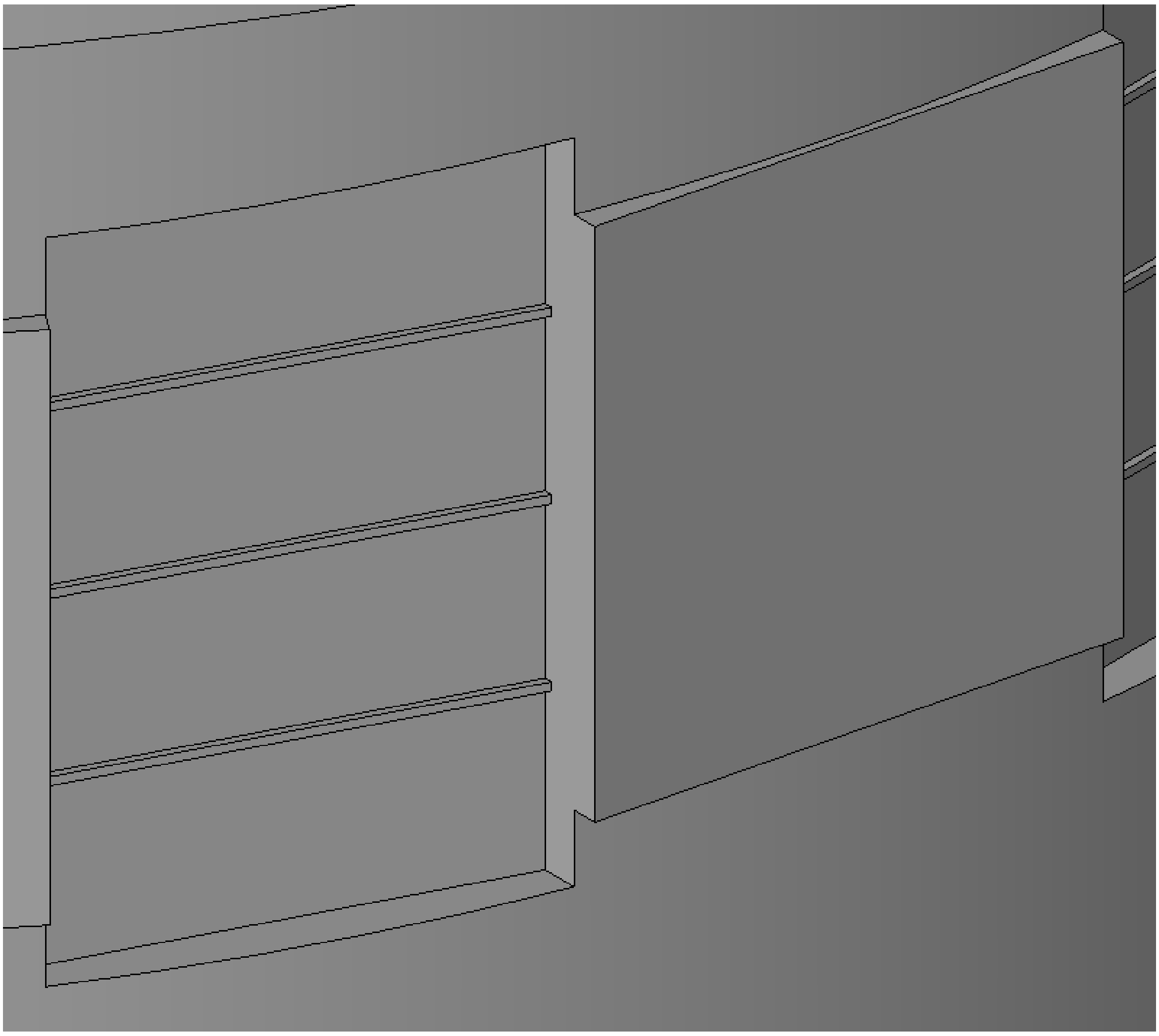


Figure 71 - Details of the finished cooler placement surface on cylindrical faces of the stator frame.

The finished surfaces are copied and rotated along the frame around the equipment creating the surfaces for all the 12 coolers modeled next. Figure 72 shows multiple views of the frame in Revit environment.

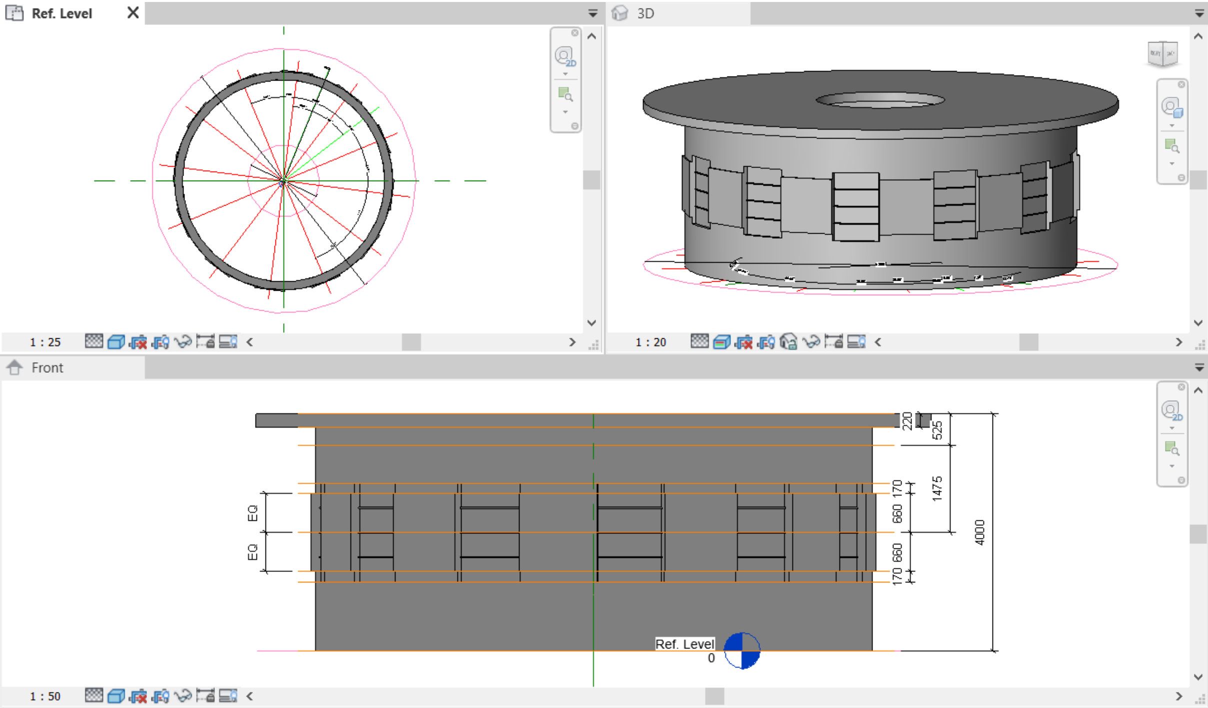


Figure 72 - Stator Frame Revit family.

For the modeling of the coolers, a surface-based family template was chosen and reference planes were created to guide the modeling. A reference plane view in shown in Figure 73.

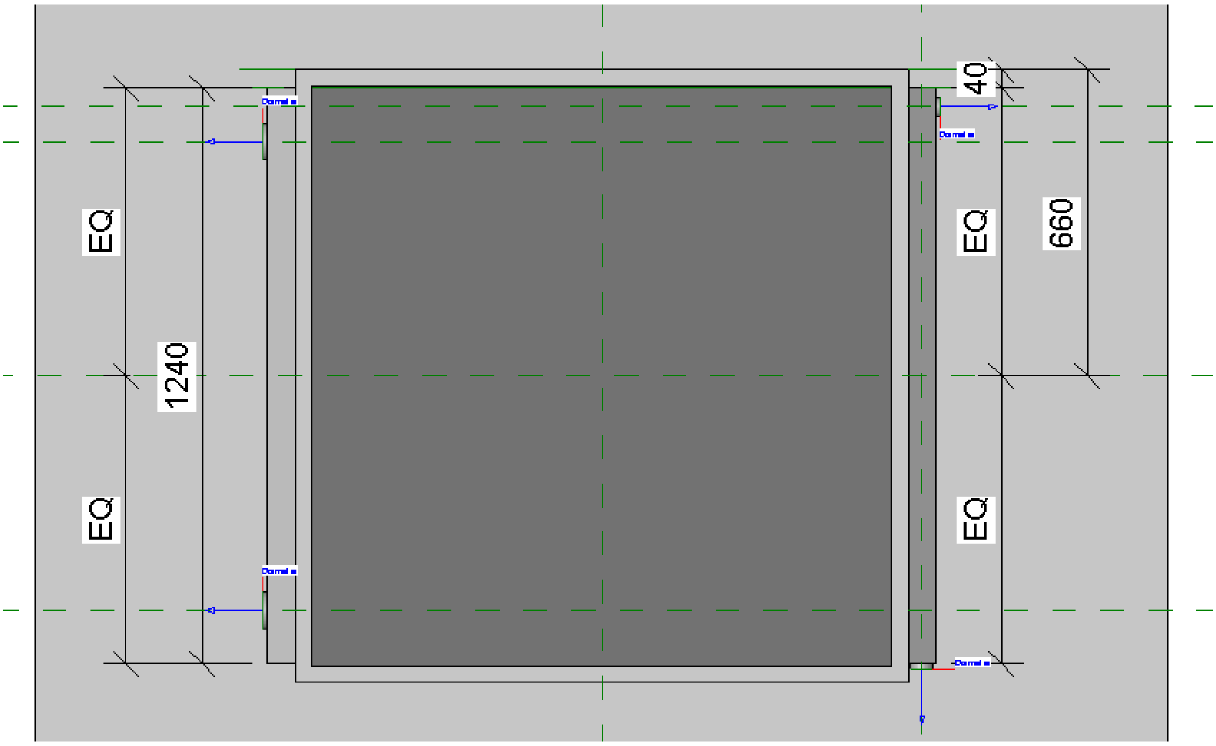


Figure 73 - Reference plane view of the stator cooler.

The basic shape of the cooler was extruded as shown in Figure 74, along with the lateral parallelogram outreaching bumps.

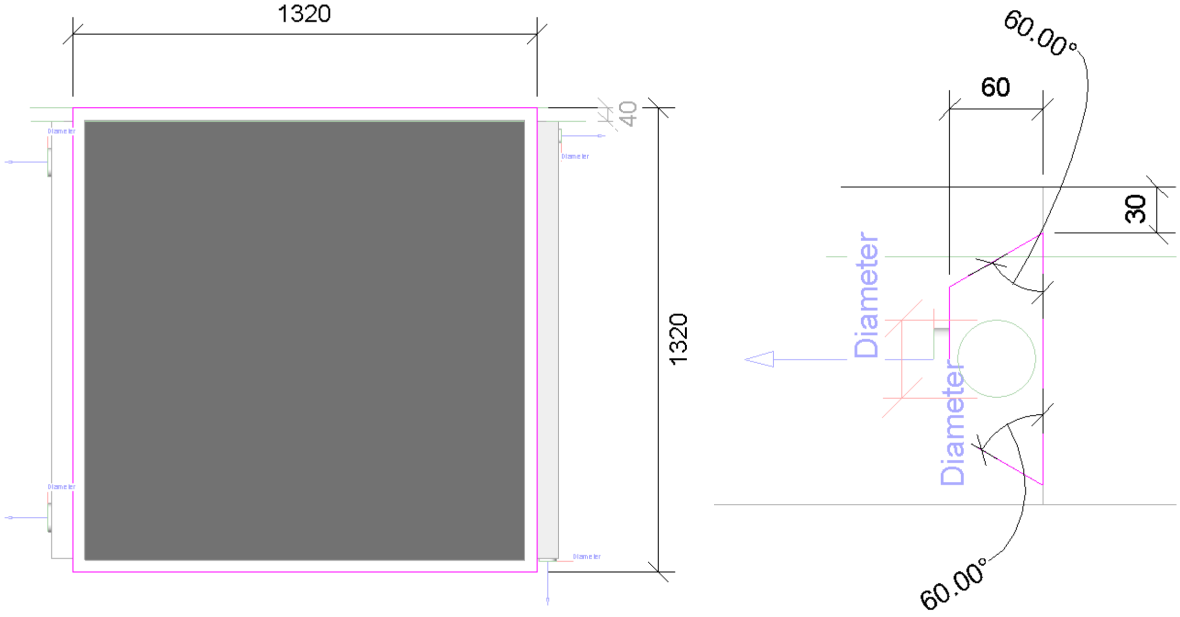


Figure 74 - Main extrusion of the cooler and side parallelogram extrusions.

Extrusions to represent the connection points for the cooling pipes and are created and the pipe connector tool is used to define the connection points at those locations. There are two types of coolers, they are a mirror image of each other in regards of the location of the connection points, so another cooler family is created for the mirrored version of the cooler as shown in Figure 75.

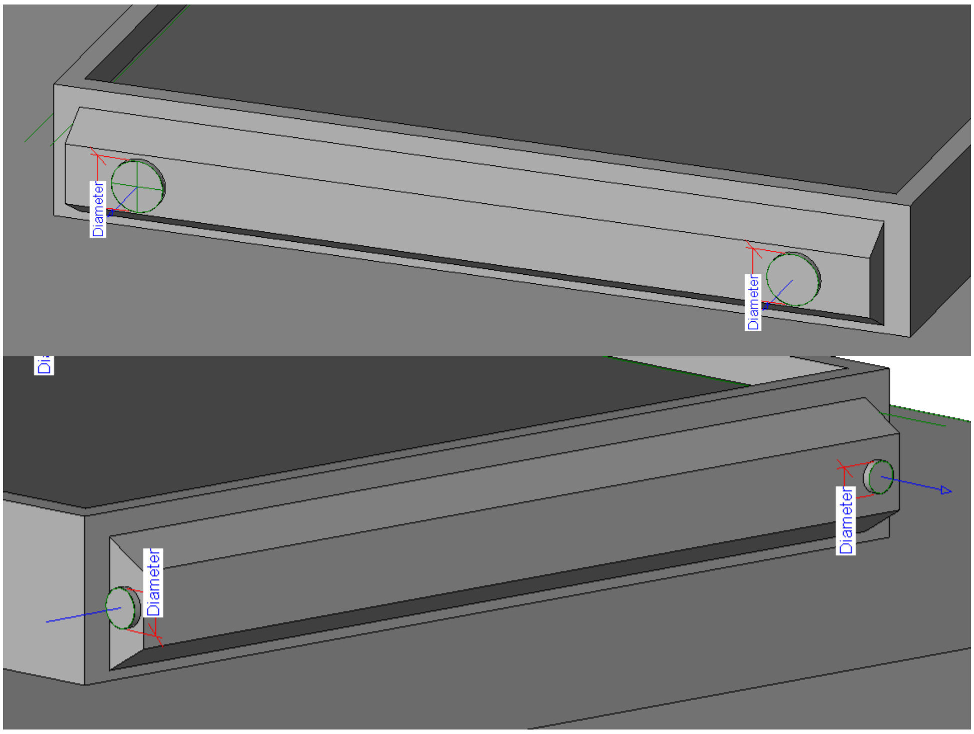


Figure 75 - Locations of the connection points on the coolers. There are two types of coolers, where the locations of these connectors are mirrored vertically.

With the coolers completed the stator frame family is brought into the Formin mechanical model, FORMIN-HSE-ZZ-00-M3-M-Strojne_instalacije_25062020-S0, as presented in Section 3.2, and positioned at the center of the Unit 1 on elevation 196,00 as shown in Figure 76.

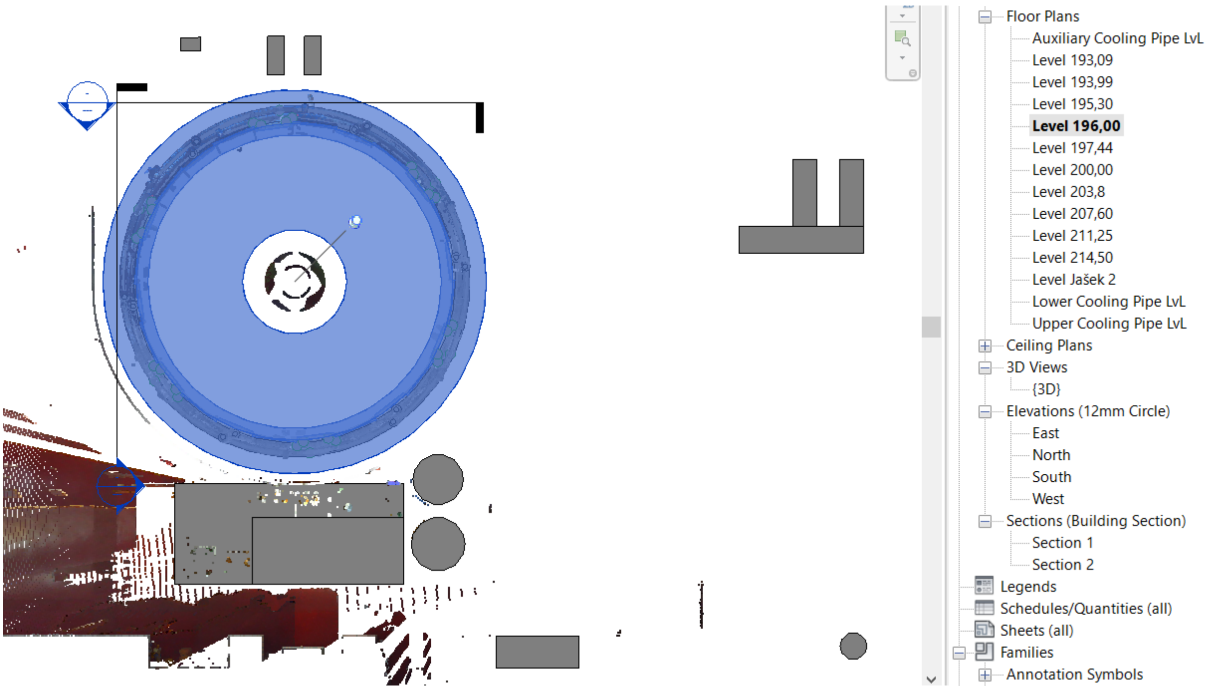


Figure 76 - Elevation 196,00 floor plan showing the stator frame positioned at the center of Unit 1.

Using a section view and the temporarily linked point cloud data model for reference the frame is positioned vertically as shown in Figure 77.

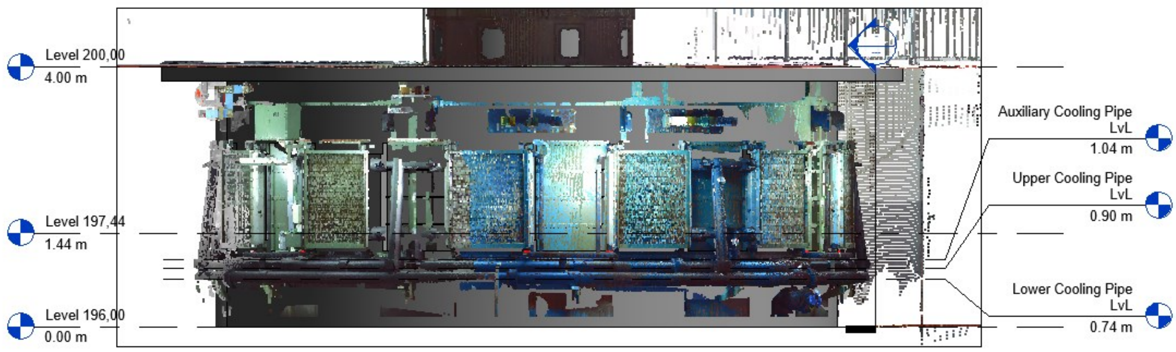


Figure 77 - Section view of elevation 196,00 showing the stator frame overlapping with the point cloud for positioning.

Next, the coolers are imported into the project and positioned on the stator frame surfaces according to the orientation of their connectors as shown in Figure 78, a section box is used to isolate this part of the unit from the rest of the model for cleared view.

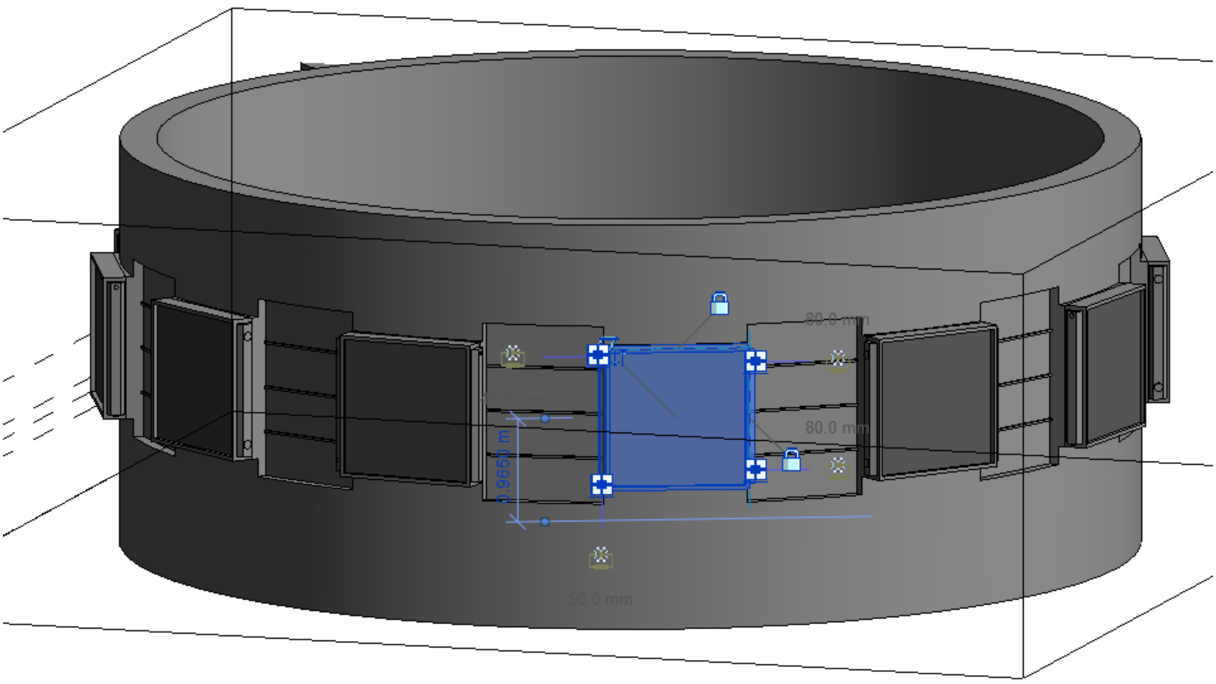


Figure 78 - Assembly of the cooler on the sides of the stator frame.

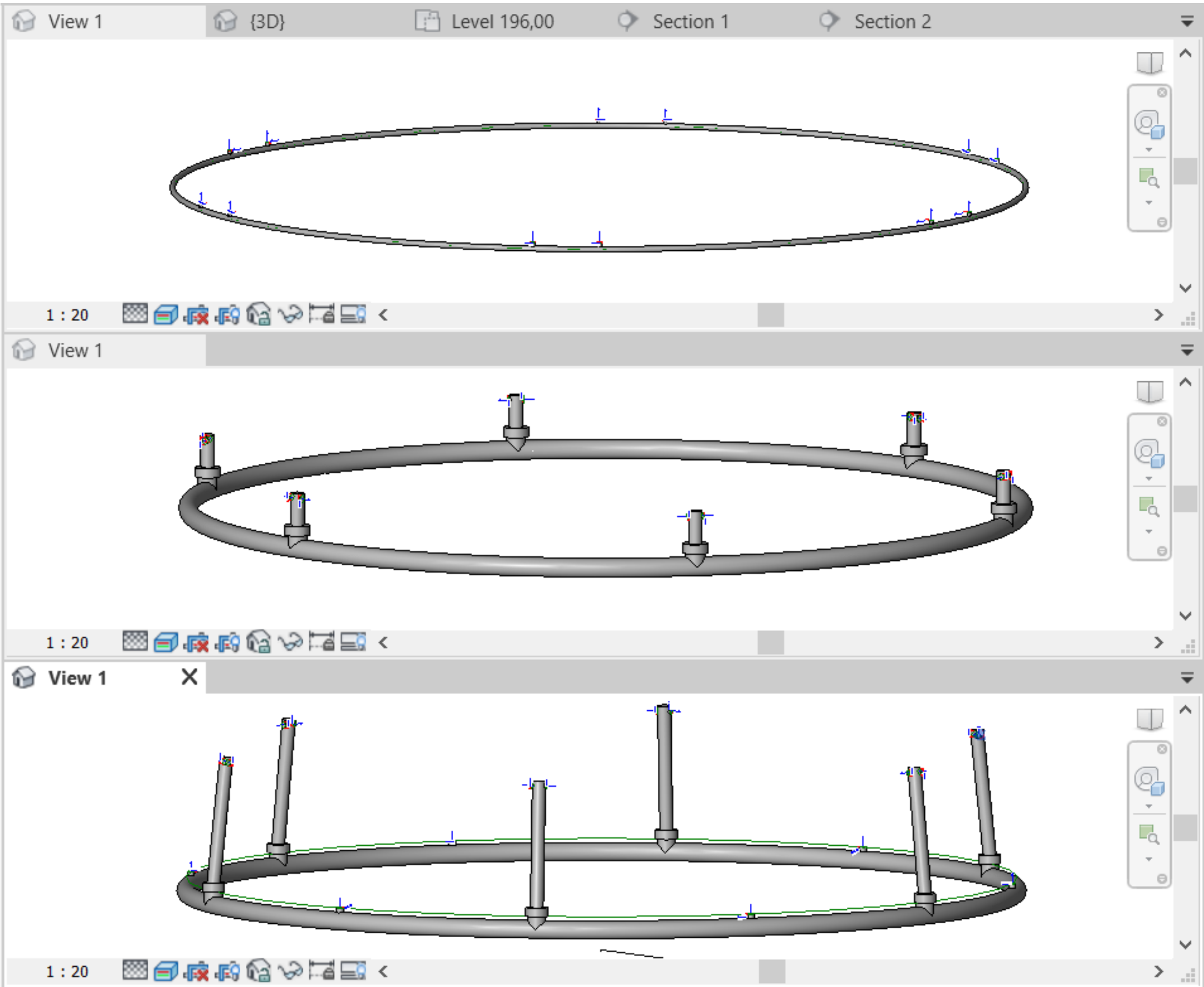


Figure 79 - The 3 circular cooling pipe arrays Revit families.

Next are the pipes that connect the coolers to the coolant supply systems. One limitation that Revit has is regarding curved pipes. Revit uses entities called system families for piping, unfortunately it is impossible to apply the default piping mechanics to curved system pipes, as a result of this limitation instead of using piping tools to model the circular array of pipes on the perimeter of the frame, regular circular family components had to be modelled with added connection points to integrate the cooling piping system.

There are 3 circular arrays of pipes connected to the cooling system. Using the point cloud as a reference for sizing, these pipe arrays were modeled as Revit families. The 3 circular pipes are shown in Figure 79. A detailed view of the connections is shown in Figure 80.

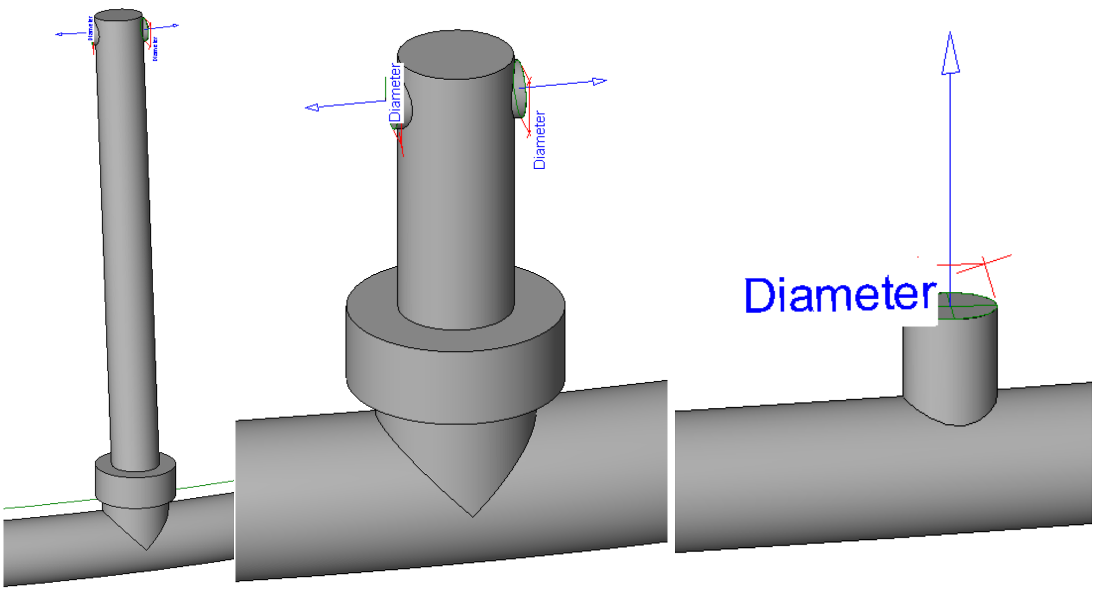


Figure 80 - Details on the circular pipe array connections.

Once again using elevation 196,00 and the section view for reference together with the point cloud the circular pipe arrays are positioned in the mechanical model as shown in Figure 81.

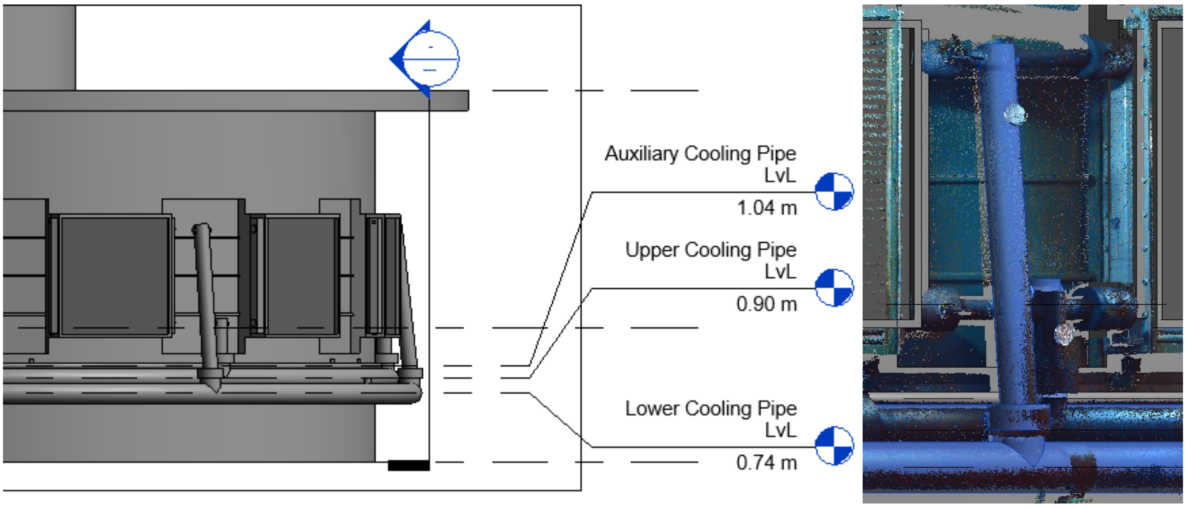


Figure 81 - Positioning of the circular pipe arrays and overlay of the point cloud with the model.

Drawing the piping systems that connect the cooling equipment using MagiCAD “pipe series” tool allow to define the routing options and the fittings for that pipe series as show in Figure 82. On this window it is possible to define the fitting families to be used during the modeling of that pipe series.

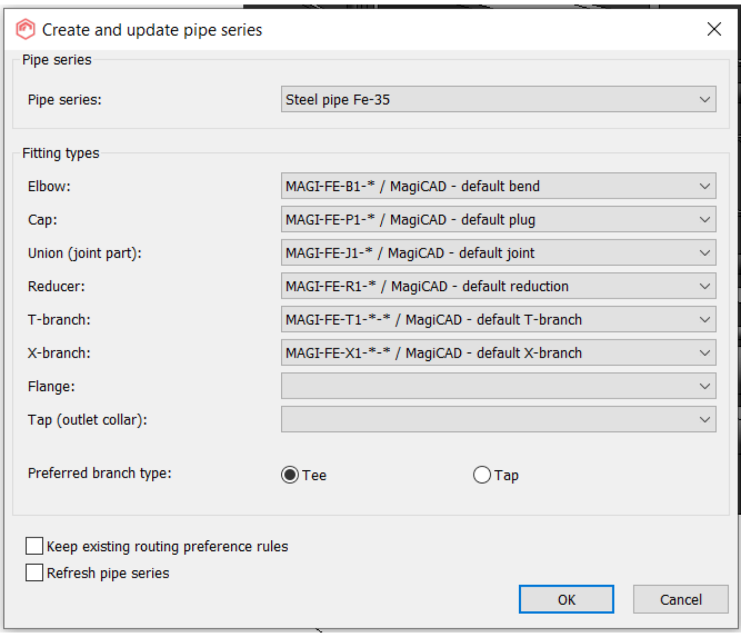


Figure 82 - Pipe series routing configuration menu.

After defining the series and selecting “create pipe” the window shown on Figure 83 appears to allow for the configuration of the pipe to be drawn, on the top left the system type at which the pipe is assigned to can be selected. The starting diameter and insulation options can be set as well as reference options for making the drawing easier.

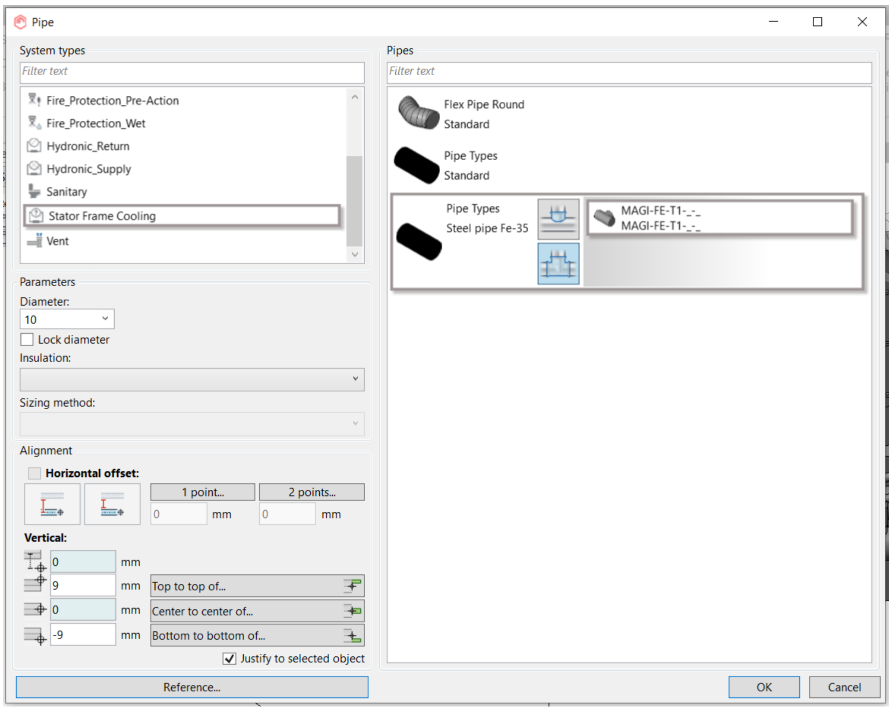


Figure 83 - Pipe drawing properties window.

After that, the pipe drawing assistant window, Figure 84, will show where routing options can be selected during the drawing process. By selecting a starting point on the model and using the options on the tools menu to configure the route the pipes can be drawn.

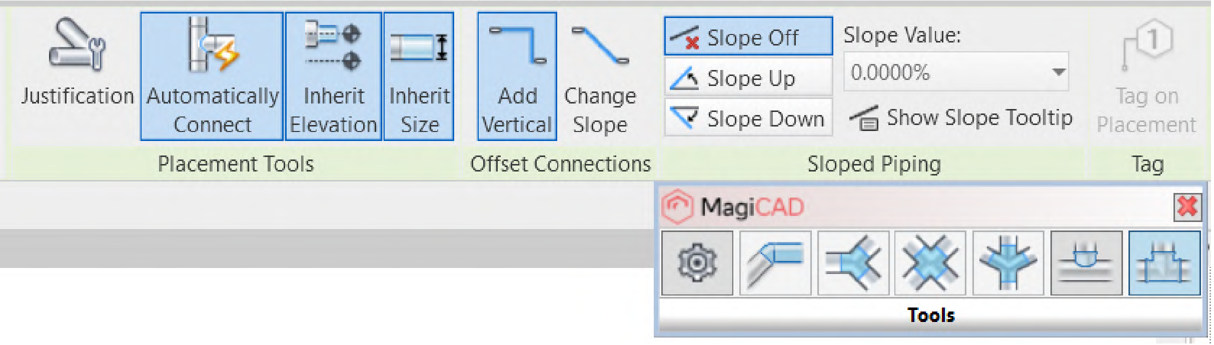


Figure 84 - MagiCAD pipe route drawing options.

Now, from the cooler's connection points to the circular pipe rings connection points the pipes can be drawn as shown in Figure 85.

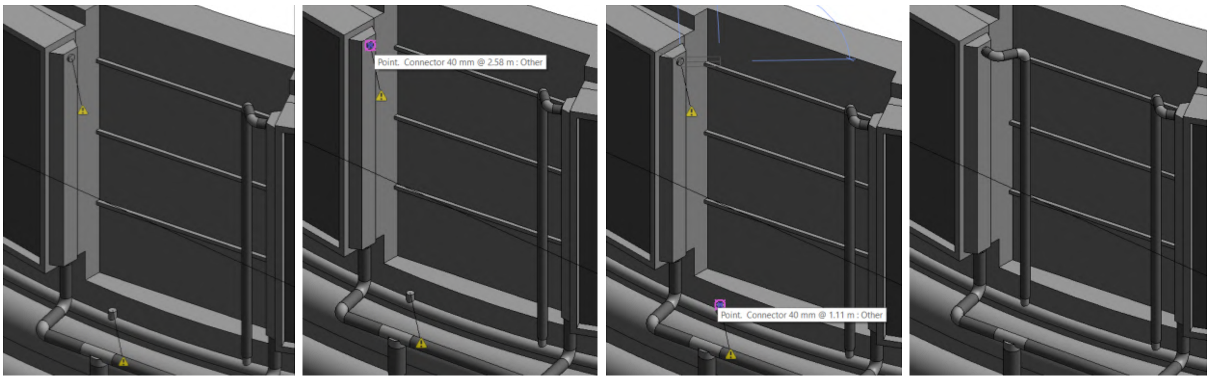


Figure 85 - Drawing a pipe from the cooler connection point to the circular pipe ring connection point using MagiCAD.

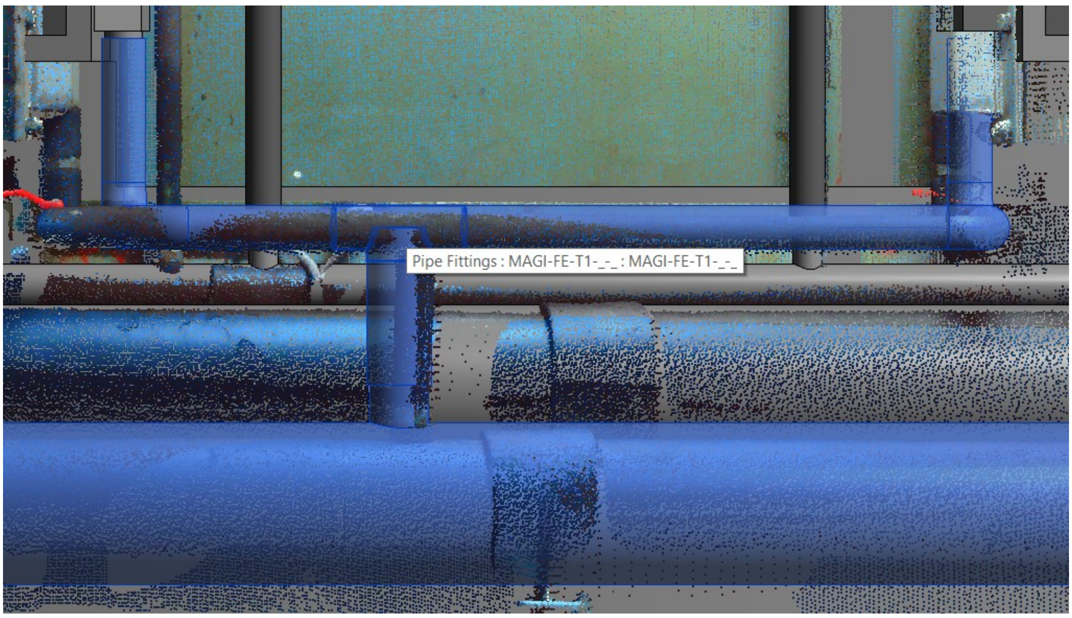


Figure 86 - Overlay of the piping model and the point cloud.

By using the point cloud as reference as shown in Figure 86 the modeling of the piping systems is done using the Revit and MagiCAD functionalities. One useful functionality is the MagiCAD "standard connection" option, it allowed to quickly connect the cooler to the input pipe ring by creating a routing solutions as shown in Figure 87.

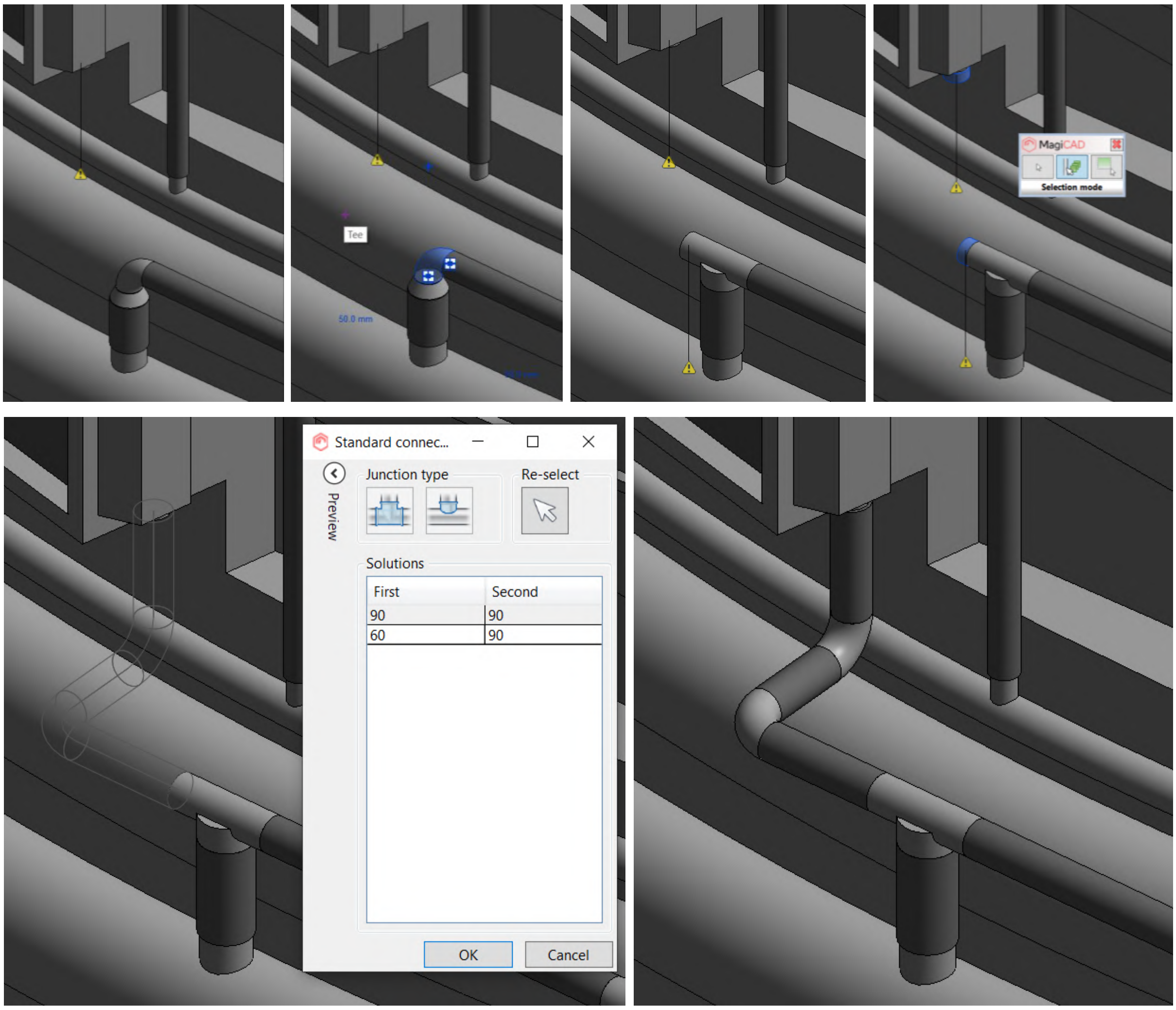


Figure 87 - MagiCAD standard connection feature allows for automatic routing solutions.

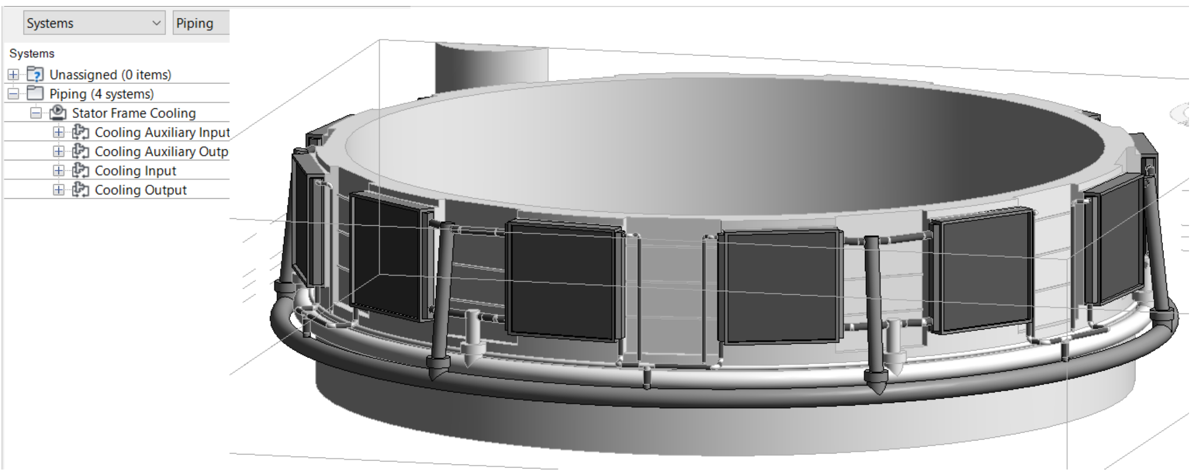


Figure 88 - The current system gets highlighted when editing.

After modeling the pipes, the installed equipment needs to be assigned to the correct systems. The system editing tool allows for the selection of unassigned components to a system, which then are highlighted in view as shown in Figure 88. MagiCAD has a tool that allows the swapping of model components to other systems as shown in Figure 89. For this model 4 systems were created, and the components assigned accordingly.

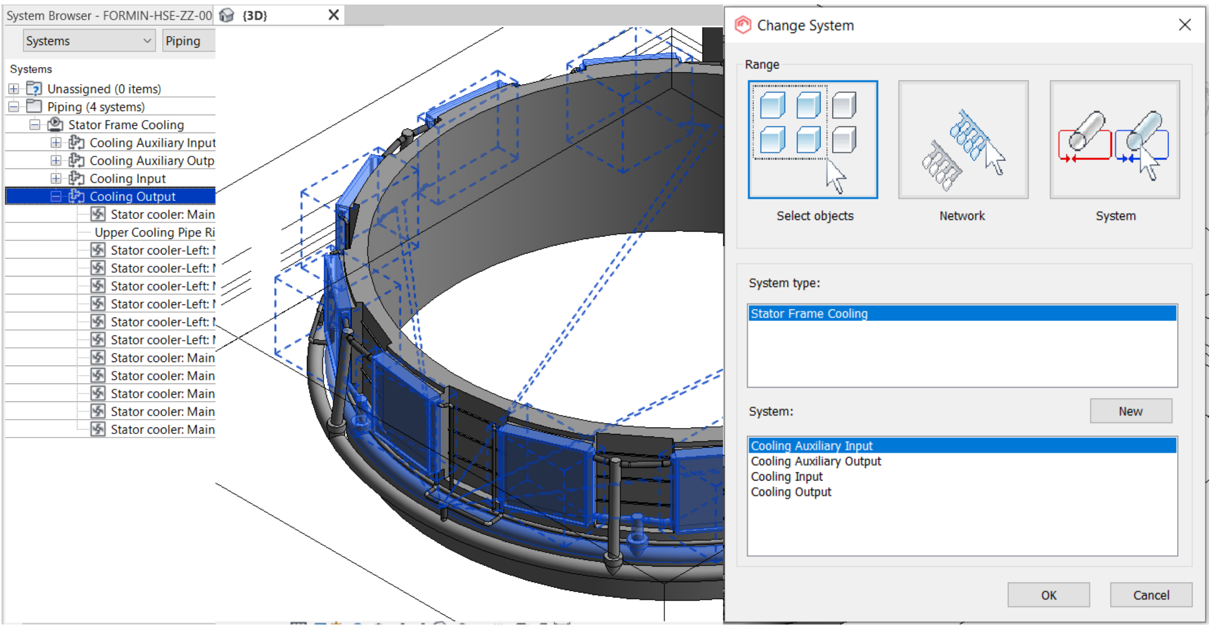


Figure 89 - Systems browser window showing the 4 different systems on the model. The highlighted system is the cooling output.

For adding auxiliary components to the pipe system, like valves, MagiCAD Connect plugin, shown in Figure 90, can be used to search components on MagiCAD cloud library. It is possible to filter the results according to the characteristics of the element needed.

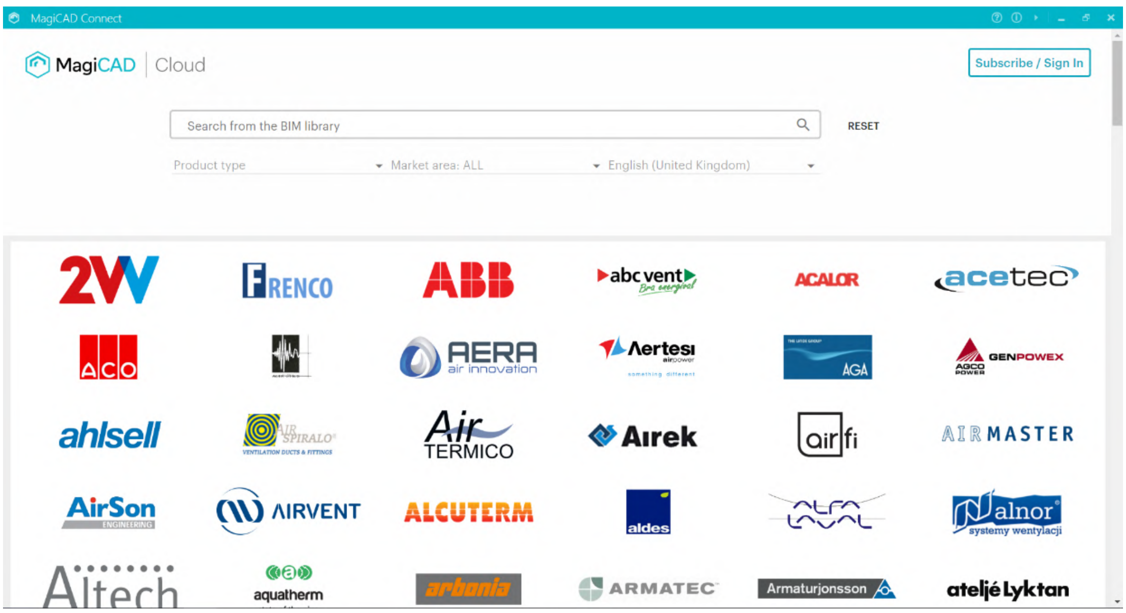


Figure 90 - MagiCAD connect interface. Allows for the filtering of ready to use model components according to multiple parameters.

For example, a stop valve is needed to be installed on the cooler pipes, by using the filters shown in Figure 91, it is possible to select manufactured components fully compatible with MagiCAD functionalities to use on the model. After selecting the desired product, the Revit family can be imported into the MagiCAD dataset.

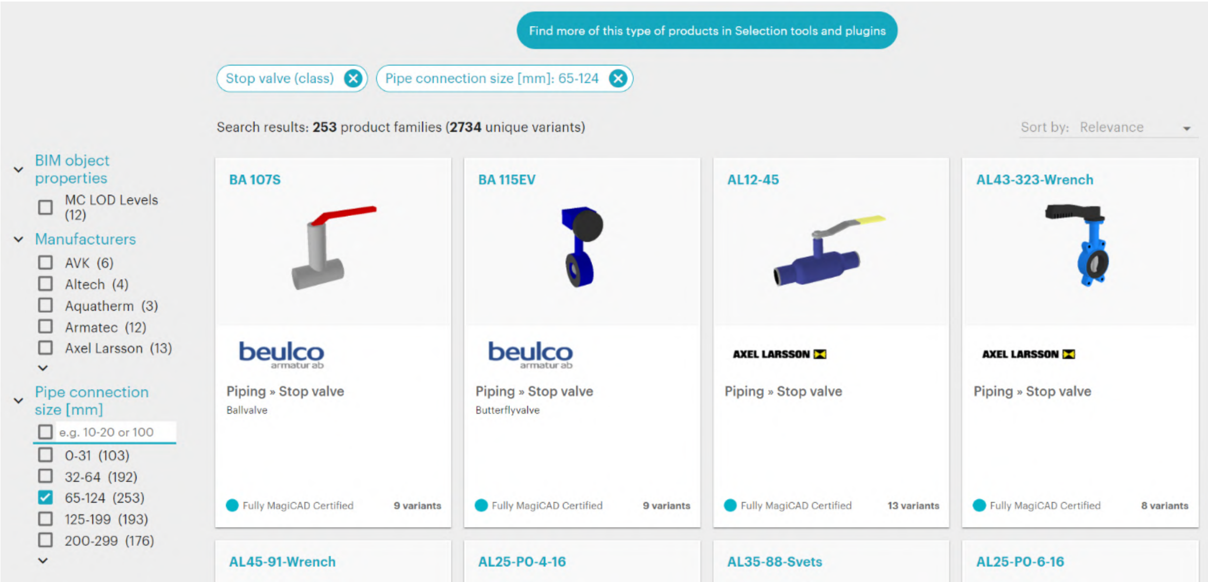


Figure 91 - Results available in the library for a stop valve of the selected size.

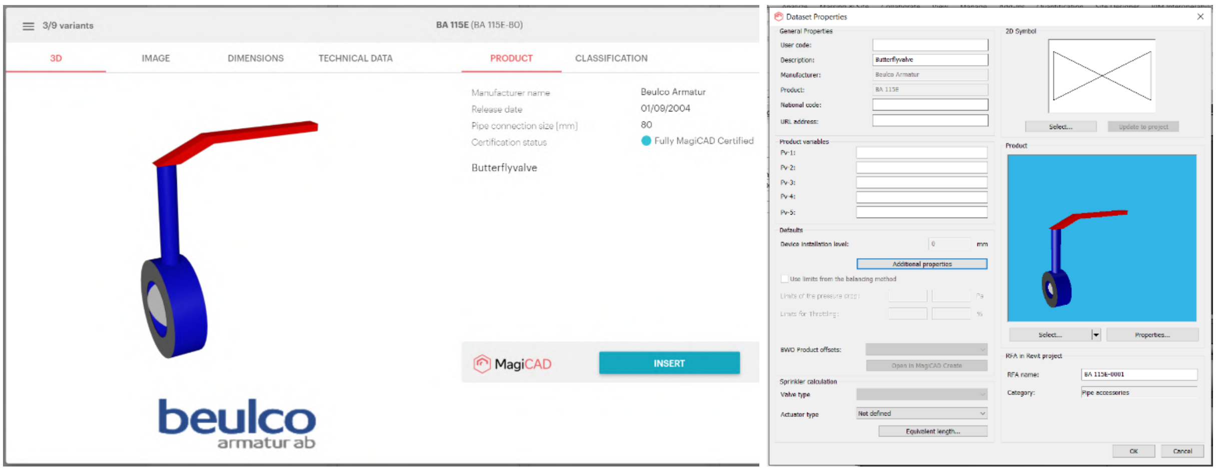


Figure 92 - Selected stop valve window in MagiCAD cloud and configuration settings in Revit.

An object properties window, Figure 92, will appear after selecting "insert product", there, additional information about the element can be specified. After that the product selection window, Figure 93, will open allowing for the selection of the inserted component to be placed into the model. Size selection and performance information are displayed. After selecting the size, the component con be inserted into the model using MagiCAD assistant tooltip as shown in Figure 94. The valve can then be rotated using the Revit option to orient it correctly as shown in Figure 95.

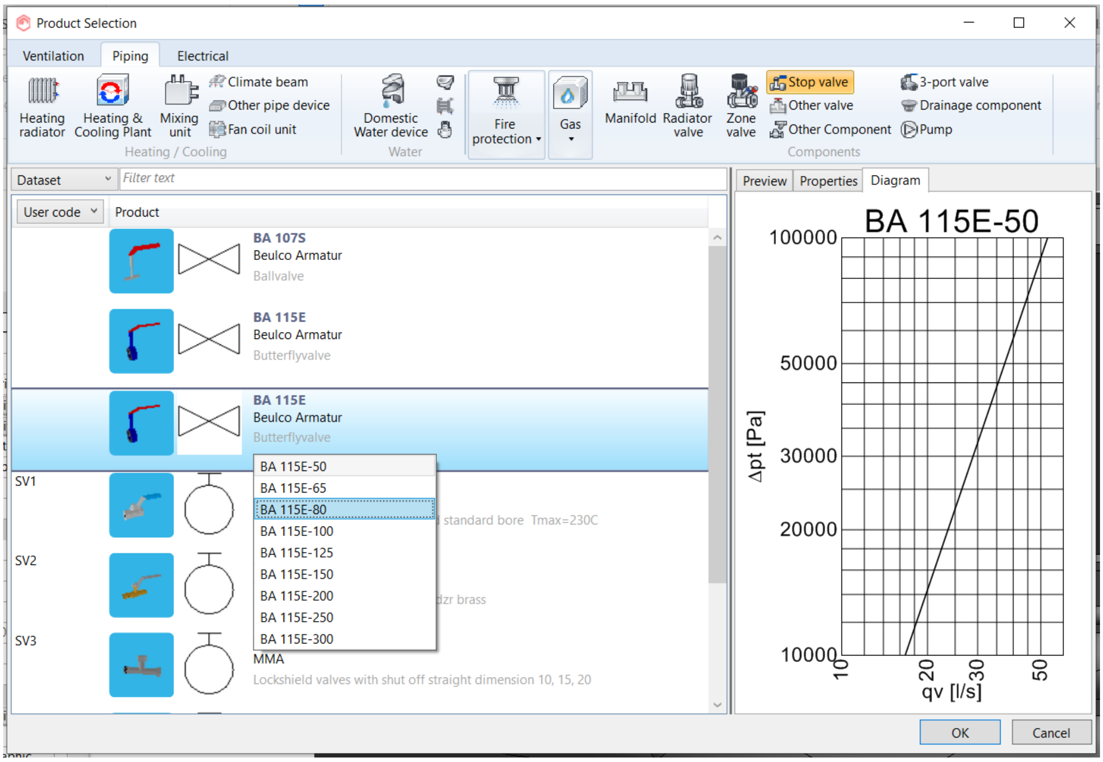


Figure 93 - Inserted valve in the product selection window.

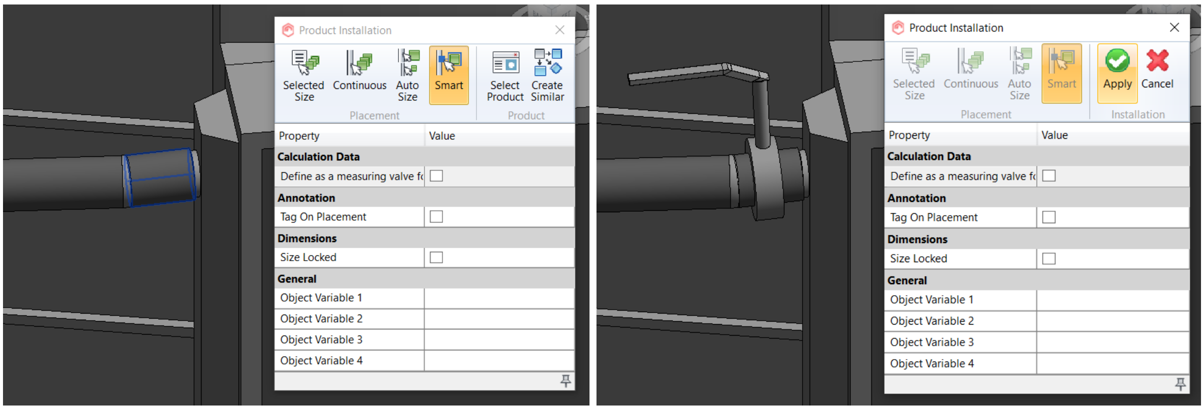


Figure 94 - Inserting a stop valve using MagiCAD.

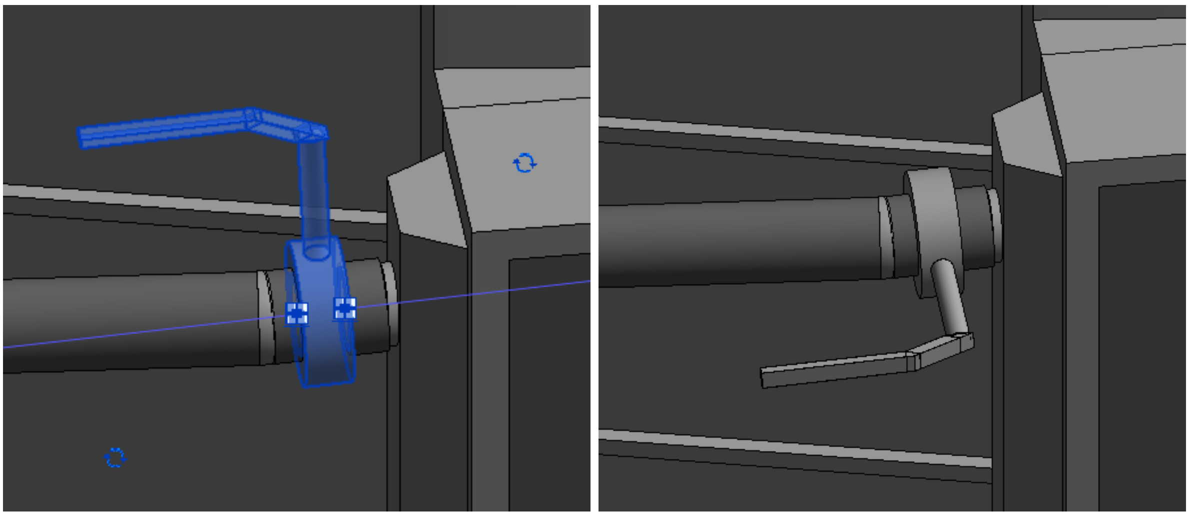


Figure 95 - Rotating the valve to the correct position.

The result is the model of the stator frame and its cooling systems for Formin HPP, shown in Figure 96.

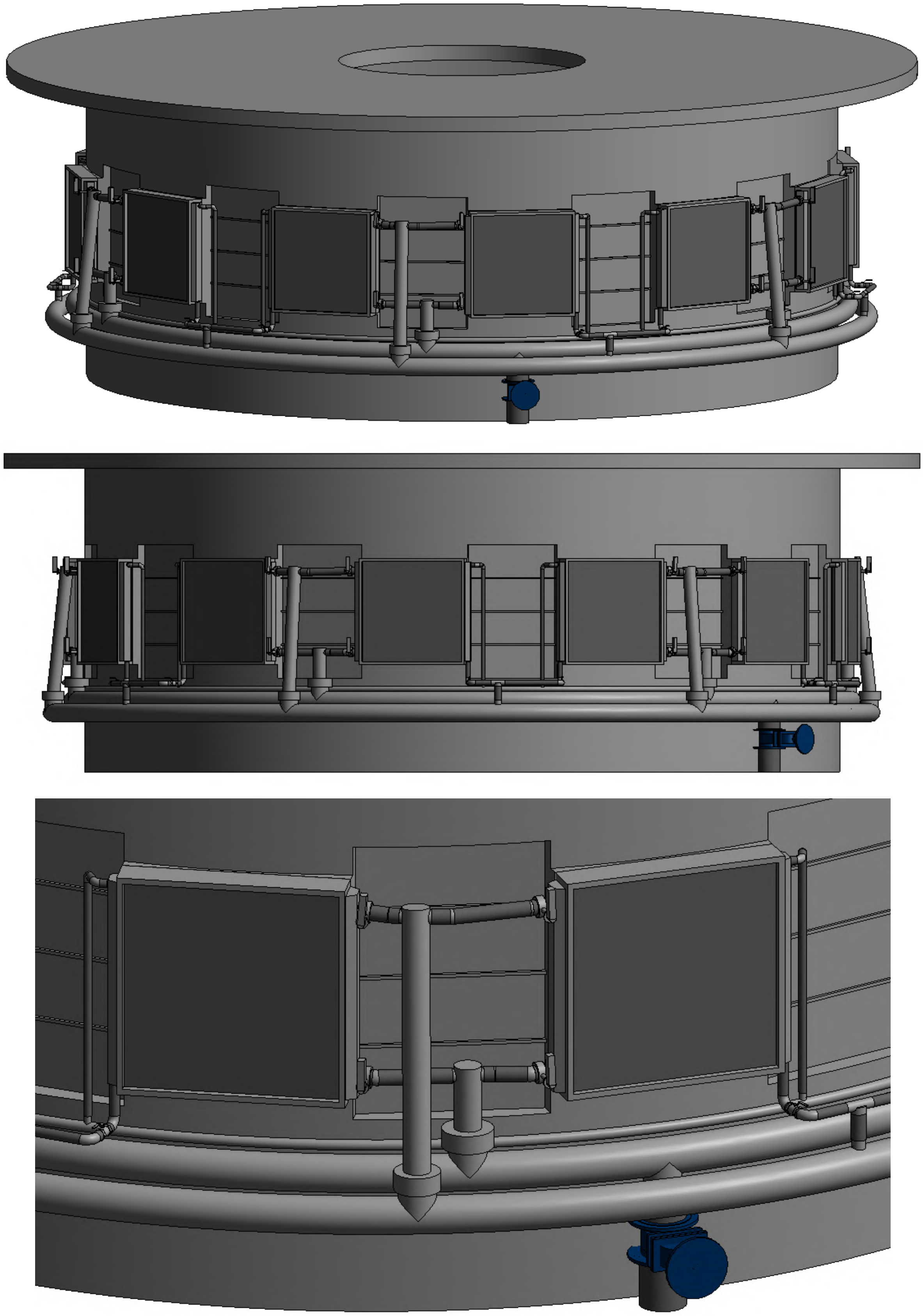


Figure 96 - Finished model of the stator frame for Formin HPP unit 1.

The stator frame and it's systems are shown in context on Figure 97 and Figure 98.

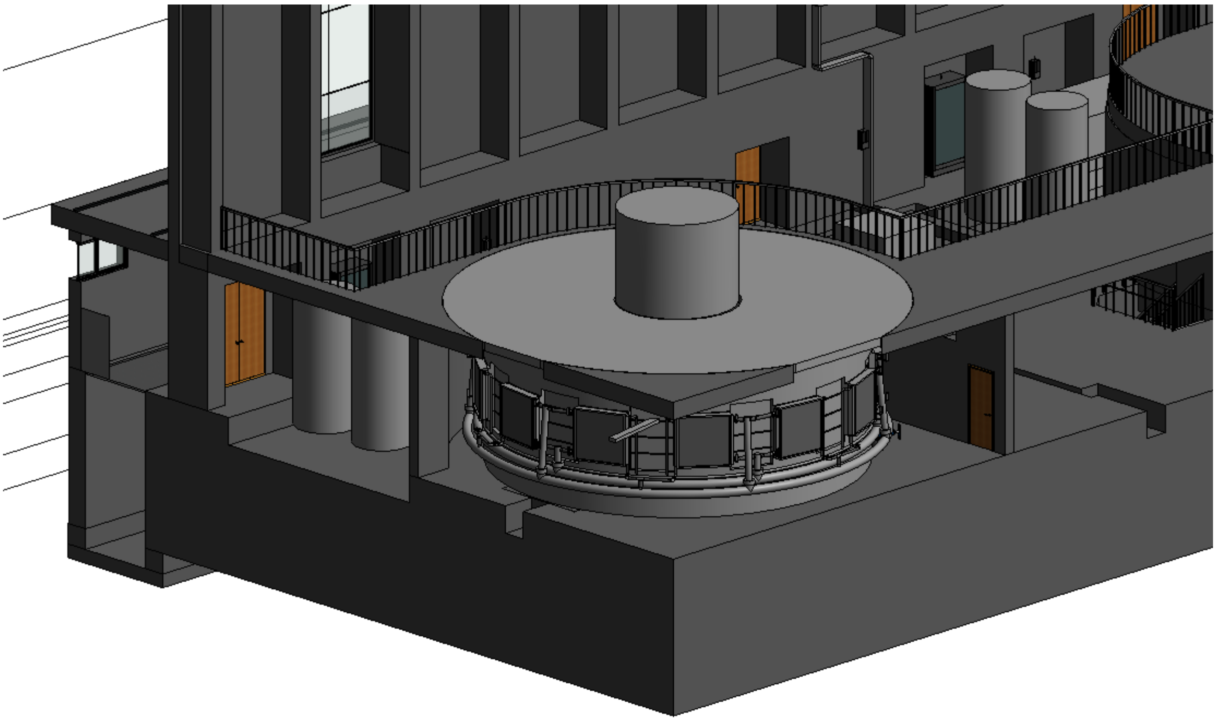


Figure 97 - Stator frame of Unit 1 in the context of the coordination model.

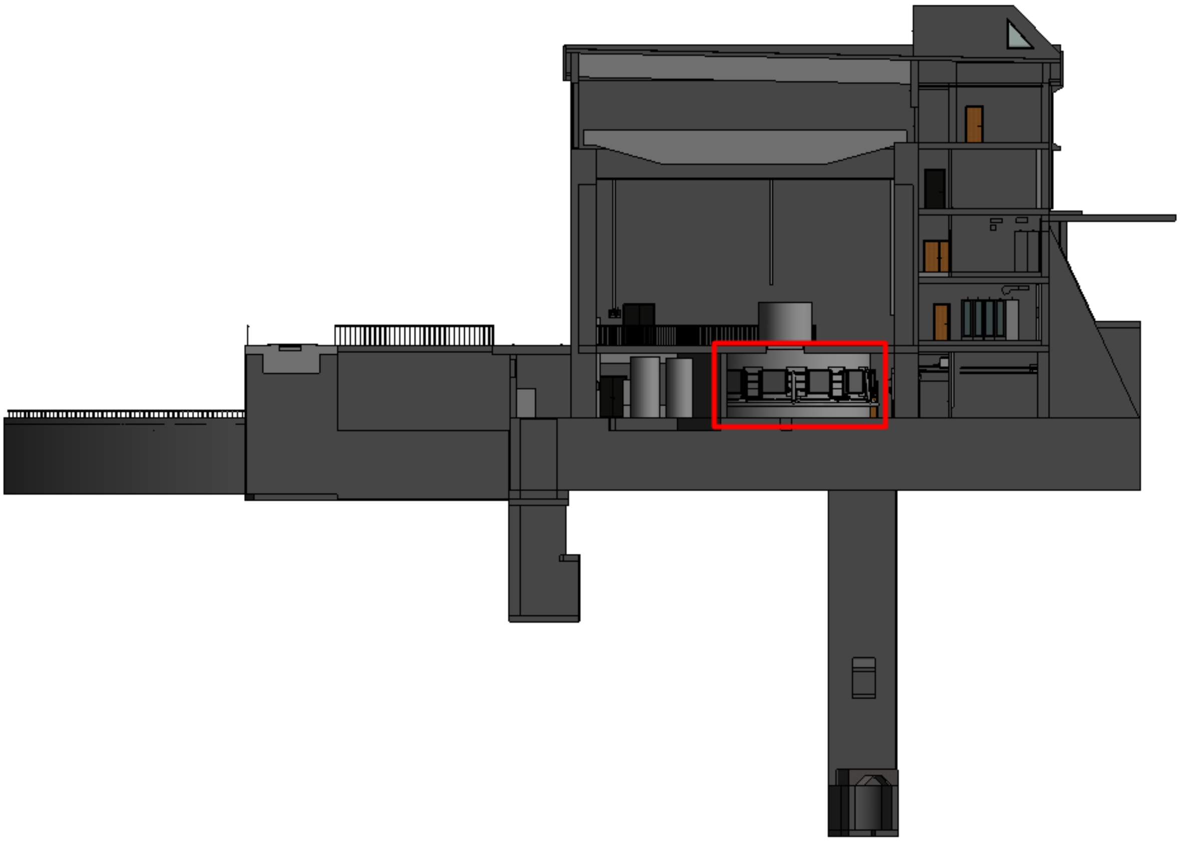


Figure 98 - Section view of Formin HPP model showing the modeled stator frame.

6 CONCLUSION

Pushed by the increase in electrical energy demand, the need for refurbishing HPPs was taken as the reasoning and starting point for the development of this thesis. Exposing the benefits the presented BIM solutions have to offer when applied to HPP refurbishment projects and having these benefits illustrated by the case study of Formin HPP is the main contribution this work aims to provide to future applications and further studies regarding BIM applied to industrial projects.

Working in a practical scenario of BIM usage, with the Formin HPP refurbishment project case study, allowed this thesis to document very relevant data and information. The knowledge acquired at Formin HPP about the facility, the refurbishment project and the high quality provided point cloud data was instrumental to developing the proposed BIM solutions as they could be shown applied in a more tangible and practical manner into that project.

By discussing with the representatives responsible for Formin HPP and by inspecting the provided data and models, the project goals, as well as the challenges to be faced, were assessed and made clear. Proposing and detailing the proposal of BIM usage into the project has the objective of helping Formin HPP refurbishment project to better achieve its goals. To achieve these goals, the challenges had to be defined and overcome through the application of specific tools for each challenge.

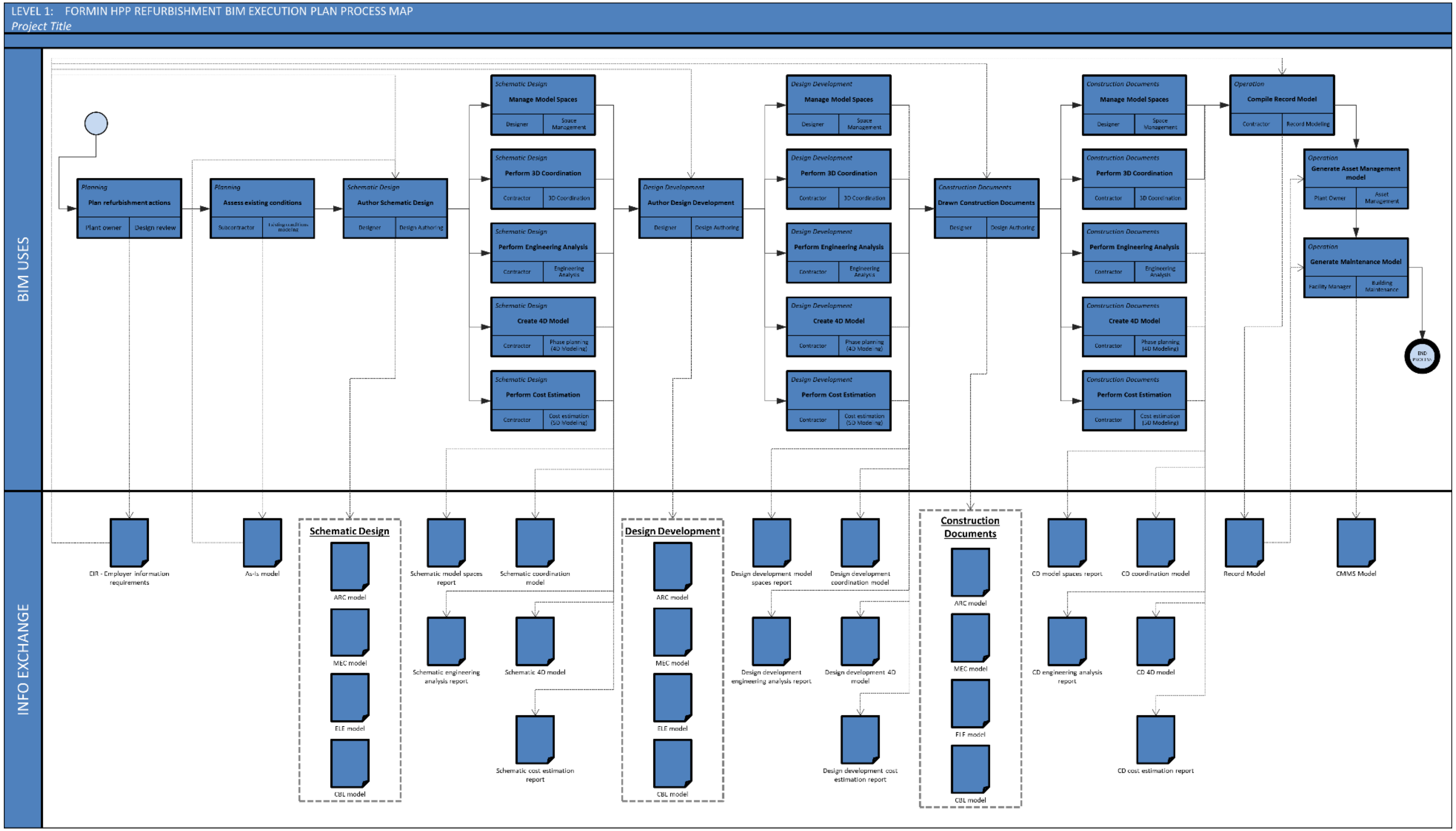
One of the challenges and one of the main focus of this thesis was on requirement specification. It was shown how the requirements can be set, using the industries best practices and guidelines, and how, by using BIM software, these requirements can be managed and integrated into the project and its models. Another challenge explored by this work was managing MEP design authoring and modeling tools, complete with library management solutions and automated routing tools to make the modeling of these disciplines more efficient and better integrated with model management.

Using the stator frame of Formin HPP unit 1 as a prototype case study for the application of the explained solutions allowed for a better understating of the tools used. How the tools integrate into the project workflow and how they interoperate with the other used modeling, management and coordination software.

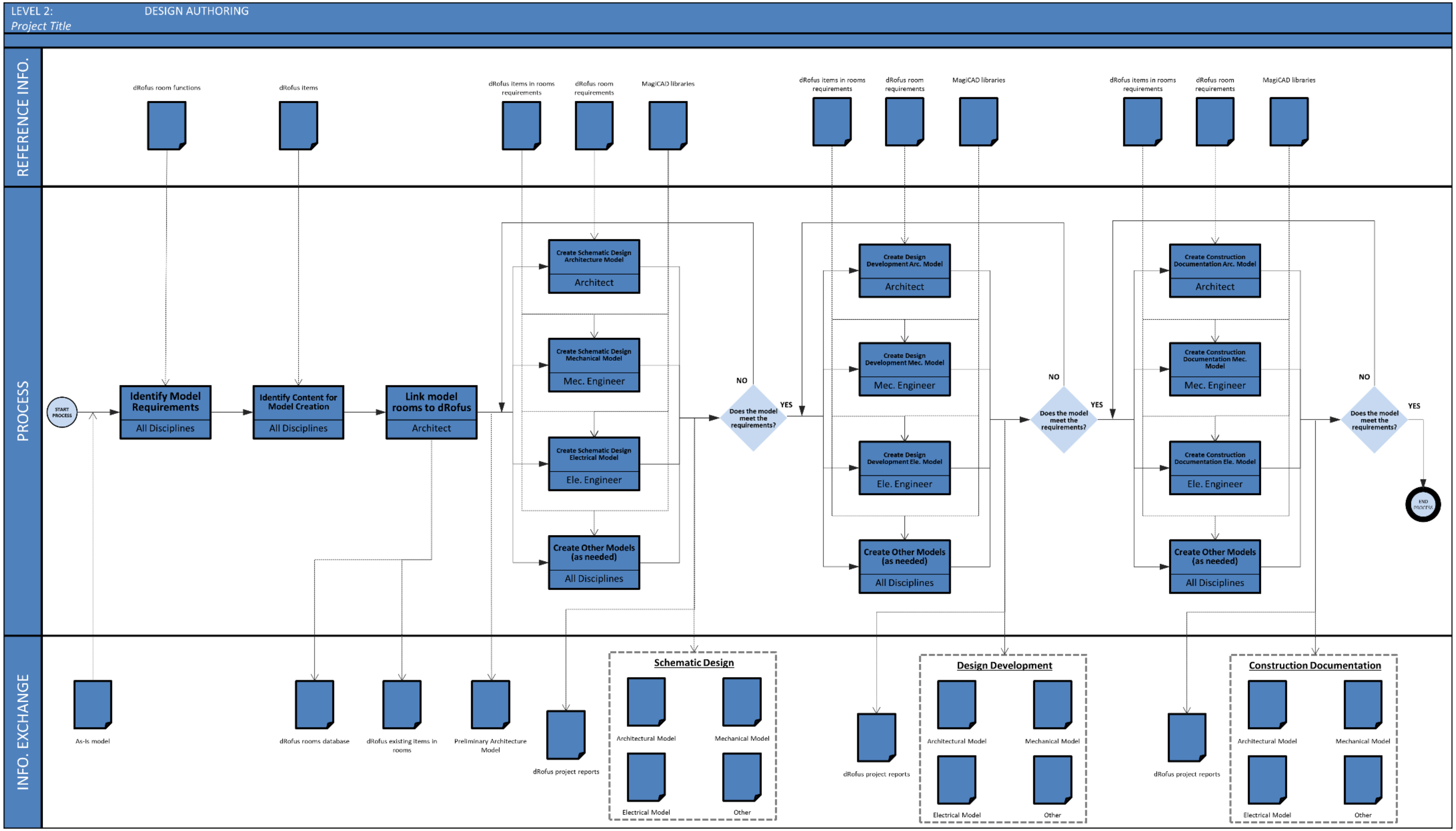
The defining perception is that the refurbishment of HPPs are projects of very complex nature, therefore having the potential for applying a number of varied BIM solutions in order to improve the project's efficiency. There are many more aspects to HPP refurbishment that this paper does not address in detail and that have large potential for further studies into the applicability of BIM for this kind of industrial applications. For example: Existing assets management, disassembly and reassembly control, 5D simulation and operation & maintenance are all challenges that can benefit from the application of BIM solutions and that can be explored further by future studies.

7 APPENDIX

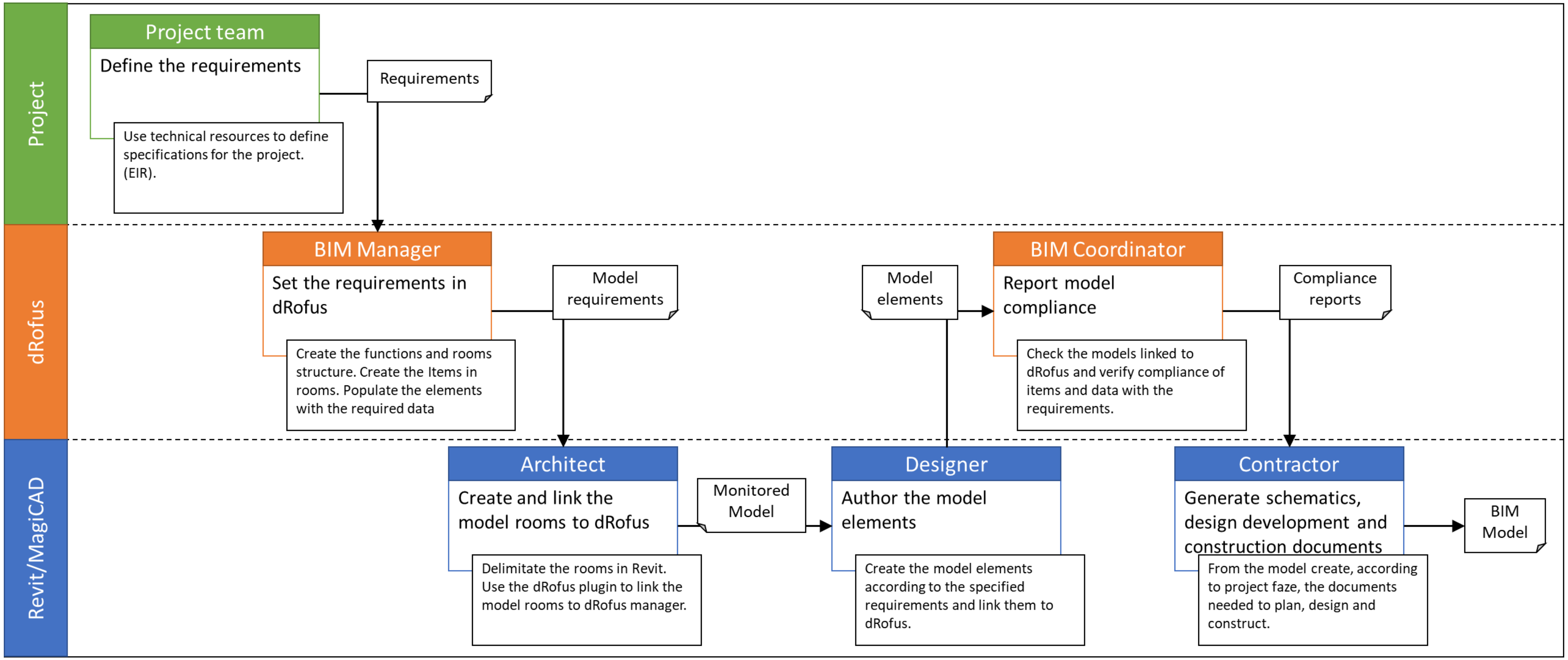
7.1 Formin HPP refurbishment overall BEP process map



7.2 Design Authoring BIM use process map for Formin HPP refurbishment project



7.3 Proposed workflow for BIM model authoring for Formin HPP refurbishment project



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