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ANDRAŽ STARC

BUSINESS PROCESS RE-ENGINEERING USING BIM TOOLS AND APIs

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BUSINESS PROCESS RE-ENGINEERING USING BIM TOOLS AND APIs

REINŽENIRING POSLOVNIH PROCESOV Z UPORABO ORODIJ BIM IN APLIKACIJSKIH VMESNIKOV

BIM A+ European Master in Building Information Modelling

Master thesis No.:

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Izvleček:

Digitalizacija je že veliko let rastoč trend v gradbeni industriji. Kljub temu, da je gradbeništvo počasno pri implementaciji novih procesov in tehnoloških inovacij, se v zadnjem času pospešeno digitalizira in informacijsko modeliranje zgradb se šteje za gonilo digitalizacije. Z uvajanjem digitalizacije in novih tehnologij morajo projektivna podjetja izvesti reinženiring svojih poslovnih procesov.

To magistrsko delo se posveča reinženiringu izdelave projektantskega popisa del. Tradicionalni način izdelave popisov želimo digitalizirati z uporabo BIM. Predstavljen reinženiring poslovnega procesa je izveden z upoštevanjem priporočil, smernic in metodologij strokovnjakov s tega področja. Obstoječi proces je najprej zajet, modeliran in analiziran. Tri alternativne rešitve so predlagane in ovrednotene. Izbrana rešitev predlaga implementacijo novega, specializiranega programskega orodja, standardizirane vhodne podatke, izhodne podatke in delovne procese, kontrolirano besedišče in razvoj rešitev po meri z uporabo aplikacijskega vmesnika programskega orodja Revit za reševanje specifičnih izzivov.

Nov proces je definiran, modeliran in implementiran skozi razvoj številnih rešitev, nato pa je uspešno uporabljen na primeru, ki dokazuje, da posodobljeni proces izpolnjuje vse kriterije, kritične za uspeh. Celotni proces poteka znotraj enega, digitalnega okolja. Število popisnih postavk, ki izhaja iz modela, se v primerjavi z obstoječim procesom poveča iz približno 20% na približno 70%. Kljub temu, da ostaja še veliko možnosti za kontinuiran napredek, analiza uporabe novega procesa na konkretnem primeru nakazuje višjo zanesljivost, efektivnost, boljši nadzor nad izvajanjem procesa in boljše možnosti za vodenje sprememb.

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BIBLIOGRAPHIC – DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

Digitalization has been a growing trend in the construction industry for many years. Even though the construction industry has been slow to adopt new processes and technology innovations, digitalization is now accelerating and building information modelling is regarded as its backbone. To adopt new technologies and digitalization, engineering and consulting companies have to re-engineer their business processes.

This work focuses on the re-engineering of the quantity takeoff process. The goal is to digitalize the traditional quantity takeoff process using BIM. The presented business process re-engineering is done adopting existing guidelines, recommendations and methodologies from the experts in the field. First, the existing AS-IS process is captured, modelled and analyzed. Three alternative solutions are proposed and evaluated. The chosen solution for the re-engineered BIM-based quantity takeoff process proposes implementing a new, specialized application software, standardization of process inputs, outputs and workflows, controlled vocabulary and development of custom solutions using Revit API to address specific challenges.

The TO-BE process is defined, modelled and implemented through a variety of developments. The re-engineered process is successfully applied to a case study of an existing project following the defined TO-BE process model, accommodating all critical success factors. The whole process was executed in a single, digital environment. The number of model-based items in the bill of quantities increased from approximately 20% in the existing process to approximately 70% in the re-engineered process. While there is still room for continuous process improvement, the analysis of the case study suggests that the re-engineered process is much more reliable, time-efficient, better in managing changes, and the overall process control is improved.

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LIST OF ABBREVIATIONS

BIM	Building Information Modelling
BOQ	Bill of Quantities
BPR	Business Process Re-engineering
CPR	Continuous Process Improvement
CSF	Critical Success Factor
ICOM	Inputs, Controls, Outputs and Mechanisms
IDEF	Integrated Definition Methods
KPI	Key Performance Indicator
R&D	Research and Development
SADT	Structured Analysis and Design Technique
TQM	Total Quality Management
QTO	Quantity Takeoff

1 INTRODUCTION

Digitalization has been a growing trend in the construction industry for many years. However, even though the industry was facing a productivity decline, the construction sector has been slow to adopt the process and technology innovations [1]. Nowadays, the digital push and speed of digitalization are accelerating, even if the construction industry players are still hesitant about the change and new technologies. The pressure for change is coming from several complementary directions – from evolving client expectations, new technological capabilities, the new generation of professionals with high technology-related skills, to supportive legal frameworks and a number of governments, including Great Britain, Finland and Singapore, mandating the use of BIM for public procurement projects [2]. Building information modelling (BIM), defined as a set of interacting policies, processes and technologies for a digital representation of built environment [3], is regarded as the backbone of the new way of working. It is triggered and targeted by the digital strategy given that different elements (application software, building and infrastructure equipment and others) should ultimately be connected to it. BIM adoption is expected to trigger significant improvement along the whole construction value chain [2].

The architectural and engineering design companies were among the first in the construction industry to implement BIM technologies and digitalize their business processes. Of course, the organizations are at different stages of BIM adoption and different levels of BIM maturity. The BIM models can be used for a wide range of model uses. One of them is BIM-based quantity takeoff (and later cost estimation, tendering, and others), and it replaces the traditional, manual and paper-based quantity takeoff. However, the adoption BIM-based quantity takeoff process is still fragmented, difficult to automate, has interoperability issues, lacks standardization and is, amongst other challenges, often tailored to specific businesses and their specific workflows [4].

The digitalization of a business process means moving away from the traditional paper-based and toward online, real-time information exchange to improve collaboration, ensure transparency, timely progress and risk assessment, quality control and eventually better and more reliable process outputs [1]. It is, however, important to note that, while necessary, digital evolution can be a threat if not approached correctly [2]. A method of adopting new technologies and digitalizing a business process is to re-engineer a business process, that is, to fundamentally rethink and radically redesign it to achieve dramatic improvements in critical, contemporary measures of performance [5].

This work focuses on re-engineering an existing, traditional quantity takeoff process to a new, digitalized and BIM-based quantity takeoff process. The work during the thesis was conducted in collaboration with company IBE d.d., the biggest independent engineering and consulting company in Slovenia.

1.1 Motivation, Main Goals and Objectives

IBE d.d. has re-engineered its business processes and implemented BIM technologies in its services almost ten years ago and has been continuously improving in this business process. The company has been successfully utilizing BIM models for various BIM model uses, for example, 3D modelling, design authoring, clash detection and coordination, and others. While the benefits in implementing BIM technologies were immense and were recognized by employees, executives and most importantly, key clients, there are still unrealized potentials, areas for improvement and many additional BIM model uses that were not yet fully explored, namely, BIM-based quantity takeoff.

BIM-based quantity takeoff delivers better reliability, accuracy and speed compared to the traditional quantity takeoff method. The process is also much less error-prone and independent from manual human interpretation. Furthermore, BIM-based quantity takeoff allows for better change management as the quantities are, in most cases, directly linked to the individual items in the BOQs. Some application software also has the capability of managing the revisions of the models and other input data. The above also results in increased revenues, a better quality of design solutions, increased client satisfaction and more.

The main goal of the thesis is to re-engineer the quantity takeoff process for and in collaboration with the engineering and consulting company IBE d.d. Considering the re-engineered process will be adopted on future projects, the highest priority is to develop a solution that would be reliable and would ultimately succeed given the characteristics of the company, its structure, employees, established workflows, market segments and also the level of BIM adoption

The main objectives in achieving those goals are to:

1. Study various topics related to process modelling, business process re-engineering, continuous process improvement, digitalization of business processes, and compare the traditional and BIM-based quantity takeoff.
2. Accurately capture and analyze the AS-IS process, create the AS-IS process model, propose various alternatives for the re-engineered TO-BE process, carefully evaluate the proposed alternatives and choose the best solution for the ultimate success of the re-engineered BIM-based quantity takeoff process.
3. Define the re-engineered process thoroughly, create the TO-BE process model, implement the re-engineered process, and develop all necessary standardized inputs, procedures, and custom Revit API solutions.
4. Apply the re-engineered process to a case study using an existing project and its bill of quantities, analyze the results, evaluate the success factors and measure the performance.

1.2 Thesis Structure

The thesis consists of three main parts. In the first part (Section 2), the main topics are overviewed, described and clarified. The section consists of multiple subsections. Firstly, the process modelling essentials are covered. The definition of processes, business processes and process models are given. Then, the IDEFØ method for process modelling is described, and the definitions of digitalization and digitization are given. Secondly, the concept of business process re-engineering is outlined. The definition of business process re-engineering is given compared with continuous process improvement. The methodology of BPR is defined, the concept of AS-IS and TO-BE process models are explained, and the BPR workflow is presented with a process model. Thirdly, the quantity takeoff process is defined, and the traditional quantity takeoff process is compared to the BIM-based quantity takeoff process. Finally, a brief overview of BIM tools is given, and different approaches to leveraging Revit API are described.

In the second part of the thesis (Section 3), business process re-engineering is depicted. The first part of this section follows the steps outlined in the BPR process model. The process subjected to re-engineering is defined, and the breakdown of activities and their general execution timeline is given. Then, the AS-IS process is captured. This includes collecting the data through interviews with IBE employees, extracting the data through analysis and reporting, and, finally, process modelling and the analysis of the AS-IS process. Following the AS-IS process modelling and analysis, the critical success factors are defined, alternative solutions are proposed and evaluated. The most suitable solution is chosen and described. The TO-BE process is modelled, described, and the key performance indicators are defined. Finally, the main parts of the TO-BE process implementation are described, including assigning roles and responsibilities, analysis of the existing BOQ (the same is used in the case study later), developing solutions for managing keynotes and classification systems, information requirements in internal data dictionaries and the model checking procedures to ensure the BIM models meet those information requirements. In the end, the developed custom solutions (using Revit API through Dynamo, DesignScript and Python) to address specific challenges are depicted.

In the third part of the thesis, the re-engineered BIM-based quantity takeoff process is applied in a case study. The quantity takeoff process is executed following the activities defined in the TO-BE process model. Following the successful execution of the process, the process and its outputs are analyzed. Similar to the analysis of the existing BOQ, the generated BOQ is analyzed. Furthermore, the critical success factors and the key performance indicators are evaluated.

The main three parts of the thesis are followed by a conclusion and an outline of goals for future developments.

2 TOPIC OVERVIEW

2.1 Process Modelling

2.1.1 Process and Process Models

A process is a set of interrelated or interacting activities that transforms inputs into outputs [6]. It may occur once-only or be recurrent or periodic. A process instance is a single specific and identifiable execution of a process. Process state is the state of a process that can be recognized if it re-occurs [7]. A defined process has a process description that is documented and maintained and contributes to work products, measures and other process improvement information to the organization's process assets. In a project, a defined process provides a basis for planning, performing and improving the project's tasks and activities of the project [6].

A process model is a result of process modelling that represents instance(s) of a process and its states. It is a description of a process, and it is roughly an anticipation of what the process will look like in reality. The goals of a process model are to be descriptive (to track what happens during a process), prescriptive (to define the desired processes and how they should be performed) and explanatory (to provide explanations about the rationale of processes) [8].

Meta process models describe different types of process models or actual processes. They use broader terms for the names of activities and ICOMs (inputs, controls, outputs and mechanisms) that neither tell what represented process does nor the exact result of the process. Meta process models represent process knowledge, independent of their domain [7]. Meta process modelling explains the critical concepts needed to describe the development process - what, when, and why [8].

Generic process models are process models that have common characteristics and types of results. They may have some steps omitted (otherwise taken in instance processes) and do not define specific activities and ICOMs (e.g. do not name specific tools or persons). Generic process models may be used as process templates [7].

Finally, customized process models are derived from meta and (or) generic process models to a more specific configuration, with specific inputs, outputs, people and tools (mechanisms).

2.1.2 Business Process and Business Process Models

A business process consists of a set of activities that are performed in coordination in an organizational and technical environment [9]. These activities jointly realize a business goal – produce a specific service or product for customers. There are three main types of business processes; management processes, operational processes and supporting processes.

A business process model is a process model that describes or prescribes a business process. In business process management and systems engineering, business process modelling (BPM) is the activity of representing processes of an enterprise so that the current business processes may be analyzed, improved and automated.

2.1.3 Integrated Definition Methods (IDEFØ)

IDEFØ is a method designed to model the decisions, actions and activities of an organization or a system. It was derived from a well established graphical language, the Structured Analysis and Design Technique (SADT). IDEFØ process model diagrams are both very effective communication tools as well as analysis tools. The models are often created as one of the first tasks in the system development effort [10]. IDEFØ is useful for strategic planning, project planning, systems design, and, of course, business process re-engineering [11].

IDEFØ notation uses boxes or nodes that show the function (process, activity), connected with arrows entering or leaving the nodes that establish the interfaces between them. To express functions, boxes operate simultaneously with other boxes, with the interface arrows constraining when and how operations are triggered and controlled. Boxes and arrows are described using labels. The diagrams have a hierarchical structure (with the primary functions at the top and with successive levels of subfunctions revealing the well-bounded detail breakdown) and can be decomposed, giving them a gradual exposition of details [10]. The nodes also have indices that provide information regarding the node's location in the hierarchical structure of the diagrams.

Activities are in the main focus and are described by their inputs, outputs, controls and mechanisms (ICOMs). Hierarchical structure allows for the activities to be readily refined into greater detail.

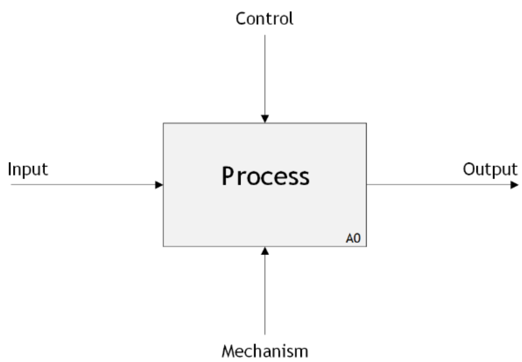


Figure 1: IDEFØ node with ICOMs (based on [7]).

The IDEFØ starts with the identification of the prime function or activity to be decomposed. This function is identified in the "*Top Level Context Diagram*" that defines the scope of the particular IDEFØ analysis. From this diagram, the lower-level diagrams (also called *child* diagrams) are generated.

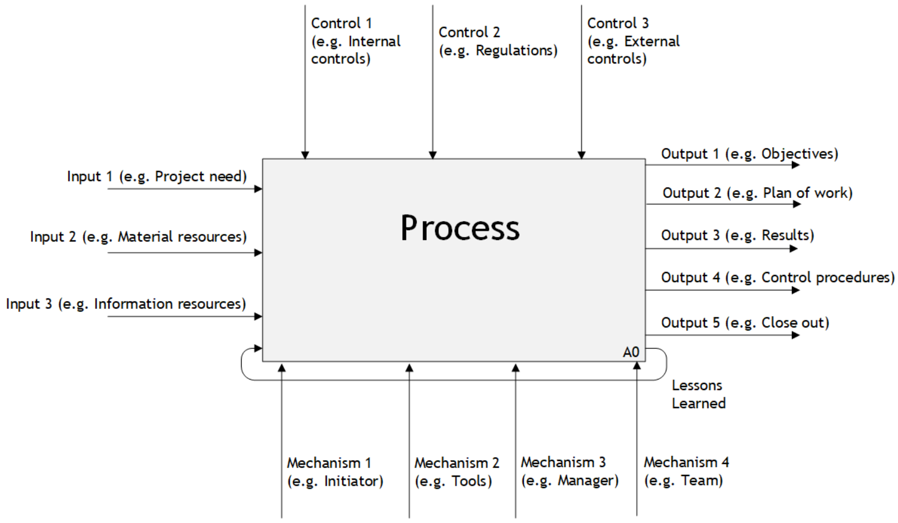


Figure 2: Context diagram for a generic process (based on [7]).

While IDEFØ does handle sequential processes, it is not to be mistaken with a flowchart since it does not prescribe a sequence of operations. Flowcharts, on the other hand, are a type of diagrams that represent a workflow (a depiction of a sequence of operations [7]) or a process [12]. It is easy to embed the sequence of activities by naturally placing them in a left to right (following the concept that the output of one activity serves as an input for another) sequence within a decomposition. There are, however, cases where this is not the case and the inputs and outputs are not so clearly connected [10].

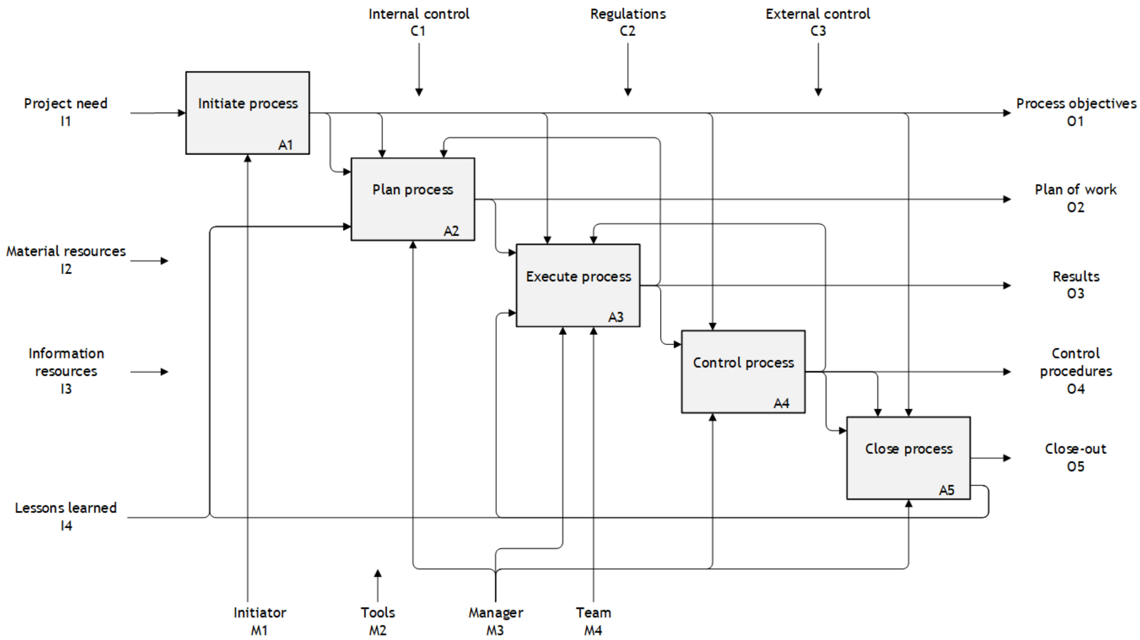


Figure 3: Simple decomposition of a generic process (based on [7]).

The nodes also have indices that provide information regarding the node's location in the hierarchical structure of the diagrams. For example, node A5 is a child node to A0 and a parent node to A5.3.

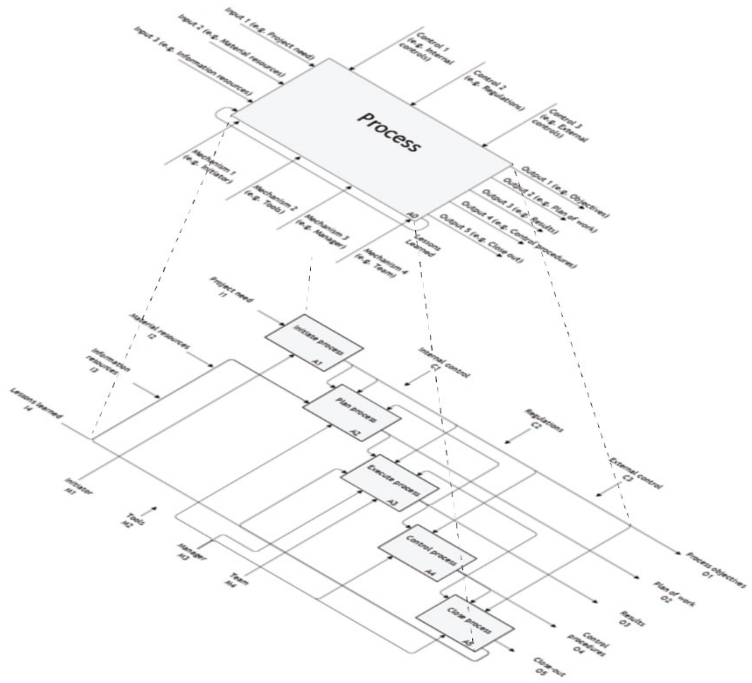


Figure 4: Display of the hierarchical structure of a generic process (based on [7]).

2.2 Digitization and Digitalization

It is essential to understand the difference between the term digitization and the term digitalization. Digitization is the process of changing from analogue to digital form (usually data or documents), meaning an analogue process is changed into a digital form, without any different-in-kind changes to the process itself. On the other hand, digitalization is the use of digital technologies to change a business process or business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business [13].

2.3 Business Process Re-engineering (BPR)

In the following section, various aspects of business process re-engineering are presented.

2.3.1 Definition of Business Process Re-engineering

There are several similar definitions of BPR available in the literature, for example ([14, 5]):

- (Hammer and Champy, 1993): "*Re-engineering is the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service, and speed.*"
- (Du Plessis, 1994): "*Business process re-engineering is the fundamental analysis and radical redesign of every process and activity pertaining to a business — business practices, management systems, job definitions, organizational structures and beliefs and behaviours. The goal is dramatic performance improvements to meet contemporary requirements - and IT is seen as a key enabler in this process*."

From the above and other definitions, we can identify the following vital elements for business process re-engineering [15]:

- A radical change.
- Change in orientation.
- Redesign business processes.
- Change in organizational structure.
- Technological improvements.
- The objective is the improvement of customer service and reduction of costs.

2.3.2 Continuous Process Improvement (CPI)

Continuous process improvement (CPI) is an ongoing effort to improve products, services or processes. Instead of seeking a radical breakthrough, these efforts seek an incremental improvement over time. Therefore, the processes are constantly evaluated, improved, and optimized in light of their efficiency, effectiveness, and flexibility [16]. Continuous process improvement is an essential part of the TQM approach.

Compared to BPR, the improvements are based on small changes rather than radical changes that may arise from R&D. The ideas are not radically different and often come from existing employees (and not from consultants or R&D) and are easy to implement. The required capital investment is, therefore, likely to be minor. The improvement is also a result of employees continually seeking ways to improve their performance, which helps encourage workers to take ownership of their work and improves their motivation [17].

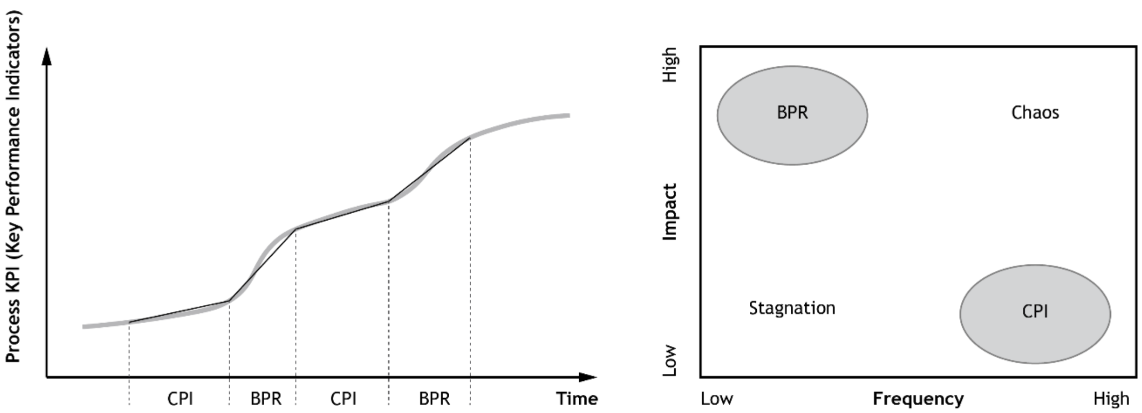


Figure 5: Effect of CPI and BPR on KPI over time (left, based on [7]) and comparison of the impact of changes in business processes and their frequency (right, based on [7]).

We can summarize the comparison between BPR and CPI in a tabular form, as presented in Table 1.

Table 1: Comparison between BPR and CPI [15].

Criteria	Cont. Process Improvement (CPI)	Business Process Re-eng. (BPR)
Change level	Incremental	Radical
Starting Point	Existing process	Clean slate
Frequency	One-time/continuous	One-time
Time required	Short	Long
Participation	Bottom-up	Top-down
Scope	Narrow, within functions	Broad, cross-functional
Risk	Moderate	High
Primary enabler	Statistical control	Information technology
Type of change	Cultural	Cultural/structural

2.3.3 Process Re-engineering Methodologies

There are many existing and documented process re-engineering methodologies, for example, the Hammer/Champy methodology, the Davenport methodology, the Andrews and Stalick methodology, the Kodak methodology, the Manganelli/Klein methodology and many others. All methodologies break down the process of re-engineering a business process into several steps. A general approach, as presented in [15], consists of the following steps:

1. *Project planning and launch*
   In this phase, the leadership team is formed, the goals and objectives are set, the scope is defined, the methodology is selected, the schedule is developed, the consultant is selected, the resources are negotiated, the change management is planned, and the team responsible is prepared.
2. *Current state assessment and learning from others*
   In this phase, the existing process is defined, assessed and benchmarked against the competition or other companies in the sector. Additionally, currently used technology is assessed.
3. *Solution design*
   In this phase, the re-engineered process is designed, the enabling technology is selected, the administrative and organizational solutions are designed, and new or changed jobs are designed.
4. *Business case development*
   In this phase, the cost and benefit analysis is carried out, and the business case is prepared and presented to the key business leaders.
5. *Solution development*
   In this phase, the re-engineered process is defined in detail, the requirements are defined, the training plan developed, the implementation planned, the operational transition plan laid out, and trials and pilot projects chosen.
6. *Implementation*
   In this phase, the re-engineered business process is fully implemented along with all trials and pilot projects. It is essential in this phase to also document the lessons learnt.
7. *Continuous improvement*
   Finally, the re-engineered business process transitions into the phase of ongoing improvements with the improvements (continuously) measured (for example, six sigma capability and others).

This thesis follows a simplified methodology (yet consistent with the one described above) to re-engineer the chosen business process. The methodology is aligned to the methodology described in [7] and is presented in an IDEFØ process diagram in Figure 6 and Figure 7.

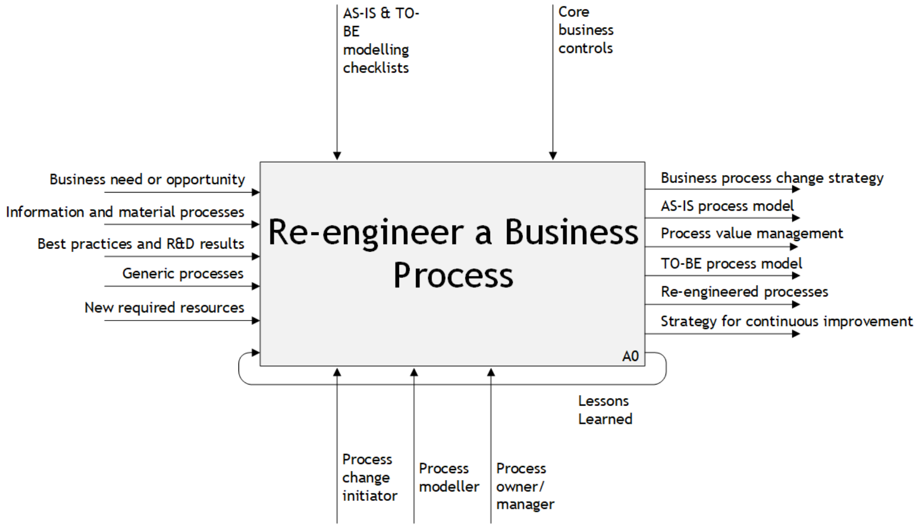


Figure 6: Context diagram of business process re-engineering methodology as per [7].

We can break down the context diagram in the main activities. In this case, this also gives us a very rough sequence of activities in the process of re-engineering the chosen business process.

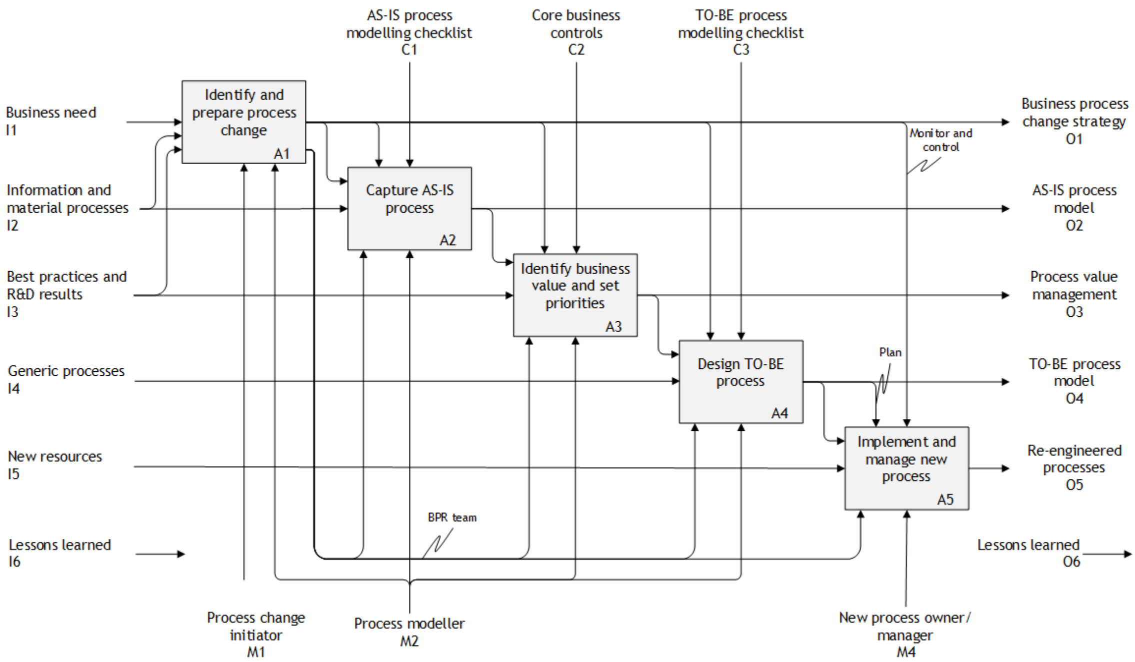


Figure 7: Main activities of business process re-engineering methodology as per [7].

2.3.4 Top-down and Bottom-up Approach

Two approaches exist in business process modelling – one is bottom-up, and the other is top-down. In the top-down approach, the expert or process change manager proposes how business processes shall be executed. It starts from an overall process and breaks it down into individual activities and tasks until a sufficient amount of details is specified. In the top-down approach, the process model often comes from the best practices and R&D efforts and is used to model the TO-BE process model used for business process re-engineering [18].

In contrast, the bottom-up approach starts documenting at the lower level, that is, how the tasks are executed on the operational level. After extracting this information, the tasks are combined into activities and activities to other activities to build processes. In this way, the whole business process model is built. By starting at the lower level, detailed insight is immediately given about the processes. Because the bottom-up approach starts from the local domain, this approach is used to AS-IS process models and generally for business process improvements (continuous process improvement or CPI) [18].

2.3.5 AS-IS Process Model

AS-IS process models represent the current stage, condition, or method at which the existing processes work in an organization [15]. In the scope of BPR, this represents the old business process. It is a prerequisite to understanding how processes are executed in the current system [18]. By mapping and analyzing AS-IS processes, we can find the flaws in the current business processes. For the AS-IS process, a bottom-up modelling approach is used, which also ensures that the involvement of experts can be minimal at this point of the process. Modelling the AS-IS process model also provokes creative thinking from the individuals involved in designing the TO-BE process [15].

The bottom-up approach starts from taking the requirements from employees about how processes are executed, and then, in a stepwise manner, the whole business process model is built. It is essential to clearly understand the relationship between the individual processes, tasks, or activities. The following types of elements are involved in the AS-IS process model [18]:

- *Involved objects;* are involved in activity processing (like inputs and outputs) and can be physical (like material, tools and resources) or non-physical (like data and information).
- *Functions/operations*; resources (mechanisms) perform operations on inputs and transform them into outputs – it is essential to understand the functions performed, the individual steps required and the sequence of the steps required to complete the task.
- *Conditions and constraints*; the business processes are subjected to various conditions and constraints defined in enterprise policies and applied during the execution of activities based on the characteristics of involved objects: a) *pre-conditions* – the conditions which must be held before the task is executed (for example, resources available); b) *post-conditions* – the conditions evaluated at the end of activity or task executions (to check whether the task has to be repeated or other measures taken); c) *other conditions*; d) *constraints* – the constraints applied to the processes based on the characteristic of involved elements (for example, a person may not be able to perform two tasks simultaneously).
- *Control structures;* are internal and external controls of the business process.

In the bottom-up approach, the model is designed from the task descriptions as explained by the employees. The overall approach is divided into three phases [18]:

1. *Data collection*; the goal is to obtain the description of information from the employees about the tasks they are executing. We can use questionnaires to collect this information.
2. *Information extraction*; we can extract all relevant information (from the collected data) for the AS-IS process model (about all elements involved, or ICOMs in case IDEFØ is used).
3. *Modelling and analysis phase*; we determine elements and their relationships (activities, inputs, outputs, mechanisms, controls). This enables us to create the process model. Once the process is modelled, the analysis can be done by the experts/consultants, and improvements can be proposed.

After the AS-IS model is finalized, the cost analysis shall be performed. Firstly, the assessment of the time required to perform a particular task shall be done. Secondly, the cost of this activity shall be measured in terms of resources [15].

Cost analysis is followed by gap analysis. This means that the BPR team weighs the current performance, displayed by the captured AS-IS model, against the desired performance, assuring that the gaps will be bridged when designing the TO-BE process [15].

Finally, the value-adding processes have to be defined. The value delivered by a process changes with the evolving business processes, requirements, technology, and other external factors. Consequently, not all processes within an organization are value-adding – some may be obsolete or redundant. In this step of BPR, the processes are classified as either value-adding or non-value-adding (NVA). The latter are dropped in subsequent stages [15].

2.3.6 TO-BE Process Model

The TO-BE process model represents the intended, new situation. The difference between the AS-IS and TO-BE process model must be clearly understood, as the TO-BE situation is meant to dramatically improve key performance indicators, which means that the gaps discovered in the gap analysis must be (if feasible) bridged. This step also includes critical decisions, as the BPR team has to choose the TO-BE process from the available alternatives (usually, there are many options or alternatives). Metrics have to be developed to measure the performance of the re-engineered process.

Firstly, the process must be benchmarked against other similar processes carried out elsewhere (can be done internally, for example, in a different department, or externally). This results in knowing the best practices and experience with similar processes. Additionally, the R&D efforts shall be considered.

Secondly, the new process is designed. Based on the benchmarking exercise, various alternatives are developed and must be evaluated. The evaluation, tailored to the company-specific goals, yields the chosen process, which is then adequately defined, modelled and documented. The evaluation process must give much attention to the critical success factors (CSFs), as these elements determine the ultimate success or failure of the project; hence the chosen alternative must be evaluated for its adequacy on all critical success factors. If needed, the process is further modified to accommodate all of the CSFs.

When the TO-BE process is designed, the order of implementation must be set based on the cost-benefit analysis results. The processes that provide the maximum benefits in the short run (with fewer resources required) are the first to be implemented.

In the process of designing the TO-BE process, the key performance indicators (KPIs) must be determined to measure the degree of success of the process. These metrics then play a critical role in the final stages of the BPR, when the process performance is monitored.

Finally, new roles and responsibilities must be defined in order to execute the re-engineered business processes. This final step is essential as the re-engineered process may require a deviation from the current team structure, roles of the individuals and their responsibilities, and the chain of the commands.

2.4 Total Quality Management (TQM)

By definition (Ciampa, 1992), total quality management (TQM) consists of organization-wide efforts to *install and make a permanent climate where employees continuously improve the ability to provide on-demand products and services that customers will find of particular value* [19]. The *total* emphasizes that all departments or professionals in the company are obligated to improve their operations. The management emphasizes that executives are actively obligated to manage quality through funding, training, staffing and goal setting. Continuous process improvement (CPI) is fundamental to TQM.

Some of the concepts of TQM are [20]:

- The customer requirements define quality.
- Top management is directly responsible for quality improvement.
- Increased quality comes from systematic analysis and improvement of work processes.
- Quality improvement is a continuous effort and conducted through the organization.

Lately, the TQM approach has been overshadowed by *ISO 9000*, *Lean Manufacturing* and *Six Sigma*.

2.5 Key Performance Indicators (KPIs)

Key performance indicators are a type of performance measurement metric. KPIs evaluate an organization's success or a particular activity (for example, a business process undergoing re-engineering) in which it engages [21]. They are indicators of progress toward an intended result and provide the focus for strategic and operational improvement, create an analytical basis for decision-making and help focus attention on what matters most [22].

2.5.1 Defining the KPIs

Good KPIs have the following characteristics [22]:

- Provide objective evidence of progress towards achieving the desired result.
- Measure what is intended to be measured to help inform better decision-making.
- Offer a comparison that gauges the degree of performance change over time.
- Can track efficiency, effectiveness, quality, timeliness, governance, compliance, behaviours, economics, project performance, personnel performance or resource utilization.

When determining the KPIs, we shall consider the following [23]:

- Does the KPI motivate the correct behaviour?
- Is the KPI measurable?
- Is the measurement of this KPI cost-effective?
- Is the target value attainable?
- Are the factors affecting this KPI affected by us?
- Is the KPI meaningful?

2.5.2 Examples of KPIs for BIM Implementation

Many companies have been implementing and adopting BIM technologies in their business process over the last decade. Some examples of meaningful key performance indicators are [23]:

- Person-hours spent per project (the possibility of comparing the person-hours spent on the project that utilizes BIM technologies and the same project using a traditional CAD system).
- Turnaround time (can improve cash flow, reduces outstanding work and costs and engenders client satisfaction).
- Revenue per head (the fees can only increase with greater perceived value by the client).
- IT investment per unit of revenue.
- Cash flow.
- Quality of the design solutions (multiple facets to be considered, for example, the number of issues that occur during the execution).

- Reduced costs, travel, printing, document shipping.
- Bids won or winning percentage.
- Client satisfaction and retention.
- Employee skills and knowledge development.

2.6 BIM-based Quantity Takeoff and Cost Estimation

2.6.1 Quantity Takeoff and Cost Estimation

Quantity takeoff (QTO) is the measurement of the materials needed to complete the construction project. It includes breaking down the project into smaller and more manageable units that are easier to measure or estimate. The process is performed by quantity surveyors during the pre-construction phase, resulting in a bill of quantities (BOQ). The BOQs are usually unpriced, with blank columns for rates and prices and are the basis for cost estimation, which is usually completed by tenderers. The BOQs are issued to tenderers for them to prepare a price for carrying out the works. Therefore, the same quantities are used for cost estimations, including the project needs like labour, overheads, permits, insurance, tools and equipment or incidentals ([24, 25 and 26]).

The accuracy of quantity takeoff indicates the reliability of the following tasks (for example, cost estimation, cost planning, material purchasing and others) [27].

There are many best practices and guidelines available for preparing bills of quantities, although the standard is not yet in place on an international scale. One example is New Rules of Measurement, published by the Royal Institute of Chartered Surveyors (RICS). Following such guidelines assures that all projects are taken off the same way and in the same order, following consistent rules ([24-28]).

2.6.2 Traditional Method of Quantity Takeoff

Traditionally, the quantity takeoffs are done using a set of drawings divided into architectural, structural, civil, landscape, electrical, mechanical and plumbing drawings. This way, the quantity surveyors must go through every single sheet of drawing and determine the quantities of individual materials [29]. Furthermore, the drawings must be correctly interpreted as the information available there (and in specifications) is the only information available. The quantity surveyor must also have a systematic approach to avoid missing any elements or counting them twice. This also makes change management very demanding.

The quantity surveyors must also use their knowledge and effort to measure the individual quantities correctly. Even with the guidelines in place, for example, NRM2 [28], the process is still error-prone as it is based on manual human interpretation [27]. The process is also very time consuming as the effort is mainly manual, which may also result in less accurate measures, as the surveyor must compromise on the accuracy of the measurement and time spent. It is assessed that, through the traditional methods, the quantification of materials can consume from 50% to 80% of the surveyor's time [29].

The reliability of the quantities in the BOQ depends on the quality and detail of the project documentation provided.

2.6.3 BIM-based Quantity Takeoff

The objects within the BIM models contain geometrical and non-geometrical information. The information within the BIM models is adapted to the requirements for a particular purpose or model use. There is plenty of BIM model uses (from 2D documentation, 4D detailing, 4D planning, clash detection and energy analysis, and many others), and quantity takeoff is one of the most often used.

BIM models can reduce time spent because the estimators extract the quantities from the model objects rather than measure them manually [25]. BIM-based quantity takeoff delivers better reliability, accuracy and speed compared to the traditional quantity takeoff method. However, similar to the low quality of the drawings that limits traditional quantity takeoff, the quality of BIM models is also a challenge in BIM-based quantity takeoff [27]. BIM models should therefore be developed adequately for this model use and follow guidelines for modelling, appropriate for quantity takeoff.

BIM-based quantity takeoff allows for better change management as the quantities are, in most cases, directly linked to the individual items in the BOQs. Some application software also has the capability of managing the revisions of the models and other input data. The process is also much less error-prone and independent from manual human interpretation.

There are, however, many challenges in BIM-based quantity takeoffs. One of the challenges lies in the fact that not all elements are included in the model, especially the specific details that would be very time consuming to model and are often represented on drawings with 2D detail items. Consequently, those items can not be quantified directly. Some studies say that only up to 50% of the data needed for the quantity takeoff is inferred from the model [29]. Another challenge is also with compound elements, which are usually modelled as one element with multiple layers. This results in losing the ability to extract the compounds individually, and the ability to adjust the size and composition of each material layer is lost, which results in some deviations between the extracted quantities and actual quantities [27]. Some items from the BOQ also may not have a graphical representation in the model (for example, paints, primers and similar items).

Additionally, BOQs also contain items that are not linked to model elements, for example, support of the surveyor on the construction site, plan of control, preparation of installation packages, various tests, and many others. Similarly, some items describe the activities assigned to objects, for example, repairs, interventions, cleaning, tests, and others. This means that one object may be linked to multiple items in the BOQ, which has to be handled systematically. There are some suggestions that such activities may be modelled with some host-based objects linked to the objects on which those actions are required [4]. A solution like this allows having an object in the model referenced to a single item in the BOQs, making eventual automation easier to implement but distances itself from an ideal solution.

Ideally, the concept of work must allow all four possibilities:

1. A single model element is linked to a single item in the BOQ.
2. Multiple model elements are linked to a single item in the BOQ.
3. A single model element is linked to multiple items in the BOQ.
4. An item in the BOQ is not linked to model elements.

According to interviews conducted within the research, two of the most significant disadvantages of BIM-based QTO is the amount of time invested in vetting and correcting the models with incorrect data and data that is not current with the design [29].

Overall, the BIM-based QTO has significant advantages over the traditional and its further use will not only increase in the future but also become an essential requirement as it provides more transparency and its adoption is in the client's interest. The current gaps, both from the modelling and quantity takeoff perspectives, will also likely start to fill [29], and standardization will play a critical role.

2.6.4 Importance of Standardization

Standardization is the process of development, implementation and deployment of standards. It leads to conformity with commonly acceptable standard rules, principles, regular usage and codes of practice [7]. The role of standards can be labelled by the "3C" – competitiveness, conformity and connectivity. Furthermore, standardization is considered a key instrument towards innovation. The three roles of any standard enabling innovation are interoperability, trust and comparability. Standards are considered a critical factor in enabling the digitalization of processes and its evolution, overcoming these issues ([30 4]).

Focusing on the BIM-based quantity takeoff process, the three roles are crucial for successful implementation and application. For example, data sharing during the QTO process between different stakeholders is only possible if the data is interoperable. The data exchange must exhibit trust, meaning that there are no errors in the process and that the receiver reads the exact message the sender intends to send. Finally, the exchanged data must enable comparability (between different versions, sources, and others). The key enablers in the BIM-based QTO process are standardized inputs, outputs, controls, and mechanisms (ICOMs).

Classification standards are amongst the standards that play a crucial role in the BIM-based QTO process. The stakeholders need to be capable of identifying and accurately describing any model element. The classification systems structure data in an agreed way allowing different stakeholders to obtain and understand the information they need [4]. They create a common ground for establishing communication amongst humans, machines and software, assuring them to use the information exchanged efficiently and accurately [31]. Due to the complexity of the projects and the network of team collaboration, project parties generate more and more data, and this data relies on standardized and structured digital solutions to serve as a source for decision-making and project development. Classification systems benefit different actors in the industry according to their necessities and associated BIM uses [4].

Different organizations in different geographical regions have developed different classification systems, for example:

- Uniclass 2015 (unified classification for the UK industry covering all construction sectors).
- OmniClass (classification system for the construction industry in North America).
- CoClass (Swedish classification system for the built environment).
- CCS (Danish classification system for the built environment).
- TALO 2000 (Finnish classification system) and many others.

2.7 BIM Tools

We can recognize upstream and downstream BIM technologies. Upstream BIM technologies are the application software that can author an object-based, data-rich, 3D model ([7], [32]). We call them BIM authoring tools. Various BIM authoring tools are available on the market, for example, Autodesk Revit, Nemetschek Allplan, Graphisoft Archicad, Trimble Tekla Structures, and many others. These upstream application software often link to other specialized downstream application software to generate various model-based deliverables [32].

The downstream BIM application software is a specialised software tool not used for authoring models but for analyzing their components or data [32]. There are many different functionalities of downstream BIM application software, for example [7]:

- Viewers (used to view, extract and comment) and checkers (used for model checking and validation and checking of collisions).
- Servers (used to receive and send models).
- Transformers (used to extract and transform models).
- Editors (used to edit model structure and properties).
- Mergers (used to merge several models) and splitters (used to split one or more models).

Some examples of various downstream BIM application software is [7]:

- Model viewers (Tekla BIMsight, Dalux viewer, BIMcollab ZOOM, and others).
- Checkers/trimmers (Solibri model checker, simplebim, and others).
- Simulation/analysis tools (Navisworks Manage, iTWO costX, Bexel Manager, and others).
- Facility management tools (Trimble Alltrak, DaluxFM, and others).

2.8 Application Programming Interfaces (APIs)

An application programming interface is a connection between computers or between computer programs. It is a type of software interface, offering a service to other pieces of software [33].

Autodesk Revit, among other upstream and downstream BIM applications, provides a rich and powerful API that can be used to automate repetitive tasks, extend the core functionality of Revit and more. The Revit API may be used through textual programming (for example, using C# or VB.Net in an external editor) or visual scripting (Dynamo). Furthermore, we can use Revit API through scripting (using DesignScript and Python nodes in Dynamo).

Dynamo is a layer over Revit API, and we can use all of the Revit API through Dynamo. In fact, Dynamo offers some additional functionalities (for example, DesignScript and its own geometry library). However, for manipulating native Revit files (.rvt file format), Dynamo offers precisely what the Revit API provides [34].

DesignScript acts as a two-way bridge between visual scripting and textual scripting [35]. It is the programming language within Dynamo, which can be used through Dynamo nodes or textual scripting. Because nearly all functionalities found in Dynamo nodes have a one-on-one relationship with the scripting language, the two can be combined within the visual programming environment to reduce the size and complexity of the Dynamo graph and to create customized mashups of existing functionality and user-authored relationships using many standard coding paradigms. In Dynamo, Code Blocks are the text-scripting interface within a visual-scripting environment [36].

Another addition to the visual programming environment in Dynamo are the so-called Python nodes. Like Code Blocks, Python nodes are a textual scripting interface within a visual scripting environment. Using Python nodes, we can extend the capabilities of Dynamo and replace many nodes with a few concise lines of code [36]. Furthermore, Python offers much more efficient methods for writing conditional statements and looping. We can also import various modules, packages and libraries in Python nodes, further extending the functionality.

For the custom solutions developed in the scope of this thesis, a combination of Dynamo nodes, Code Blocks containing DesignScript syntax and Python nodes was used.

3 BUSINESS PROCESS RE-ENGINEERING

3.1 The Company and the Business Process Subjected to Re-engineering

The work during the thesis was in its entirety conducted in collaboration with company IBE d.d., the biggest independent engineering and consulting company in Slovenia with around 160 employees in three branch offices. IBE d.d. renders its services in the most demanding market segments home and abroad: energy sector, industry, service buildings, infrastructure, and environmental protection.

The company has multiple departments, including Civil Engineering, Architectural and Surveying Department, Electrical Engineering Department, Mechanical Engineering and Technology Department, R&D Department and others. The departments collaborate on larger interdisciplinary projects and deliver high quality integrated project solutions, which is recognized as one of the key advantages over the competition. As an employee in the Civil Engineering, Architectural and Surveying Department and because of the limited time resources, the business process re-engineering is conducted in this department. However, the solutions will naturally be implemented by other departments on future interdisciplinary projects.

IBE d.d. has re-engineered its business processes and implemented BIM technologies in its services almost ten years ago and has been continuously improving in this business process. The company has been successfully utilizing BIM models for a variety of BIM model uses, for example:

- 2D documentation,
- 3D modelling,
- As-built representation,
- Laser scanning,
- Design authoring,
- Clash detection and coordination,
- VR simulation,
- Construction planning,
- Constructability analysis,
- Structural analysis,
- Quantity takeoff,
- Cost estimation,
- Selection and specification and
- Others.

While the benefits in implementing BIM technologies were immense and were recognized by employees, executives and, most importantly, key clients, there are still unrealized potentials, areas for improvement and many additional BIM model uses that were not yet fully explored, namely, BIM-based quantity takeoff.

3.2 Identification and Preparation for the Process Change

3.2.1 Identification of the Process

The company has determined that one of the unused potentials of BIM technologies is the use of BIM models to perform quantity takeoff and provide bills of quantities and cost estimations that are entirely based on and connected to the elements in the BIM model. While IBE d.d. is already utilizing BIM technologies and BIM models to extract some quantities from the BIM models, the whole business process is still very similar to the traditional method of quantity takeoff. The bills of quantities are written in a digital format using MS Excel, but the process is not fully digitalized yet. The company's goal is to have a workflow that would allow the whole bill of quantities to be prepared within a single application software and flexible enough to resolve all gaps present in the BIM-based quantity takeoff process.

The re-engineered process should also allow for better change management and have a potential for partial or complete automation. Hence, the process would be less time-consuming, and the results would be more accurate and reliable, as the process would be less prone to mistakes.

3.2.2 Preparation for the Process Change

The collaboration with the company on this master thesis was an ideal chance to explore various alternatives, re-engineer the business process and adequately document the process. First, the breakdown of the planned activities was developed. The breakdown contained individual steps and was later, when the approach to BIM-based quantity takeoff was already determined, revised. The breakdown also included the thesis writing and defence, as this was also one of the significant elements and imposed time constraints. The breakdown is shown in Figure 8.

Once the critical tasks within the breakdown were determined, a general timeline was developed. The general timeline was relatively conservative and allocated sufficient time to perform the tasks. However, some tasks are impossible to complete for all possible cases (for example, the development of libraries and data dictionaries for all types of objects). Those were executed for a certain number of cases and those that occurred within the case study. For the rest of the cases, those developments will be made during the phase of continuous process improvement, that is, during future projects. The general timeline is shown in Figure 9.

Additionally, the roles and responsibilities were assigned. As the re-engineering process was part of the thesis, several roles (process modeller, engineer, BIM coordinator) were mine. Other roles were assigned to adequate personnel (executive, process initiator, quantity surveyors, architects, BIM manager and other roles within the BPR team).

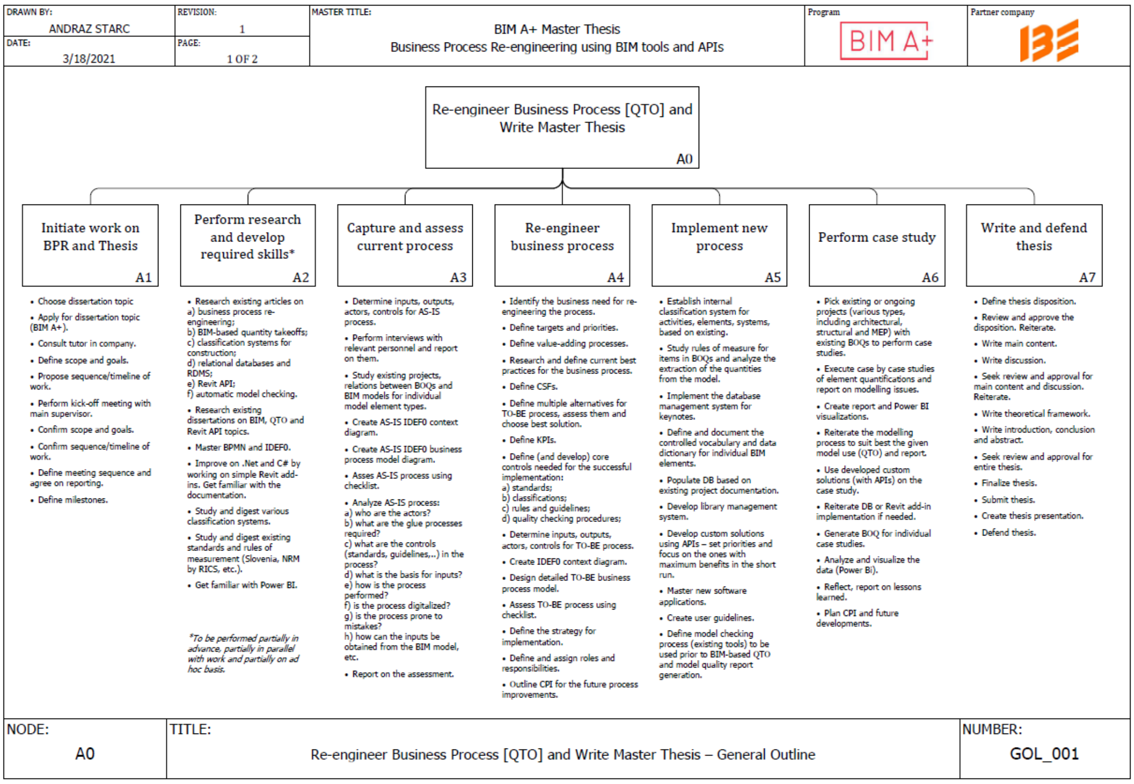


Figure 8: Breakdown of the business process re-engineering (QTO) and thesis writing activities.

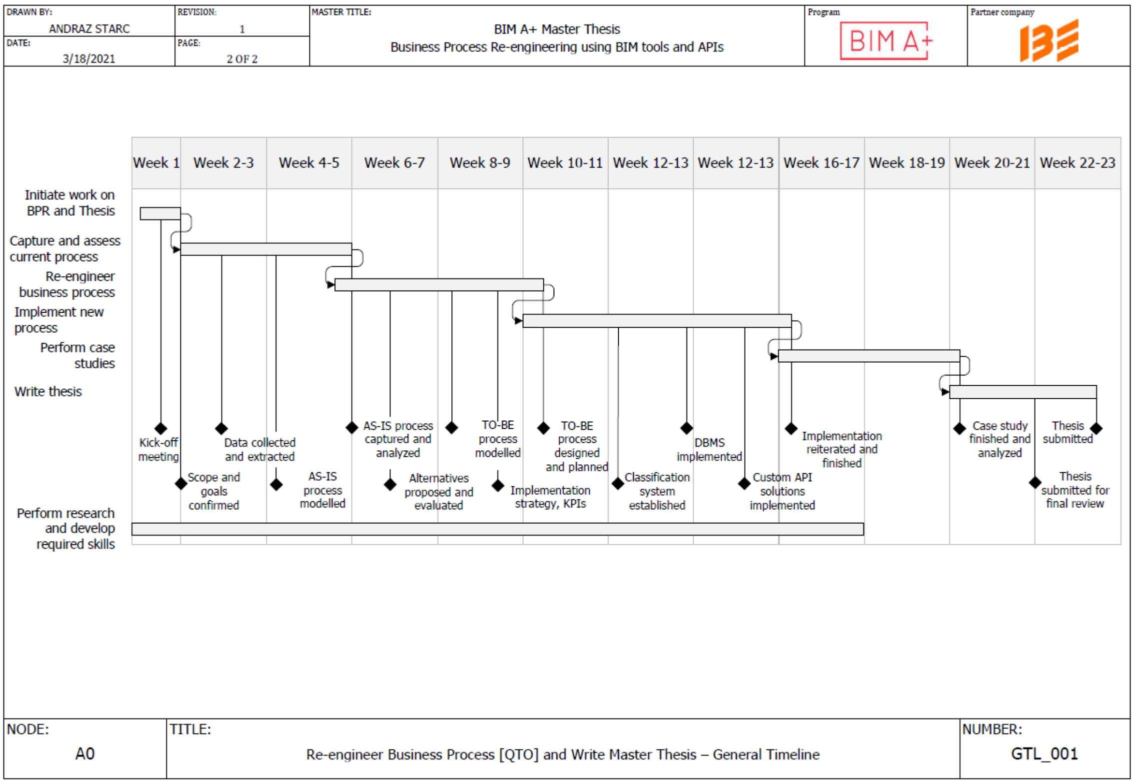


Figure 9: General timeline for business process re-engineering (QTO) and thesis writing activities.

3.3 AS-IS Process Model

As defined in Section 2.3.5, we captured the AS-IS business process in several steps.

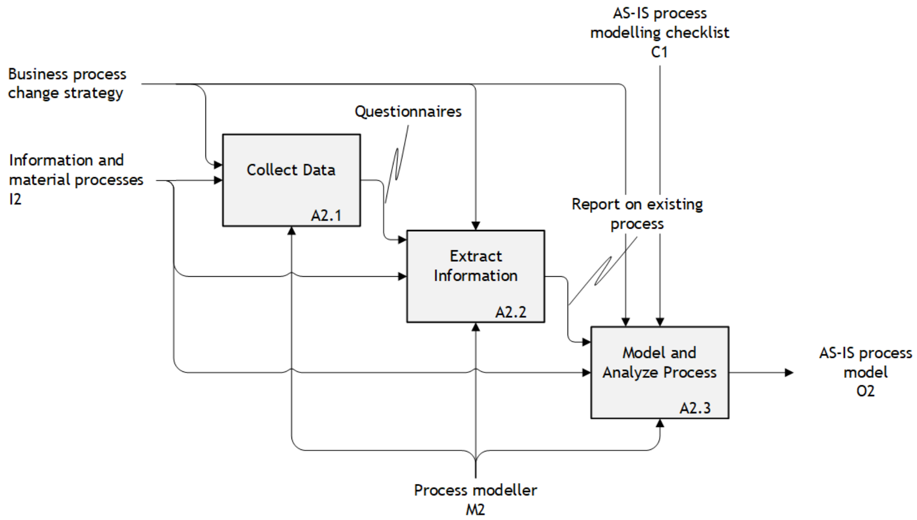


Figure 10: Steps in AS-IS process capturing and modelling.

3.3.1 Data Collection

Firstly, we collected the data. This was done through interviews with quantity surveyors. The basis for the interview was the questionnaire, developed specifically to capture and provide an in-depth understanding of how the quantity takeoff process is performed. The questionnaire consisted of three parts.

The questionnaire specifically targeted the process of quantity surveying for civil works. The questions were tailored to specific aspects of quantity takeoff for civil works on projects typical for IBE d.d.

In the first part, the goal was to collect the information that would give us an understanding of the inputs, outputs, controls and mechanisms of the quantity takeoff process. Later, this gave us the context of the AS-IS process. The quantity surveyors also provided their comments and views on individual items.

The second part of the questionnaire contained 27 general questions regarding the quantity takeoff process. The questions targeted many topics, from the use of templates, what applications are used and how the quantities are measured, to classification standards, internal and external reviews and others. The list of questions is given in Table 2.

Table 2: General questions regarding the current QTO process from the questionnaire.

	Question
1.	Is there a template available for the QTO process?
2.	What is the project documentation considered in the QTO process?
3.	What are the quantities extracted from BIM models?
4.	In what scope are the existing BOQs used?
5.	How are the standards considered and input into the BOQ? For example, the standard for execution of the concrete structures.
6.	How are product specifications considered and input into the BOQ? For example, specifications about the hydro insulation layer. At what point?
7.	How are client-specific specifications considered in the BOQ? For example, a specific client in the energy industry.
8.	Is the work performed individually (as a quantity surveyor)? Is there an option that at some point (large projects) it will be in a group?
9.	What is the interaction with project engineers and BIM modellers?
10.	What application software is used to create a BOQ?
11.	What application software is used to extract quantities?
12.	What application software is used to view the documentation, drawings and models?
13.	How and at what point are the surveyed quantities measured?
14.	Which office equipment is required to perform QTO?
15.	What are the guidelines/standards/procedures considered to survey quantities?
16.	What are the guidelines/standards/procedures considered to create BOQs?
17.	Is there a classification standard used on a national level (e.g., Uniformat)?
18.	Is there a classification standard used on a company level for civil works?
19.	How is the internal review for BOQs performed? Is it reported?
20.	How is the external review for BOQs performed? Is it reported?
21.	What is the output of the QTO process?
22.	How is the information reused? How are the lessons learned incorporated into the next project?
23.	What are the most time-demanding tasks?
24.	What are the tasks where good automation is exhibited?
25.	What part of the process has the highest potential for automation?
26.	What part of the process would be challenging to automate?
27.	What are the personal preferences/wishes for BPR?

The third part of the questionnaire contained questions inspired by and followed the BIM Excellence Maturity Matrix structure [37]. The questions targeted three different areas:

1. Technological area:
    - Application software, deliverables and data (for example, whether the exchanges are defined, if BIM models are used, what application software is used, is the data interoperable, how the data flow is documented and others).
    - Hardware - equipment, deliverables and location/mobility (for example, whether the equipment used is adequate, if it allows mobility, is the equipment considered an enabler for BIM integration and others).

- Network – solutions, deliverables and security/access control (for example, whether any network solutions are used, is the knowledge is shared through network access, are there any network solutions that allow integration and others).

2. Process area:
   - Resources - physical and knowledge infrastructure (for example, whether the knowledge and experience regarding the QTO process are documented, are they easily accessible and reused, the experience with BIM objects, and others).
   - Activities and workflows (for example, whether the roles are defined, is the collaboration within the QTO process enhanced with tools available, are the processes defined, documented and possibly standardized, and others).
   - Products and services (for example, whether there are any object breakdown specifications in use, are the current BIM models appropriate for QTO, and others).
   - Leadership and management (for example, whether there is a strategic vision to implement BIM in the QTO process, any action plans in place, any business opportunities that will arise from BIM-based QTO, and others).
3. Policy area:
   - Preparatory – research, educational/training programmes and deliverables (for example, whether there is training available concerning BIM-based QTO, is it appropriate, are the methods available, and others).
   - Regulatory – codes, regulations, standards, classifications, guidelines and benchmarks (for example, whether standards, guidelines and quality procedures are in place for the QTO process, and others).
   - Contractual – responsibilities, rewards and risk allocation (for example, whether the QTO process is defined in contracts, are there systems for resolution in place, what are the responsibilities of stakeholders providing information, and others).

The questions and answers of the questionnaires were documented and used in the following steps.

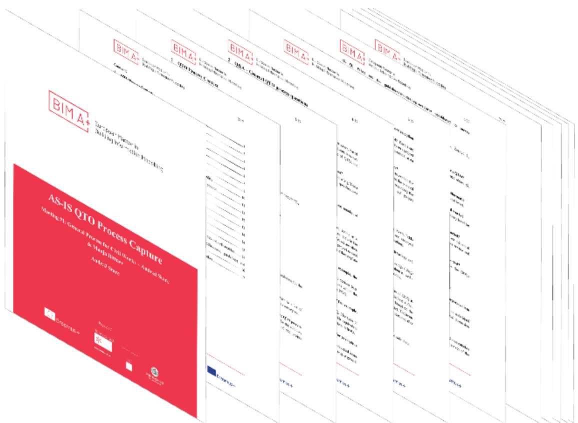


Figure 11: Documented questionnaires for data collection during the AS-IS model capture.

3.3.2 Information Extraction

Secondly, we extracted the information regarding the AS-IS business process based on the data collected with the questionnaires and the examples of the existing BOQs provided. The information extraction was focused on a detailed description of the individual ICOMs.

3.3.2.1 Inputs

A summarized description of the inputs is given below:

a) **Project execution plan:**
The objectives, approach and timeline are given in the project execution plan. The work is delegated, and resources are accounted for. In the AS-IS model, the project execution plan typically specifies that the quantity takeoff process starts before the design documentation is fully complete. This means that not all information is always available in advance, and the documentation may be subjected to some changes.

b) **Project documentation and the basic quantities extracted from BIM models**
The project documentation is the primary input for the QTO process. It is usually delivered in a pdf format and later printed on paper to give the quantity surveyor a better overview of the design solutions. Physical copies also allow for hand-written notes, as the calculations are performed manually (in a notebook stored with the documentation, which allows for manual change management).
The documentation includes 2D drawings generated from BIM models, technical reports, and material schedule of basic quantities from BIM models, such as basic quantities for concrete works, basic quantities for steelworks, embedments, doors, windows, spaces, and others). In addition to 2D documentation, quantity surveyors also use federated BIM models and view them in Navisworks to better understand the design solutions and possibly check some dimensions.

c) **BOQ templates**
For the BOQ template, the BOQs from similar past projects are usually used. This means that the BOQ structure and element breakdown structure are already defined when the BOQs are cleaned (irrelevant information deleted). Additionally, some key clients provide their own templates or specify the breakdown structure of the BOQs, as they want them to be tailored to their needs and unified across various projects with various design offices.

d) **Existing BOQs**
The existing BOQs are, as mentioned above, often used directly in the quantity takeoff process as a basis in the new, similar project. This is especially common with key clients with similar projects (for example, electric substations). Therefore, an existing BOQ that fits the new project best is chosen before the quantity takeoff process is executed. A significant factor in choosing a good existing BOQ as a template is a structural system (in the case of civil works).

e) Product standards and specifications

Product standards and specifications are considered as input in the QTO process. Usually, a product or its equivalent is specified, and a specification is given as a reference. There are also cases when key clients have developed their own specifications, and the items in the BOQ use the identifications of the products from their specifications (for example, the system of corrosion protection of steel structures). Those specifications are listed in the general notes in the BOQ and are also referenced within the individual items.

f) Lessons learned

Lessons learned are usually in the form of existing BOQs, which show how individual items were resolved. The lessons learned are usually communicated verbally, and no document or report on lessons learned is created after the project close-out.

3.3.2.2 Controls

A summarized description of the controls is given below:

a) Guidelines

Several guidelines are currently in use to prepare BOQs. All of them are made by Slovenian authors:

- *Kalkulacija gradbenih del, M. Pajk, UL FAGG, 1964* [38].
- *Gradbene kalkulacije in obračun gradbenih objektov, Žemva Š., CPU, 2006* [39].

The guidelines are considered a reference for the structure or element breakdown in the BOQs, for units of measure of individual items, for rules of measurement of items and others.

b) Classification standards

In the AS-IS process, no classification standards are used or are prescribed on a national or international level.

c) Standards and procedures

The standards concerning the products and design solutions are incorporated into the BOQs in general notes and in the individual items in the BOQ.

Currently, there is no standard prescribing any aspects of the QTO process or the BOQs.

Some key clients have procedures that have to be followed. For example, what information must be defined in the BOQ, what fields are required, and what specifications must be followed.

d) Internal review

Currently, the unofficial internal review is performed by the project manager or the leading architect of the given project. Additionally, the BOQs and other project documentation undergo the internal review as a part of the QA procedure on the project.

e) **External review**

Formal external review is rarely done. Usually, the external review is linked to the project solutions, not to the BOQs. For the public clients or clients where the tendering process is following the design process, external review is (in most cases) performed by the client or third party (consultancy company).

3.3.2.3 Mechanisms

A summarized description of the mechanisms is given below:

1. **Project manager**

   The project manager initiates the quantity takeoff process according to the project execution schedule and the actual stage of the design process. The approach for the QTO is defined (based on the project stage, contractual agreements, type of project, and other factors), the schedule is agreed upon (also considering the budget), and work is delegated.
2. **Quantity surveyor**

   The quantity survey is responsible for the quantity takeoff of the majority of building elements. Quantities of some elements are also obtained from the BIM models and manually inserted into the BOQ. The quantity surveyor plans the process, provides estimates for the schedule and gathers the required information in collaboration with project engineers, architects, and BIM modellers. The quantity surveyor then chooses an existing BOQ (regarding the structure and surveyed items) and executes the QTO process, and reiterates the process multiple times if necessary after the BOQ's internal and external reviews.
3. **Project architects and engineers**

   Project architects and engineers consult with the quantity surveyor to explain the design solutions and provide the missing information (either regarding items that are not yet in the documentation delivered for the QTO process either how the building project will be executed). Finally, they also serve as an informal internal control to see whether their design solutions are correctly reflected in the BOQs.
4. **BIM modellers**

   BIM modellers deliver basic quantities from the BIM models (concrete volumes, door schedules, window schedules, the weight of steel elements, and others). They also help with viewing and checking the federated BIM model in Navisworks.
5. **Office equipment and application software**

   Basic office equipment and application software is used and required for the AS-IS QTO process (desktop computer, PDF reader, MS Excel, Navisworks or equivalent, DWG reader, and others).

3.3.2.4 Outputs

Bill of quantities is the main output of the quantity takeoff process. It is prepared in MS Excel with manual inputs of measured quantities and descriptions of individual items in the BOQ.

The structure of the BOQs is not necessarily defined in advance or defined by the BOQ template but follows a certain logic and guidelines (for example, [38] and [39]). There are currently no standards that would prescribe the breakdown structure of the BOQs. Because the BOQ structure is adapted to what is required on a given project, some additional sections may be added. This is displayed in the example in Figure 11 below.

Client:		***Client - Example***
Facility:		**Facility - Example**
Type of works:		**Construction and Finishing Construction Works**
		SUMMARY OF COSTS
1.	**CONSTRUCTION WORKS**	**GRADBENA DELA**
1.1.	PREPARATORY WORKS	PRIPRAVLJALNA DELA
1.2.	EARTHWORKS	ZEMELJSKA DELA
1.3.	CONCRETE WORKS	BETONSKA DELA
1.4.	MASONRY WORKS	ZIDARSKA DELA
1.5.	CARPENTRY WORKS	TESARSKA DELA
1.6.	SCAFFOLDING	ODRI
1.7.	CONSTRUCTION WORKS - support for installations	GRADBENA DELA - podpora za instalacije
1.8.	SITEWORKS	ZUNANJA UREDITEV
	TOTAL CONSTRUCTION WORKS	**SKUPAJ GRADBENA DELA**
2.	**FINISHING CONSTRUCTION WORKS**	**ZAKLJUČNA GRADBENA DELA**
2.1.	FACADE WORKS	FASADERSKA DELA
2.2.	ROOFING AND SHEETING WOORKS	STREHA IN KROVSKO KLEPARSKA DELA
2.3.	ROOF DRAINAGE SYSTEM	ODVODNJAVANJE STREŠNE VODE
2.4.	LOCKSMITH'S WORKS	KLJUČAVNIČARSKA DELA
2.5.	PAINTING WORKS	SLIKARSKO PLESKARSKA DELA
2.6.	FLOORING WORKS	TLAKARSKA DELA
2.7.	SEALING WORKS	TESNENJE PREBOJEV V AB STENAH IN PLOŠČAH
2.8.	FLOOR DRAINS	ODVODNJAVANJE - DRENAŽA
2.9.	DOORS AND FLOOD BARIERS	VRATA IN PROTIPOPLAVNE BARIERE
	TOTAL FINISHING CONSTRUCTION WORKS	**SKUPAJ ZAKLJUČNA GRADBENA DELA**
TOTAL Preliminary assessment of cost:		**SKUPAJ predračun:**
	Note: Prices do not include VAT	Opomba: Cene ne vključujejo DDV

Figure 12: Example of a Level 1 BOQ breakdown structure in the AS-IS process.

3.3.3 AS-IS Process Modelling and Analysis

Using the information from the previous two steps, we can develop the AS-IS process model. Modelling followed the bottom-up approach, which means that the individual activities were modelled on the operational level and connected into processes. The ICOMs were already extracted from the questionnaires and were described in Section 3.3.2. The context diagram is shown in Figure 13.

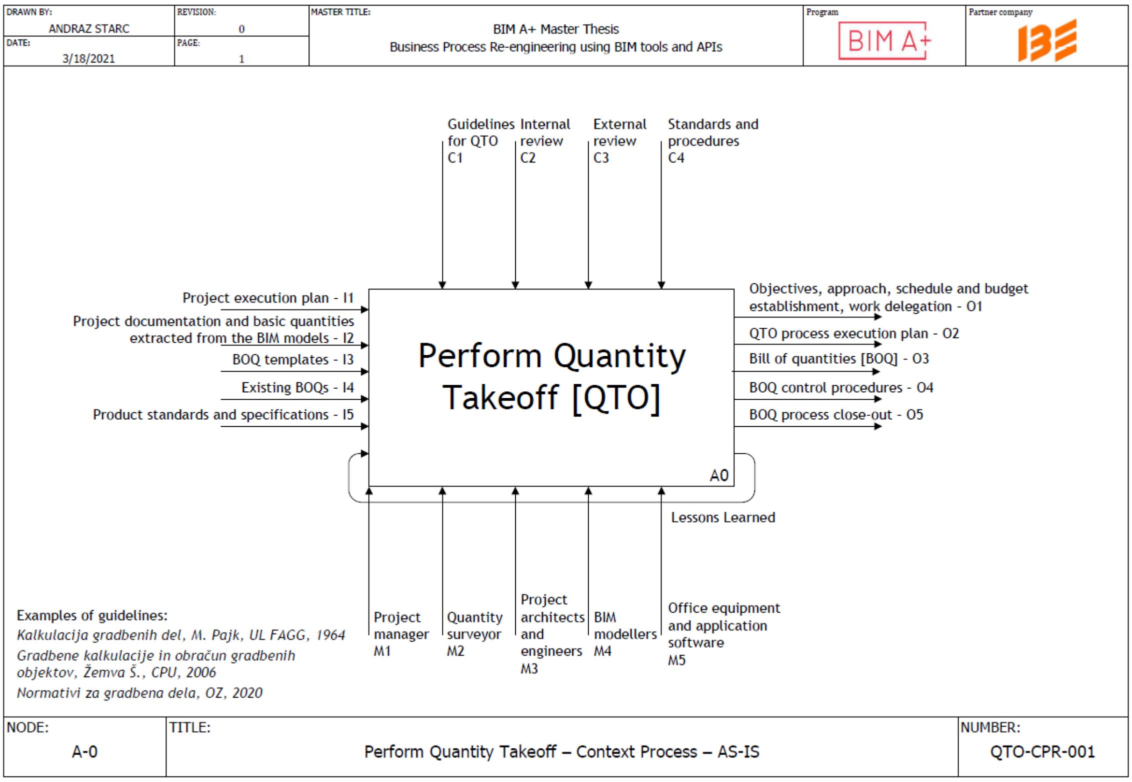


Figure 13: Context diagram for the AS-IS business process (QTO).

There are five main activities or processes:

1. **QTO process initiation -** the project manager initiates the process, meaning that the objectives are set and presented, the schedule is defined (although the work does not necessarily start yet), the budget is established, and the work is delegated to the chosen quantity surveyor.
2. **QTO process planning** – after being assigned the project, the quantity surveyor receives the project documentation and basic quantities extracted from the BIM models. Considering the objectives, schedule, project type, and size plans, the QTO process, based on previous experience (lessons learned), decides on the BOQ template and creates a QTO process execution plan (not necessarily documented).
3. **QTO process execution** – the main activity of the QTO process. After receiving and studying the project documentation and viewing BIM models, the quantity surveyor defines the structure of the BOQ and the rules of measurement. An existing BOQ is chosen and prepared for the QTO process on the given project. For individual items in the BOQ, the surveyor defines the

description and the unit of measure and measures the quantity by hand calculation. The general standards and procedures are followed in the execution of the QTO process and are referenced in the general notes. The product standards and specifications are referenced in individual items in the BOQ and are defined by project architects and engineers. They also provide additional information and explain the design solutions when needed. The BIM modellers assist with model viewing and provide material schedules extracted from the BIM models. These quantities (and all others) are manually inserted into the BOQ. The BOQ is exported into a pdf document from MS Excel. The process is iterative, subject to feedback loops from controls and changes with a simple (and manual) change management system.

4. **QTO process control** – following the execution or revision of the QTO process, the BOQ is internally reviewed by the leading architect or engineer to check if the items in the BOQ match the design solutions. When this process is complete (possibly in multiple iterations), the official internal QA review follows. After the BOQ is internally approved, possible external reviews follow.
5. **QTO process close-out** – after the approval, the BOQ is added to the rest of the project documentation and archived for later revisions or future use as a template or reference. All notes made while calculating the quantities and the project documentation used for the QTO process are archived. Lessons learned are currently not documented or reported on. With this, the process is concluded.

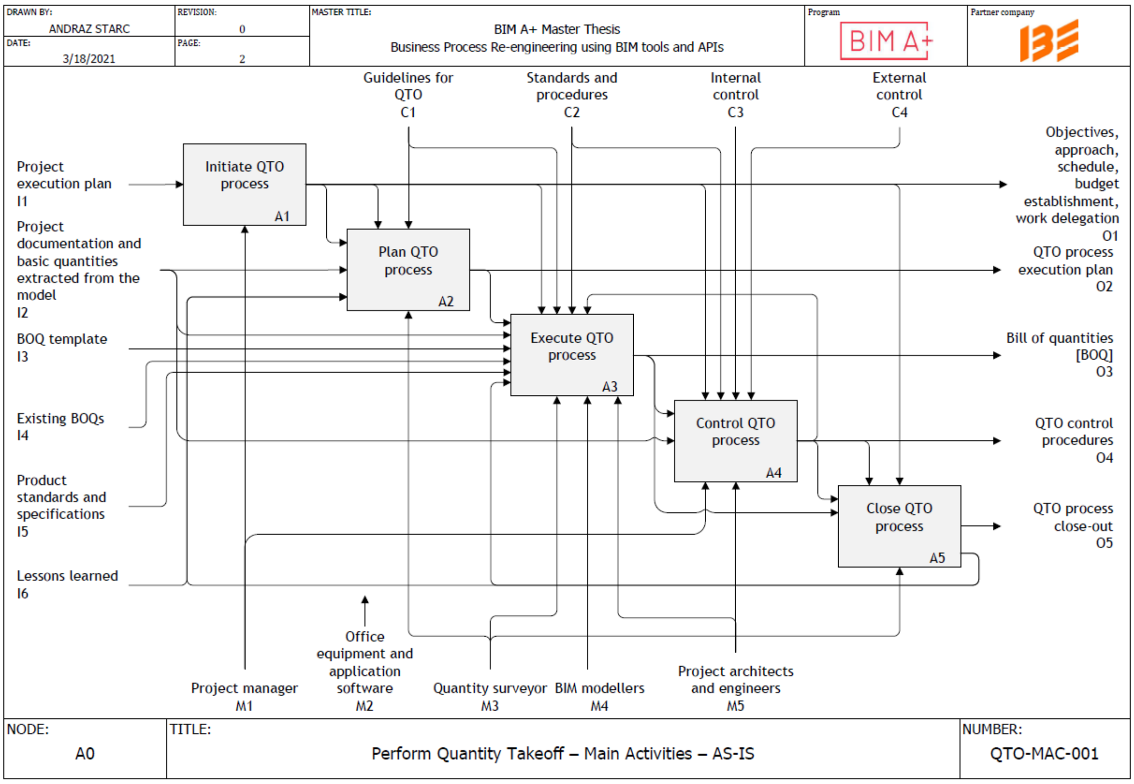


Figure 14: Diagram of the main activities for the AS-IS business process (QTO).

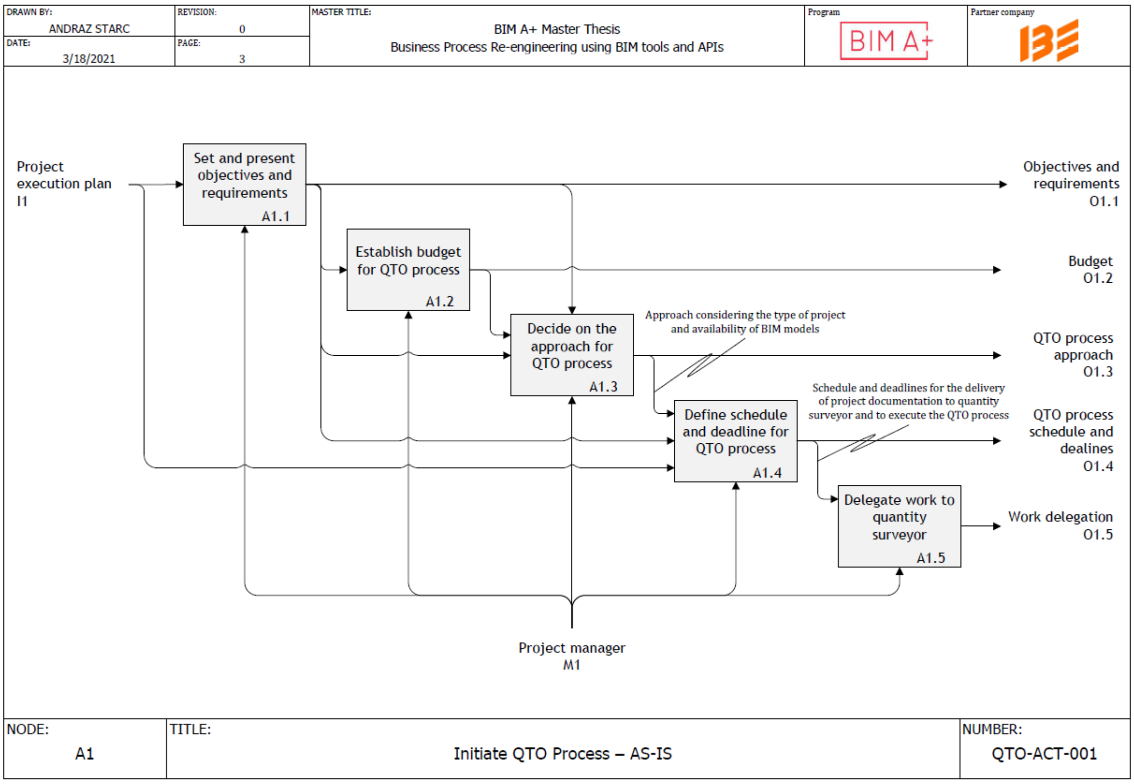


Figure 15: Diagram of the QTO process initiation (AS-IS).

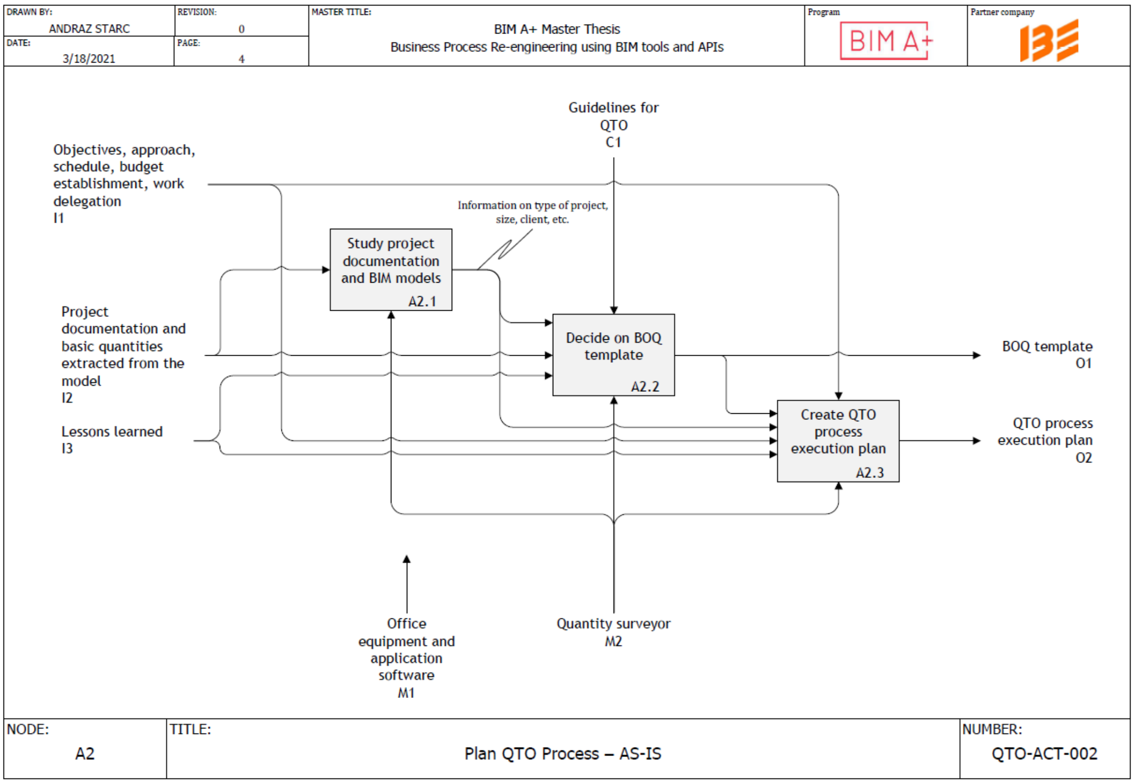


Figure 16: Diagram of planning of the QTO process (AS-IS).

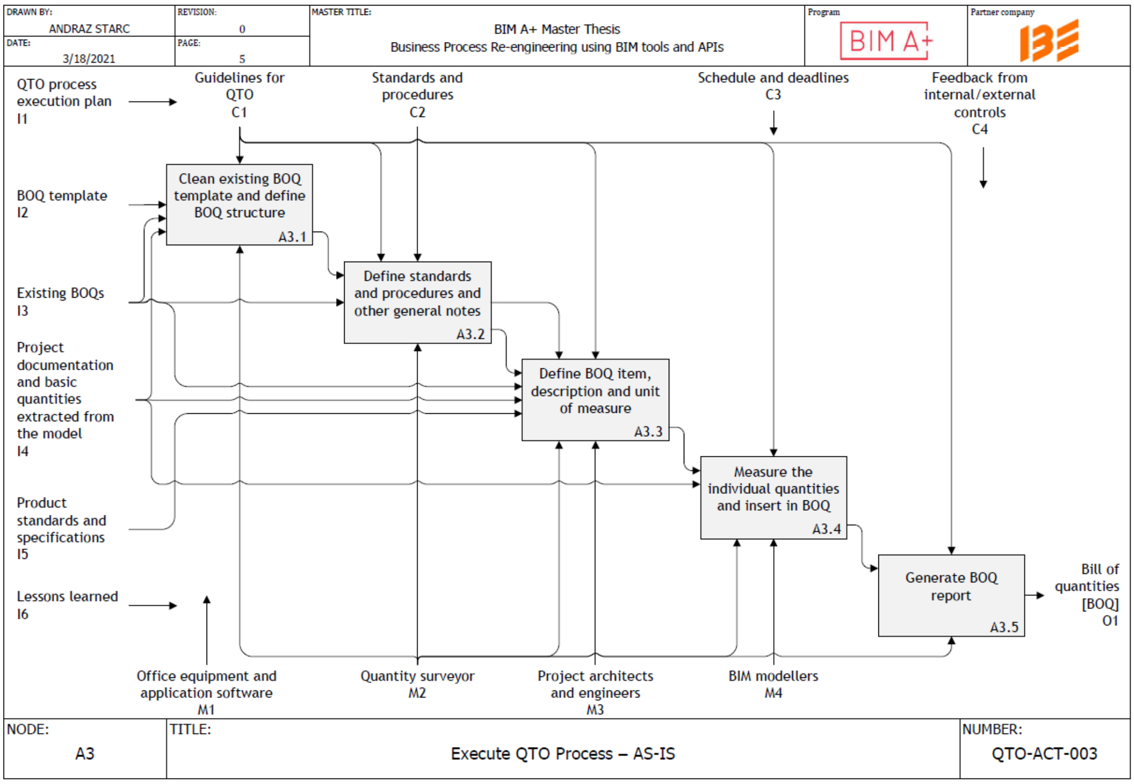


Figure 17: Diagram of execution of the QTO process (AS-IS).

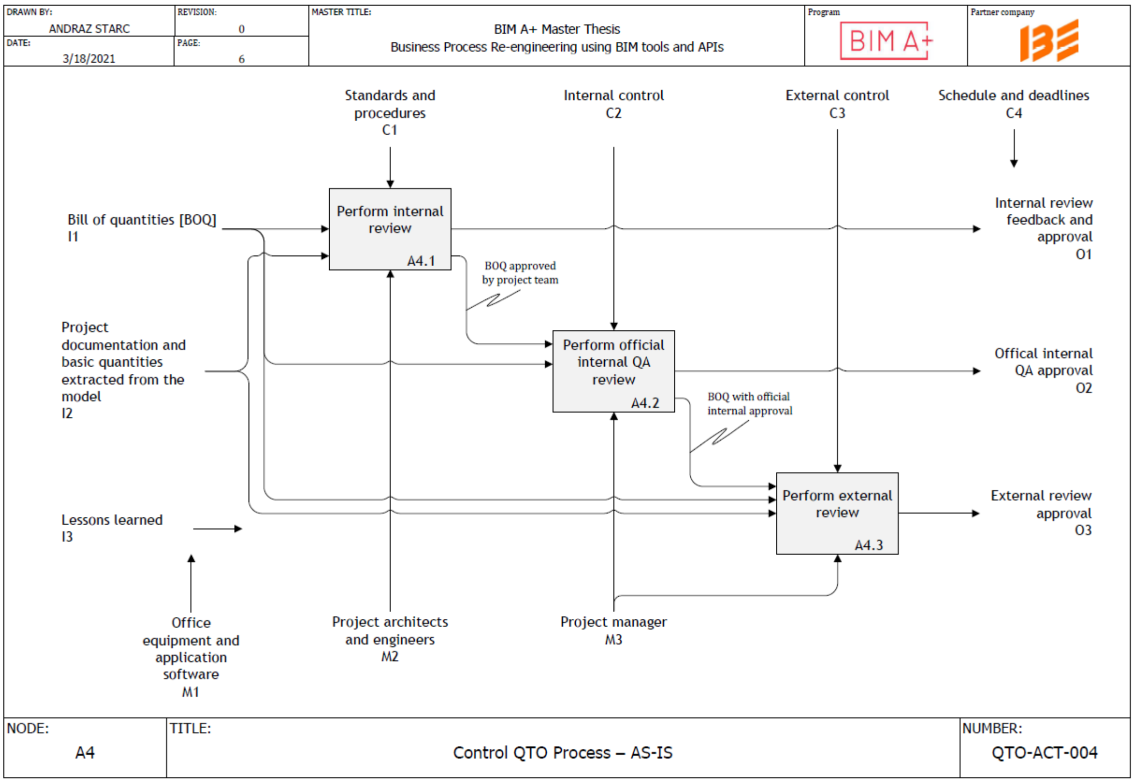


Figure 18: Diagram of control of the QTO process (AS-IS).

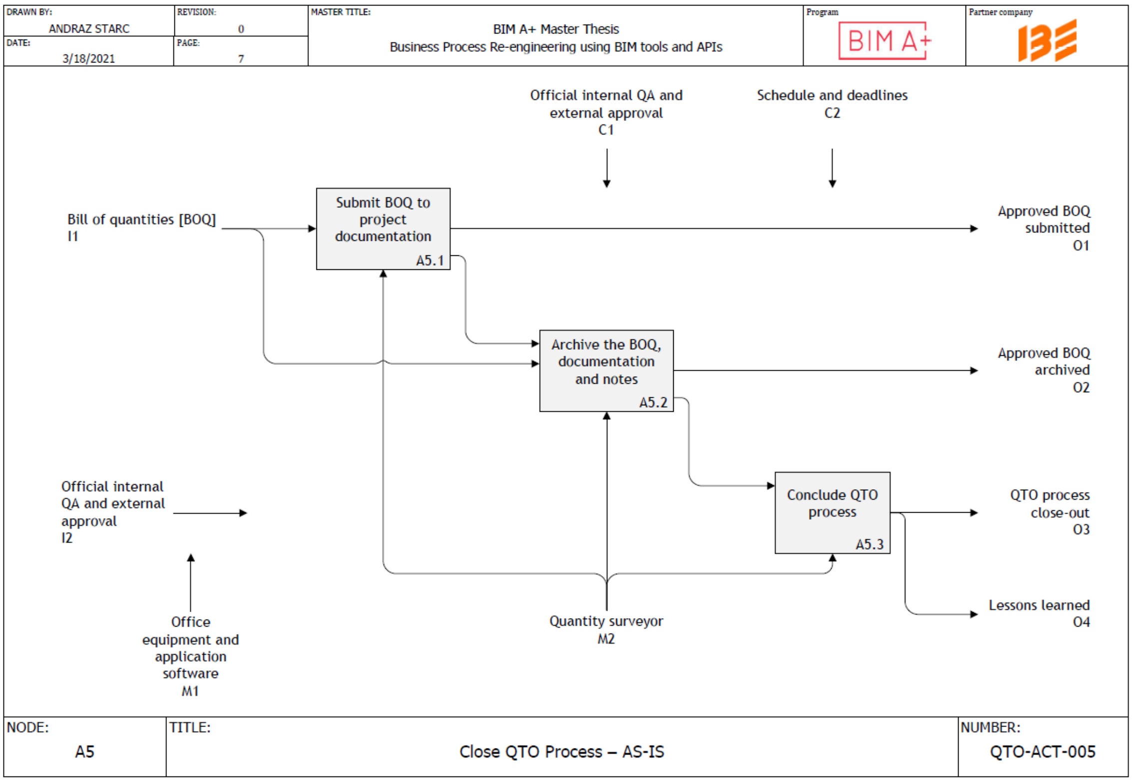


Figure 19: Diagram of close-out of the QTO process (AS-IS).

3.3.3.1 AS-IS Process Model Analysis

From the defined and documented AS-IS process, we can determine the bottlenecks, gaps, and weaknesses that may be bridged in the re-engineered process. The main points observed during the process analysis are summarized below:

1. **Manual measurements**

   Even though the BIM models are already available, the quantities are surveyed manually. This means that the process is still analogue, even though the final deliverable is digital. The manual measurements are much more time-consuming, and the quantity surveyor spends the majority of time performing the calculations. This can be considered a significant gap because extraction of the quantities from the model would significantly reduce the time spent on quantity measurements. It can also be considered a weakness because the potential of BIM models is not fully utilized and a bottleneck because of the time required to perform and possibly repeat the task.

2. **Error-prone process**

   Because of the manual measurements, the process is much more error-prone, as the quantity surveyor may easily make a mistake in calculating the quantity. Additionally, some elements can be overlooked, and others may be measured twice, which is considered a weakness.

3. **Change management**

   Change management is considered one of the most significant weaknesses, gaps, and bottlenecks in the process. Because of the manual measurements, all changed quantities must be surveyed again, meaning that the same amount of time and effort must be reinvested. This can be considered a significant bottleneck because some minor changes in the design solutions may delay the project delivery or close-out. It is also hard to observe all the changes to the design solutions, and some changes can easily be overlooked if they are not communicated with the project team. Furthermore, it is hard to track the changes. Since it is a manual process, the changes must be tracked manually, and new documentation revisions must be systematically archived and labelled. The above can be considered a weakness and a gap to be bridged in the re-engineered process.

4. **Accuracy of the surveyed quantities**

   Because of the analogue nature of the quantity surveying, the accuracy of the quantities measured may be compromised with the time required to measure them. The differences are not significant, but extraction of the quantities from the model would deliver more accurate results, which may have an impact, especially on larger projects.

5. **Communication with the design team**

   Communication with the design team is either in person, e-mail or communication tools (for example, MS Teams). Potentially, the quantity surveyor may also communicate with the design team through BIM models and RFIs.

6. **Automation**

   The AS-IS process currently has very few possibilities for automation. Since the quantities have to be surveyed manually and manually inserted in the BOQ in the next step, the potential for automation is limited, even if the quality of the BIM models would allow for it.

7. **Lessons learned and CPI**

   Currently, the lessons learned are not documented and do not improve the KPIs of the process (for example, the number of standardized BOQ items remains the same), but help with the process on future similar projects. Since there are no mappings between the model elements and the BOQ items, the time required to perform the process remains the same. There is no general database in the AS-IS process with the BOQ items or cost items with their descriptions and units (or costs) defined.

To conclude, the gaps, weaknesses, and bottlenecks listed above will be the key targets in re-engineering the AS-IS process. The highest priority will be those representing the maximum benefits in the short run and those fully aligned with the strategy of re-engineering the QTO process to a BIM-based QTO process.

3.4 Critical Success Factors (CSFs)

Before we propose and analyze the alternative solutions for the TO-BE process, we must determine the critical success factors. The chosen solution must accommodate all CSFs to ensure that the solution is not destined for ultimate failure. The critical success factors and their explanations/justifications are listed in Table 3.

Table 3: Critical success factors (CSFs) for TO-BE process solutions.

Critical Success Factor	**Explanation**
TO-BE process fully digitalized.	The first CSF is that the re-engineered process is digital. As assessed in the AS-IS process assessment, the manual execution of the existing process is the reason for most gaps, weaknesses, and bottlenecks. Metric: All (or the majority of) tasks must be executed in a digital environment.
BIM-based QTO process.	The quantities must be, wherever possible, extracted from the BIM models. The models and their information content must be developed to allow the extraction of the quantities. All items linked to model elements but not present in the model (for example, paint) are calculated based on model elements (for example, wall-length multiplied by the height of the painted surface). This is a strategic CSF as the main goal is to extend the BIM uses to the QTO process. Metric: More than 70% of the BOQ items are model-based. The percentage is determined (estimated) empirically.
Reduction in time spent and increase in profit	The re-engineered process must reduce the cumulative hours required to execute the process. By reducing the hours spent, the profits increase. The continuous improvement of the re-engineered process must further reduce the time spent. Metric: Cumulative hours spent to execute the BIM-based QTO process are lower than the hours spent with the traditional QTO process. The breakeven point must come after two major projects (+ pilot project) after the TO-BE process implementation (the initial investment must be manageable).
Workload and responsibilities distributed across the project team	In the re-engineered process, the workload has to be evenly distributed across the project team. The responsibilities of individual professions are kept within them (for example, the quantity surveyor is the person executing the QTO process and is responsible for it). Metric: The core tasks within the re-engineered process remain assigned to the same roles, and they are responsible for their deliverables.
Single environment	From the perspective of the quantity surveyor, the QTO process has to be performed within one environment. Moving quantities from one environment or application software to another would complicate the process and aggravate change management. Metric: Single environment allows the execution of the BOQ process and the generation of all reports and analyses required.
Change management	The solution must accommodate intelligent change management. The changes in the BOQ must be tracked through various revisions, and there must be a capability of comparing the values. Ideally, the application software can automatically compare the inputs and outputs, and no changes shall be overlooked. Metric: The changes must be managed within the application software, and the time to implement the changes must be reduced compared to the AS-IS process. No overlooked changes.

Standardized inputs and automation	The re-engineered process must benefit from the standardized inputs (templates, BIM models, cost item catalogues and rates, and others). A good example of leveraging the standardized inputs is automatically extracting the quantities based on the classification, keynotes or IFC parameters. Metric: Number of items in BOQ extracted automatically based on the standardized inputs and mapping rules defined.
Lessons learned and CPI	The re-engineered process must incorporate the lessons learned. The lessons learned must be reflected in the number of standardized cost items, the number of rates in the rate library, the development of the model mappings. Additionally, the lessons learned should also be reflected in BIM object libraries. Metric: Increased number of items in rate library, development of model mappings, new elements and updated elements in BIM object libraries.

3.5 Re-engineered Process Alternatives

Three conceptually different solutions for the TO-BE process were proposed and evaluated. All three solutions consider using various upstream BIM application software (for example, Tekla Structures, Autodesk Revit, Allplan and others) and corresponding application programming interfaces (APIs) as their foundation for the BIM-based QTO process. The three conceptually different alternatives are:

1. Internally develop, maintain and upgrade application software that targets domain-specific challenges within the organization and allows execution of the TO-BE QTO process.
2. Use application software already in use (Autodesk Navisworks) and develop, maintain, and upgrade add-ins that extend the application's functionality to the required level to execute the BIM-based QTO process as defined in the TO-BE process. Use APIs to target the remaining domain-specific challenges within the organization.
3. Buy software solution available on the market (iTWO costX) that specifically addresses the BIM-based quantity takeoff process and use APIs to target the remaining domain-specific challenges within the organization.

Without evaluating the details of the individual alternatives, we can see that the fundamental difference between them is whether the main software solution will be developed internally or bought from a software vendor. There are good examples of the solutions developed internally (for example, Veira, 2020, [4]).

3.5.1 Pros and Cons of Developing Software Internally

The development of software internally may be justified:

- For ad hoc applications specific to a single business process.
- For problems unique to your organization and the currently available software does not address it adequately.
- To solve a siloed problem that does not affect other areas of the business.
- If you have a strong IT department and have the resources to build, maintain and support the application long-term.

The pros of developing your own software are:

- Getting total control over the development and features.
- The software and its reporting capabilities meet exact needs.
- Retaining the ownership of the software code.
- Standing out from the competition.

The cons of developing your own software are:

- Lots of time is required to develop and test the code and integrate it with other business systems.
- Indefinite maintenance and support of the application.
- Making rapid adaptations to the application when the business need changes and when new releases of the integrated application software occur.
- Typically the internally developed software will have lower functionality than the one bought from vendors would.

3.5.2 Pros and Cons of Buying Software From a Vendor

Buying software from a vendor is recommended if:

- The software is critical to business operations.
- There is a common problem that available and possibly customizable software can address.
- The software will be used throughout the organization and can integrate with other applications.
- The IT department is not equipped to build, maintain and support the application long-term.

The pros of buying software solutions are:

- The solution is ready-made and available when needed.
- Much effort was invested into the development – high quality and reliability assured.
- Expert support and training (and online community) are available.

The cons of buying software solutions are:

- The developer retains the right to code.
- The functionality is determined by the vendor and may not meet the exact business needs.
- The vendor is relied upon to fix the issues.

3.5.3 Evaluation of the Re-engineered Process Alternatives

Firstly, the SWOT analysis was performed for the three alternatives. The summary is given in Table 4.

Table 4: SWOT analysis for the re-engineered process alternatives.

	Alternative 1: Develop software internally.	**Alternative 2:** Use available software (Navisworks), extend functionality with an add-in and target domain-specific challenges with APIs.	**Alternative 3:** Buy specific software for the QTO process from the market and target domain-specific challenges with APIs.
Strengths	-Flexibility. -Control over the solution. -Ownership of the solution. -Meeting exact needs.	-Software is already partially available. -Employees already master the software. -Partial flexibility.	-Software is already available. -High-quality solution. -Support and maintenance assured. -Reliability and high chances for ultimate success.
Weaknesses	-Lower quality/functionality. -Not available immediately. -Maintenance and upgrades are required.	-Not available immediately. -Updates required with new versions of Navisworks. -Limited functionality.	-Up-front investment. -Employee training and development of inputs required. -Possible limits to functionality.
Opportunities	-Development of new skills. -Expanding business domain. -Standing out from the competition.	-Development of new skills. -Mastering existing software and its API. -Standing out from the competition.	-Collaborating with and learning from other companies. -Use of functionalities that were initially not expected.
Threats	-Ultimate failure. -Development and maintenance costs are not justifiable.	-Ultimate failure. -Limited reporting functionality.	-Increased prices with renewed licences. -The solution no longer matches the business need. -Issues not getting fixed within a reasonable period.

As can be observed from the SWOT analysis, alternatives 1 and 2 offer the best opportunities and have some considerable weaknesses. Alternative 1 is also the most likely to ultimately fail, as the burden on the IT department may be far too great. Alternative 3 exhibits fewer opportunities but has the biggest strengths and is not subjected to significant threats, making it the most likely to succeed if the up-front investment is moderate.

Secondly, the alternatives were evaluated against the critical success factors. The ultimate success of the re-engineered process will depend on the actual metrics of the CSFs, but the factors may be evaluated in advance to ensure that the ultimate success is viable in the first place.

The evaluations of CSFs for individual re-engineered process alternatives are given in Table 5 below.

Table 5: Evaluation of CSFs for the re-engineered process alternatives.

Critical Success Factor	**Alternative 1***	**Alternative 2***	**Alternative 3**
TO-BE process fully digitalized.	✓	✓	✓
BIM-based QTO process.	✓	✓	✓
Reduction in time spent and increase in profit	✓	✓	✓
Workload and responsibilities distributed across the project team	✗	✓	✓
Single environment	✓	✓	✓
Change management	✗	✗	✓
Standardized inputs and automation	✓	✓	✓
Lessons learned and CPI	✓	✓	✓

* *the evaluation is based on the assumption that the functionality developed application software would meet the requirements.*

As can be observed from the evaluation of CSFs for re-engineered process alternatives, the alternatives (as initially proposed) can accommodate most critical success factors. The assumption is that the development of the software solutions (standalone solutions or add-ins for Revit or Navisoworks) would be successful and meet the requirements. However, for alternative 1, the threat is that the quantity surveyor's responsibility would not remain with the quantity surveyor but rather with BIM modellers or BIM coordinators. This is unacceptable both from the perspective of workload and responsibility. Another threat is that an adequate change management system may be challenging to implement within a reasonable time and with reasonable resources, as most existing commercial software solutions do not exhibit this feature.

From the evaluation above, it can be concluded that the most appropriate alternative is *alternative 3*. Finally, this was the re-engineered process alternative that was developed and implemented.

3.6 TO-BE Process Model

3.6.1 Overview of the Proposed Solution

As anticipated, the re-engineered process will implement BIM-based quantity takeoffs. The goal is to digitalize the process in its entirety. There will be several essential changes and improvements to the initial process:

- Implementation of a new software solution (iTWO costX).
- Adoption of standardized inputs (BIM models) through classification systems, keynotes, internal data dictionaries and controlled vocabularies.
- Development of (Revit) API solutions to target specific challenges (quantities).
- Development of model maps, rate libraries and phraseologies for an efficient BIM-based QTO process.
- Improvements in overall process control (quality checks, change management, and others) and leveraging the lessons learned through continuous process improvement.

3.6.2 TO-BE Process Modelling

The development of the re-engineered TO-BE process model followed the top-down approach, meaning that first, the overall process implementing the abovementioned changes and improvements was captured. The overall process was then broken down into individual activities and tasks until sufficient details were specified. The TO-BE business process context diagram is shown in Figure 20 below.

The differences in ICOMs compared to the AS-IS business process are clear. Compared to the AS-IS business process, the primary inputs to perform the quantity takeoff are BIM models (accompanied by model-based CAD drawings ensuring that all quantities can be adequately measured if the elements are not available in the models as 3D BIM objects). Instead of using existing BOQs and BOQ templates, the re-engineered process uses a basic iTWO costX workbook template and libraries (BIM templates, model mappings, code libraries, rate libraries, phraseologies, and others), which are partially developed in advance, partially developed during the QTO process execution and continuously improved through CPI (throughout multiple projects). The main output (BOQ) is, therefore, a model-based bill of quantities. The BIM models must be prepared to suit the quantity takeoff model use. Thus, some additional quantities must be calculated within the BIM authoring environment, and the models must be exported to IFC format using user-defined property sets. The mechanisms in the TO-BE business process include BIM authoring tools, application software for BIM-based quantity takeoff and a BIM coordinator (responsible for all model checks, exchanges of BIM models, implementation of lessons learned and others). The controls include model checking procedures and are generally linked to BIM-based quantity takeoff. Lessons learned are documented and implemented in process developments.

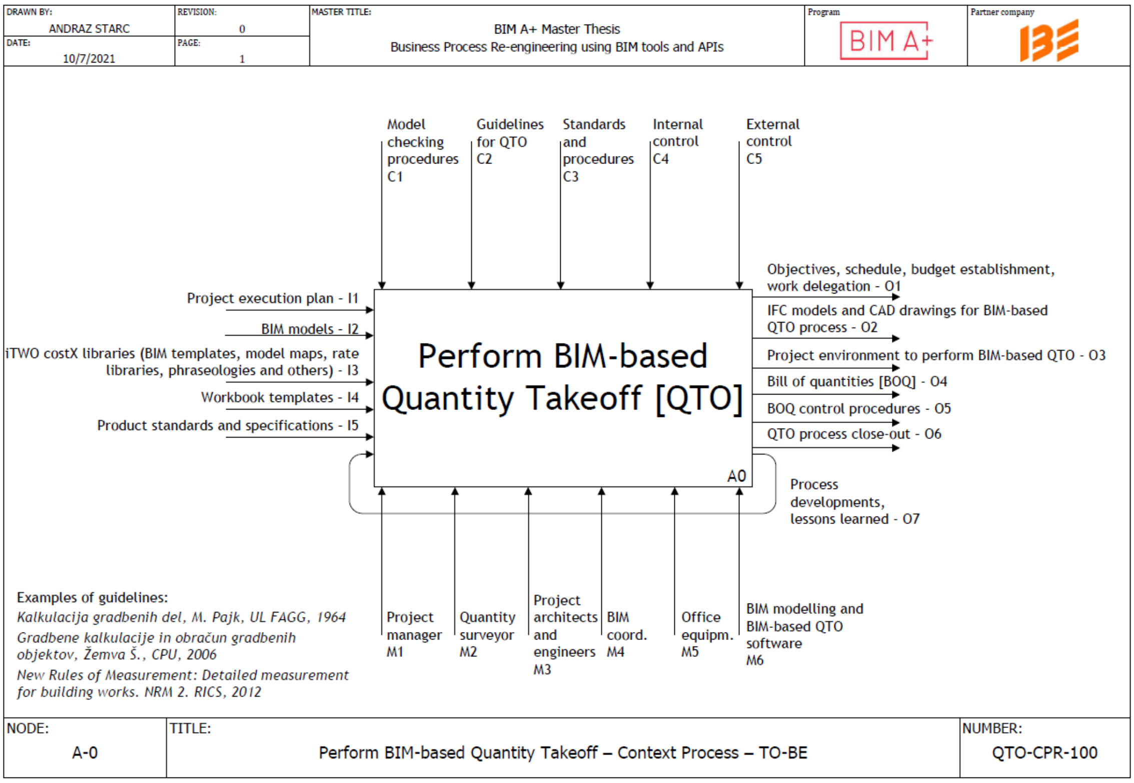


Figure 20: Context diagram for TO-BE business process (BIM-based QTO).

The individual tasks are merged into six main activities. The process diagram of the main activities of the BIM-based quantity takeoff process is shown in Figure 21 below (not all connections are visible).

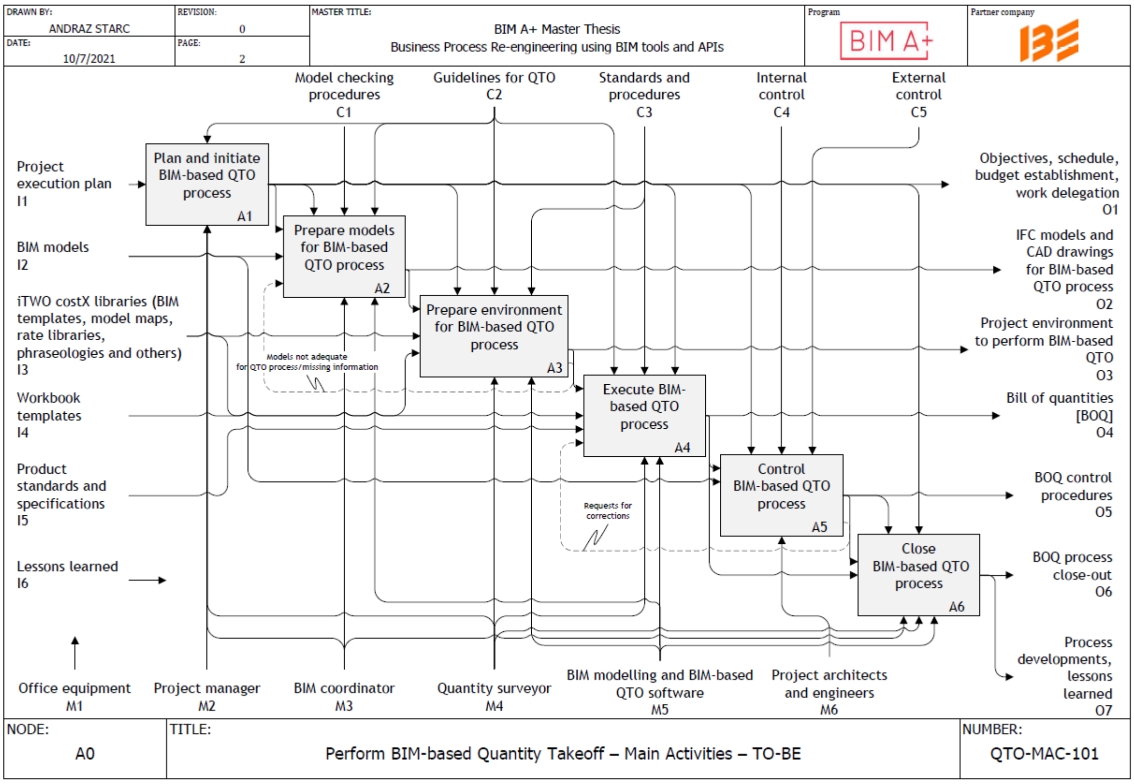


Figure 21: Diagram of the main activities for the TO-BE business process (BIM-based QTO).

Descriptions of individual main activities are given below.

1. **BIM-based QTO process planning and initiation** – the project manager initiates the process, defines the objectives and requirements for the BIM-based QTO process, establishes the budget and delegates work to a quantity surveyor. Compared to the AS-IS process, the schedule is agreed upon between the project manager, quantity surveyor and BIM coordinator. The latter is essential, as an adequate quality of the models meeting the requirements for the QTO process must be delivered to the quantity surveyor early in the process.
2. **Preparation of BIM models for the BIM-based QTO process** – the BIM coordinator prepares the models to meet the requirements for the BIM-based QTO model use. Firstly, the specific quantities are calculated for model elements (for example, net formwork areas for concrete elements). Secondly, the models are checked for completeness of the design solutions and corrected if needed. Thirdly, an automatic model check is performed, assessing if the models meet the information requirements. Finally, the models are exported to IFC format using user-defined property sets. Additionally, the model-based CAD drawings are exported.
3. **Preparation of iTWO costX environment for BIM-based QTO process** – the quantity surveyor prepares the project environment in iTWO costX software by importing the models/drawings, defining general project information and units of measure, performing visual checks of the imported models/drawings, preparing the inputs required to extract the quantities (BIM templates, model mappings, and others) and preparing the inputs required to create the workbook for the BOQ (workbook template, BOQ structure, code and rate libraries, phraseologies and others).
4. **Execution of BIM-based QTO process** – the quantity surveyor executes the QTO process. Firstly, the surveyor defines the standards and procedures in the general notes. Secondly, the surveyor surveys the quantities in several steps (extracting the standard quantities from the models using model maps, BIM templates, extracting custom quantities and measuring/extracting the remaining quantities that can not be extracted automatically) and populates the workbook with quantities and other information (descriptions, codes, and others). Finally, the surveyor generates the BOQ report.
5. **Control of the BIM-based QTO process** - following the execution or revision of the BIM-based QTO process, the BOQ is internally reviewed by the leading architect or engineer to check if the items in the BOQ match the design solutions. Additionally, the BOQ is checked with the BIM coordinator to check if the basic quantities match the quantities in the material schedules available in BIM authoring tools. When this process is complete (possibly in multiple iterations), the official internal QA review follows. After the BOQ is internally approved, possible external reviews follow.

6. **Close-out of the BIM-based QTO process** - – after the approval, the BOQ is submitted to the rest of the project documentation. All project files, inputs and outputs are digitally archived. Additionally, the quantity surveyor and BIM coordinator update the iTWO costX libraries (model mappings, code and rate libraries, and others) with the developments from the project and the BIM coordinator also updates the BIM libraries. This ensures that the business process continuously improves and the developments made on one project are utilized on all future projects. Finally, the project developments and lessons learned are documented. This concludes the BIM-based QTO process.

The diagrams of individual activities in the re-engineered business process are presented in Figure 22 - Figure 31 below.

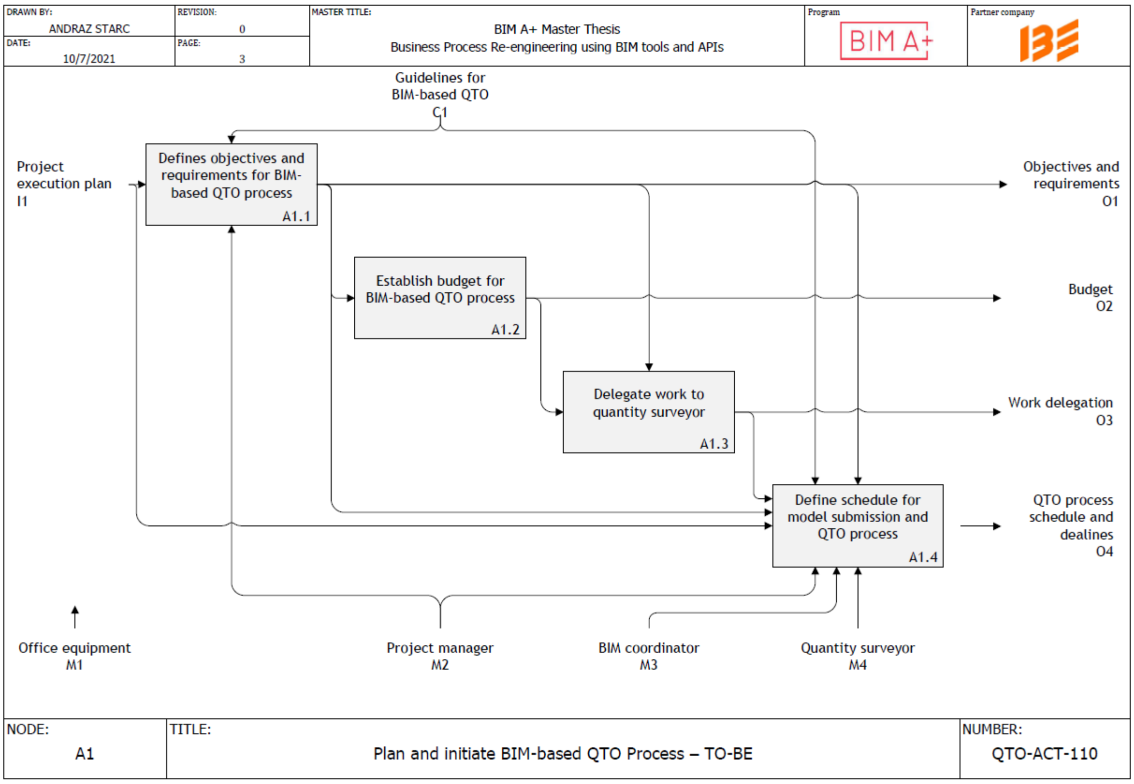


Figure 22: Diagram of the planning and initiation of the BIM-based QTO process (TO-BE).

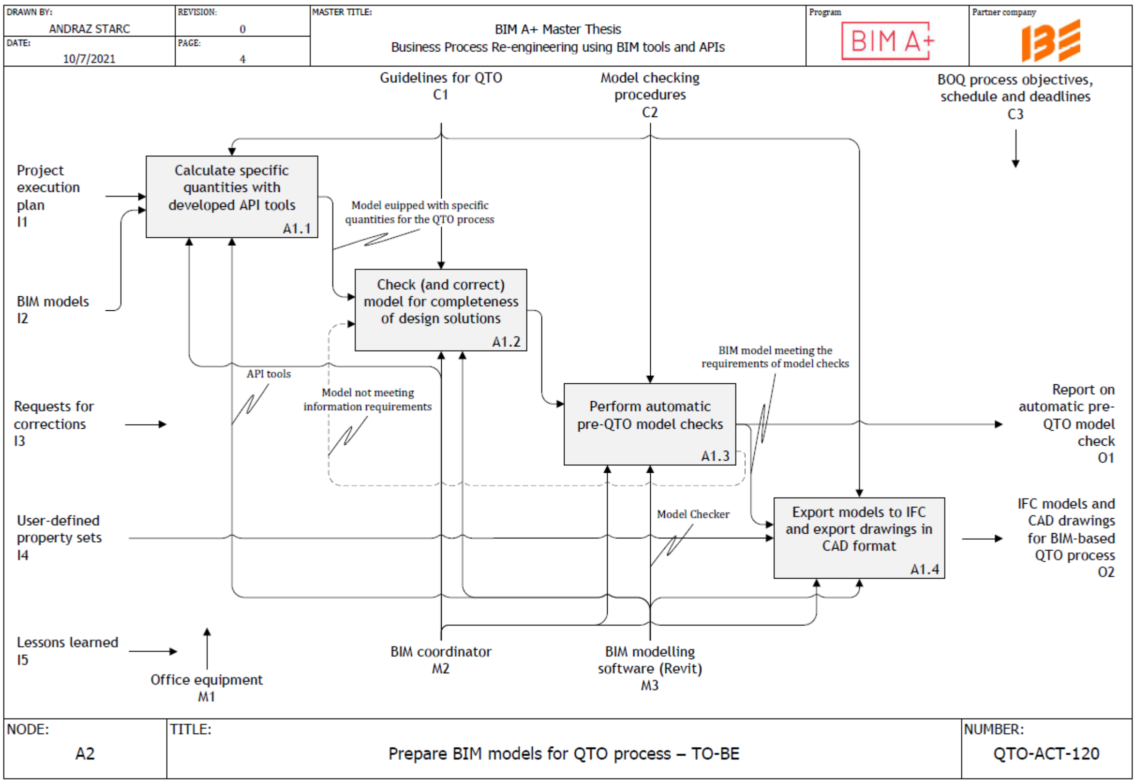


Figure 23: Diagram of the preparation of BIM models for the BIM-based QTO process (TO-BE).

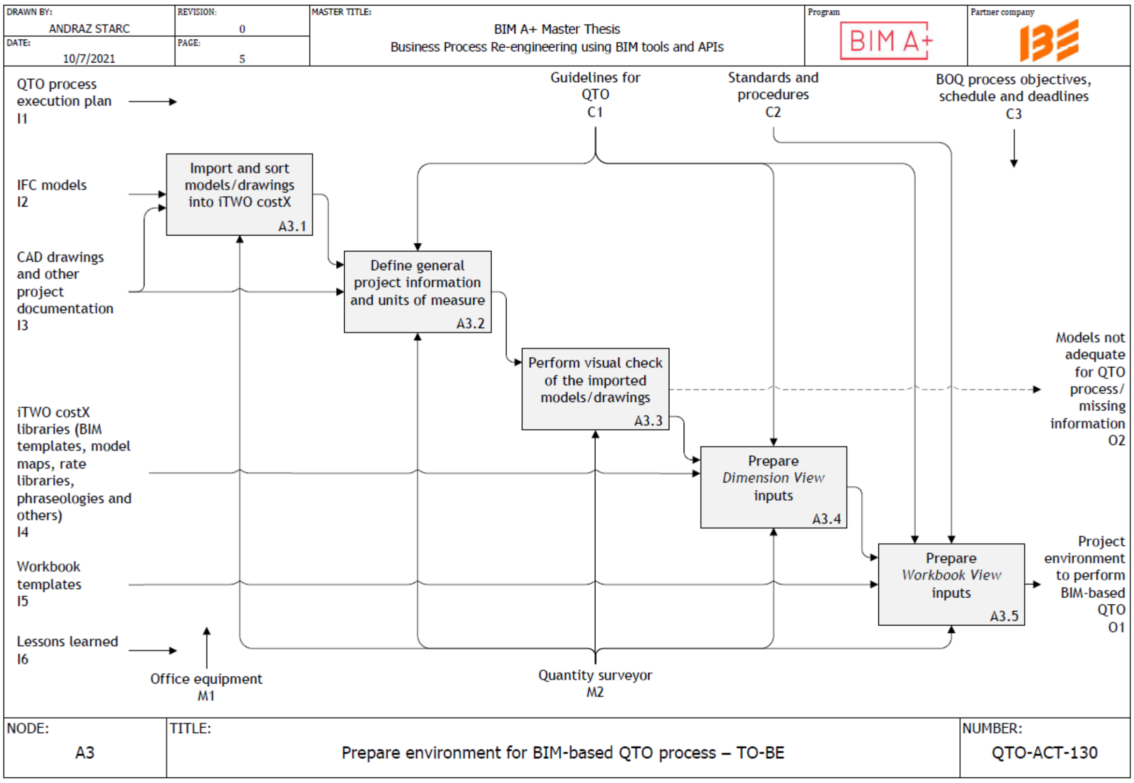


Figure 24: Diagram of the preparation of the iTWO costX project environment for the BIM-based QTO process (TO-BE).

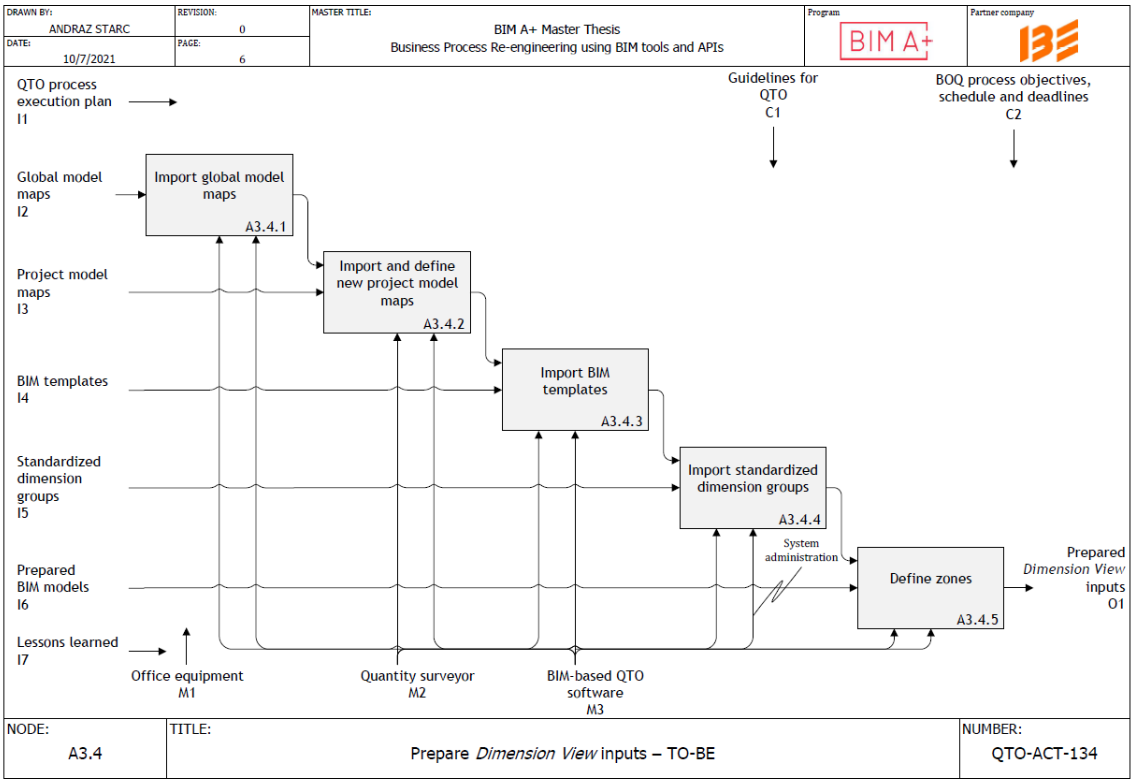


Figure 25: Diagram of the preparation of the Dimension View inputs within the iTWO costX project environment for the BIM-based QTO process (TO-BE).

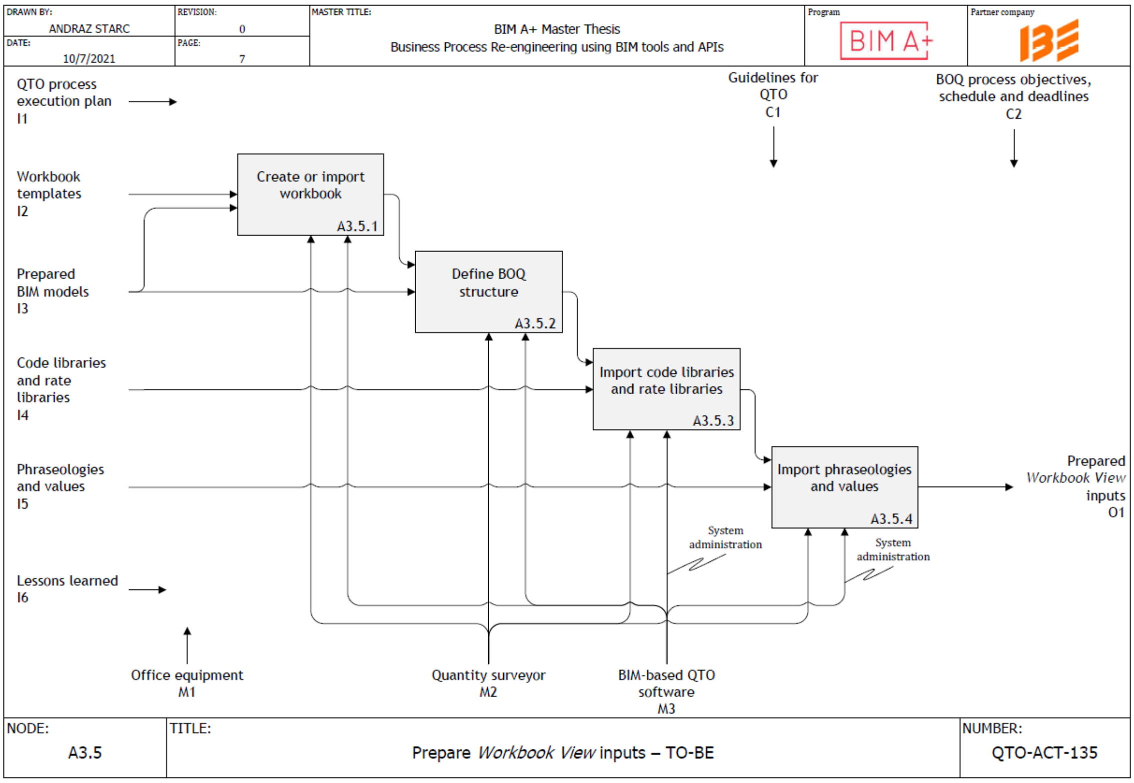


Figure 26: Diagram of the preparation of the Workbook View inputs within the iTWO costX project environment for the BIM-based QTO process (TO-BE).

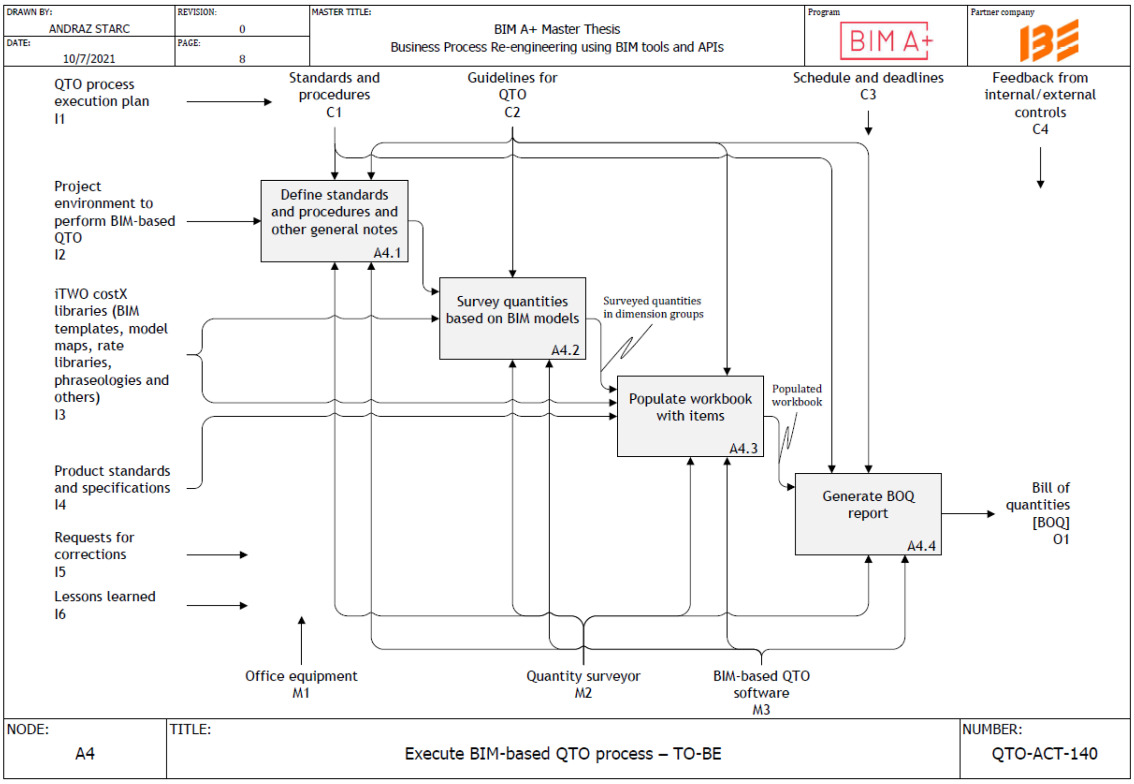


Figure 27: Diagram of the execution of the BIM-based QTO process (TO-BE).

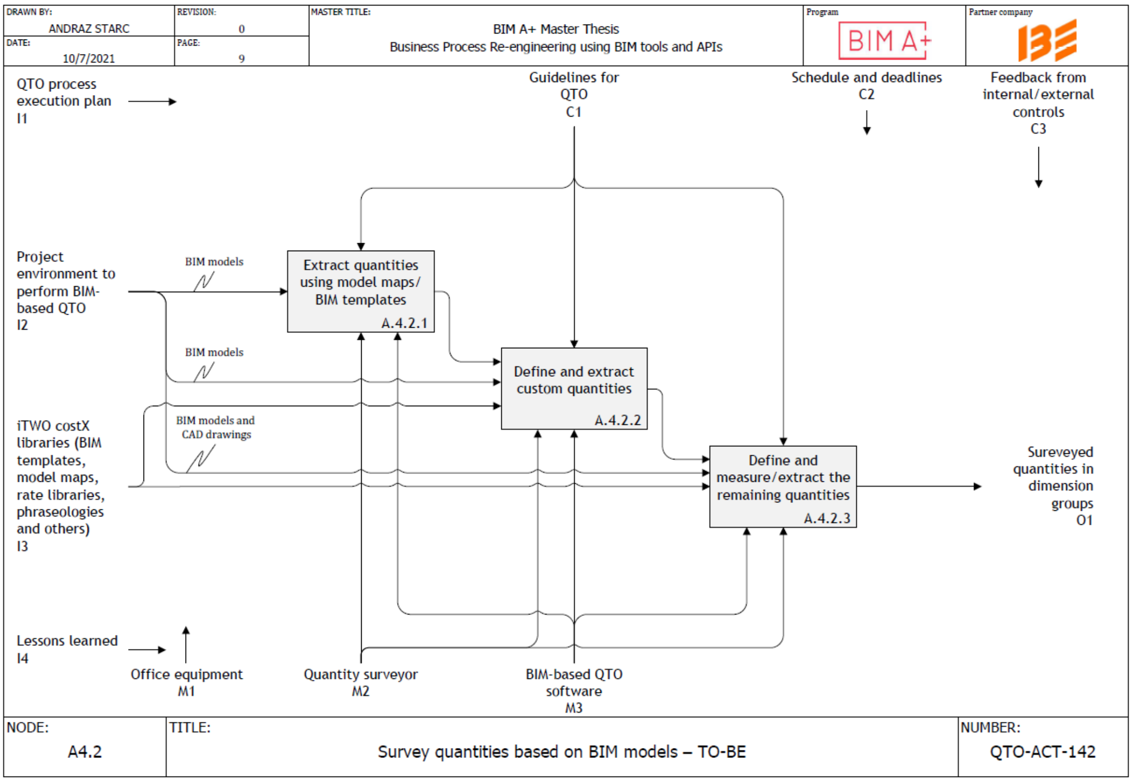


Figure 28: Diagram of the quantity surveying in the execution of the BIM-based QTO process (TO-BE).

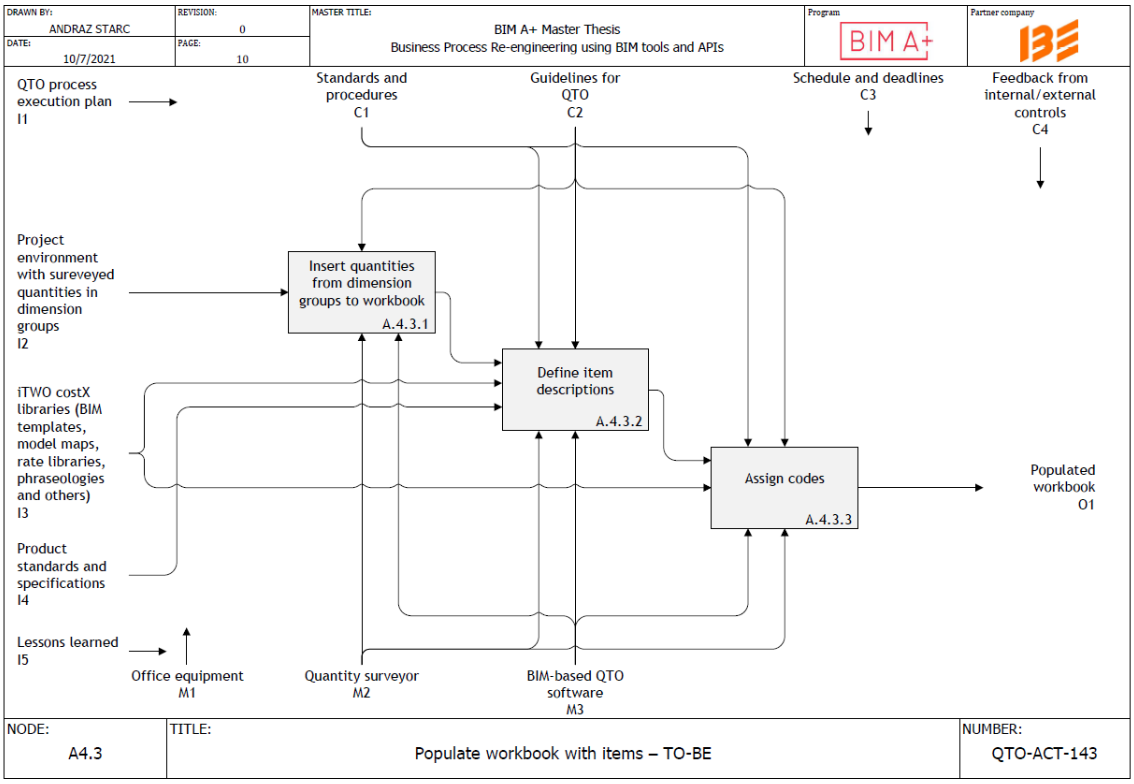


Figure 29: Diagram of workbook populating in the execution of the BIM-based QTO process (TO-BE).

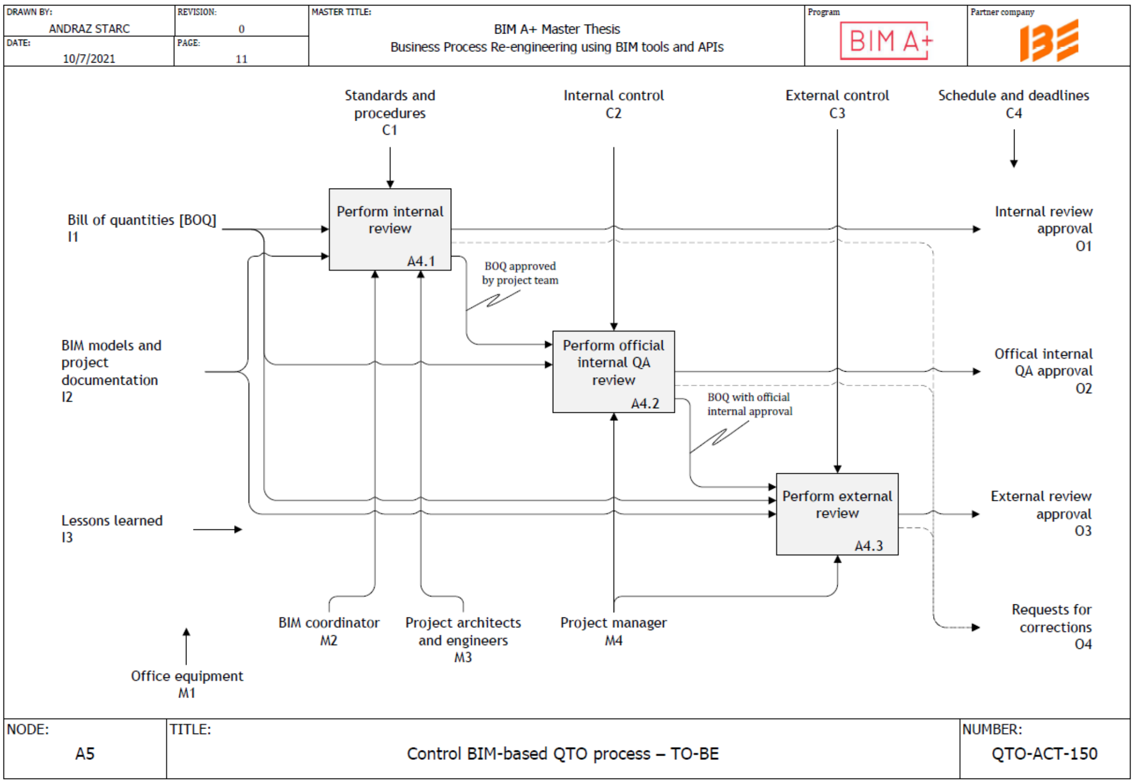


Figure 30: Diagram of the control of the BIM-based QTO process (TO-BE).

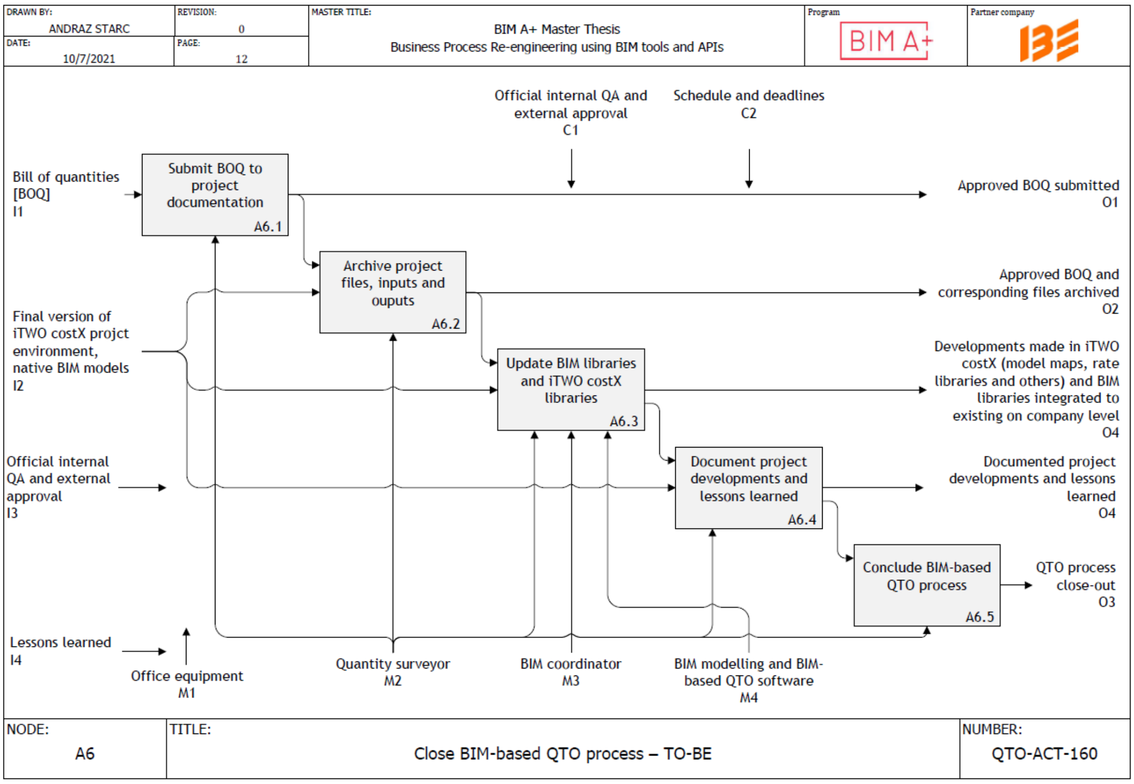


Figure 31: Diagram of the close-out of the BIM-based QTO process (TO-BE).

3.6.3 Key Performance Indicators for the TO-BE Business Process

To continuously evaluate the success of the re-engineered business process, the key performance indicators were defined. The KPIs will indicate if the company is progressing towards the intended results and expose the areas that need more focus during continuous process improvement. The chosen KPIs for the BIM-based QTO were:

1. The number of model-based BOQ items compared to the number of items that could be extracted from the model (excluding items that are not linked to model objects, for example, preparation of safety plan, protection of surroundings, and others).
2. The summed cost of model-based BOQ items compared to the total cost (applicable for cases where costs are calculated).
3. Person-hours spent per project (and comparison to the assessment of the person-hours required using the traditional method of QTO).
4. The amount of time spent implementing changes for existing items in the workbook compared to the time required to survey the items in the first iteration.
5. Amount of standardized (and documented) inputs and processes in the QTO process.
6. Overall control of the process (reliability, correctness, change management, and others).
7. Amount of items in libraries (BIM object libraries, keynotes, rate and code libraries, phraseologies, model maps, and others).

3.7 Implementation of the Re-engineered Busines Process

The implementation of the re-engineered business process was divided into several areas and between several key roles. Multiple developments were required to implement the TO-BE process successfully:

- Analysis of existing BOQs to understand the rules of measurement and corresponding quantities in modelled BIM objects.
- Adoption of classification standards and their implementation in BIM libraries.
- Development of a keynote system and its implementation in BIM libraries.
- Development of internal data dictionaries and their implementation in BIM libraries.
- Development of an alternative library management system.
- Development of model checking procedure and its implementation in Revit.
- Definition of model exchange for QTO model use.
- Development of iTWO costX libraries (BIM templates, model maps, code libraries, rate libraries, phraseologies, and others).

Due to the limited time resources, the BPR, in combination with the thesis, covered the development of conceptual solutions and their implementation in a limited number of cases (for example, the development of an internal data dictionary focused on cases that were later used in a case study).

3.7.1 Roles and Responsibilities

For successful implementation, a BPR team has to be defined, and the roles and responsibilities have to be assigned to all team members. One way of assigning responsibilities is by using the *RACI* matrix, where:

R = *Responsible,* A = *Accountable,* C = *Consulted,* I = *Informed.*

The *RACI* matrix is given in Table 6 below.

Table 6: RACI matrix for BIM-based QTO implementation.

	BPR Team			
Role	**Manager**	**Process owner**	**BIM manager**	**Appointed quantity surveyor**
Resource management & approval	R, A	C	I	I
Strategy for implementation	A	R	C	C
Implementation of classification standards	I	A	R	I
Development and implementation of keynote system	I	A	R	I
Development and implementation of int. data dictionaries	I	A	R	C
Development of alternative library management system	I	A	R	I
Development and impl. of the model checking procedure	I	A	R	C
Definition of model exchange for QTO model use	I	A	R	C
Development of iTWO costX libraries	I	A	C	R

3.7.2 Analysis of Existing BOQs

Analysis of the existing BOQs can help us a lot with the implementation of the TO-BE business process. Firstly, we can analyze the origin of the quantities in the existing BOQs. This will give us information on how many quantities were extracted from the model (and manually input into the BOQ), how many were calculated manually, and why.

The analysis was made on an existing project, later used in the case study (see section 4). Comparing the results of both studies will give us one of the KPIs. The BOQ was analyzed item by item, and the analysis results were documented in an Excel spreadsheet. The analysis was made using visual inspection of the BOQ combined with modelling software (Autodesk Revit) and analysis software (Navisworks). Each item was shortly described and assessed: a) whether the quantity within the existing BOQ was model-based, b) whether the quantity could be model-based in the current (AS-IS) process (the model objects allow extraction), and c) whether the quantity could be model-based in the re-engineered (TO-BE) process. The specific rules of the individual disciplines were considered.

The reason codes assigned to individual items (from the specific BOQ) were:

1. General item / Not linked to model elements.
2. Items are not modelled.
3. The modelling does not allow extraction of the quantity (not modelled correctly).
4. Extracted from the model and manually input into BOQ
5. Not extracted from the model but could be.
6. Grouping in BOQ is different from grouping in the model.
7. Needs calculation based on modelled elements.
8. Needs specific quantity (net) to be calculated.
9. Defined by the manufacturer in advance.

The results of the analysis were visualized using Microsoft Power BI. An interactive dashboard was created, giving us a better insight into the relationships between the reason codes, types of BOQ items, and the items' section (for example, Concrete Works). The results were shown in three pie charts, each displaying assessment a), b), or c).

The results show that 62 (out of 325) quantities in the existing BOQ were model-based. We can also see that 150 (out of 325) quantities could be extracted from the BIM models. The most common reason codes for the quantities that could not be extracted were [1] General item/ Not linked to model elements and [3] The modelling does not allow extraction of the quantity (not modelled correctly). The results also show that 265 (out of 325) quantities could be extracted from the BIM models in a re-engineered (TO-BE) business process. The latter is an essential takeaway because not all BOQ items will have quantities extracted from the model (in this case, around 80%).

The overall dashboard (without any filters applied) is shown in Figure 32.

Figure 32: Overall Power BI dashboard with existing BOQ analysis results.

We can also filter the results displayed on the dashboard. For example, we can focus on the Concrete Works section of the BOQ and realize that even though only 5 (of 47 quantities that could potentially be extracted from the model) quantities are model-based, 38 (out of 47) items could already be extracted from the model. The latter indicates that the models of concrete structures already meet most of the requirements for the BIM-based QTO. The dashboard for the Concrete Works section is shown in Figure 33 below.

Figure 33: Power BI dashboard with existing BOQ analysis results for concrete works.

We can also summarize the (overall) results in two gauge diagrams. The results are shown in Figure 34 below.

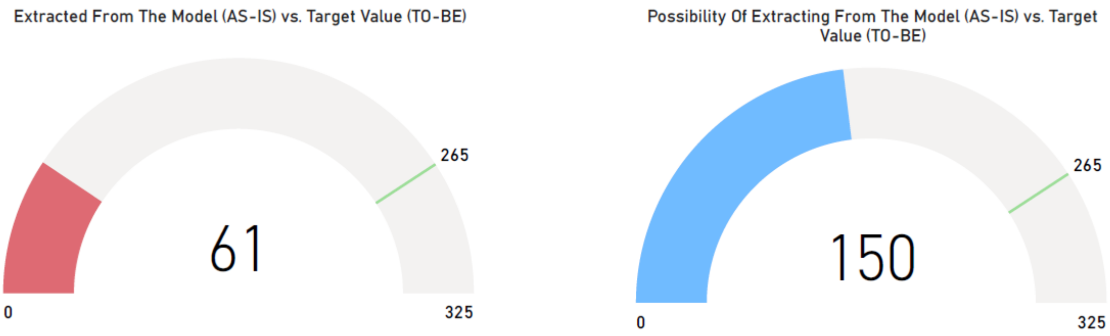


Figure 34: Power BI gauge diagrams with summarized existing BOQ analysis results.

Secondly, we can analyze how various quantities from the existing BOQ can be extracted from the BIM models. This analysis gathered information on how to model the elements to perform BIM-based QTO and the correct parameters (or formulas) to extract the quantities from BIM objects. The results of the analysis were documented in a tabular form. A section (concerning excavation, lean concrete and formwork) is shown in Figure 35 below.

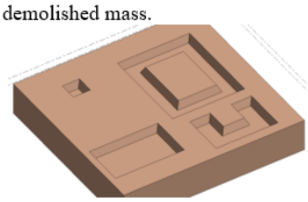
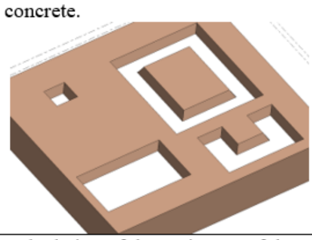
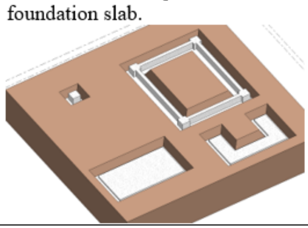
Item	**Unit**	**BIM-based QTO (Revit)**	**Formula**
Excavation of soil material for the foundations.	m3	Calculation of the volume of demolished mass. 	*Gross Volume*
Lean concrete as the basis of foundation slab – no formwork required.	m3	Calculation of volume of lean concrete. 	*Gross Volume*
Formwork of the foundation slab (less than 30 cm thick)	m	Calculation of the perimeter of the foundation slab. 	*Perimeter*

Figure 35: Section of the analysis results concerning excavation, lean concrete and formwork for a foundation slab (less than 30 cm thick).

3.7.3 Classifications and Keynotes

As defined in section 3.7.4, assigned classifications are considered minimum requirements for any BIM object within a model. Several classification standards were implemented into internal BIM object libraries, allowing us to choose any of the implemented classification standards on the given project. Classification Manager add-in (Autodesk BIM Interoperability Tools) was used to manage and assign classifications to individual objects.

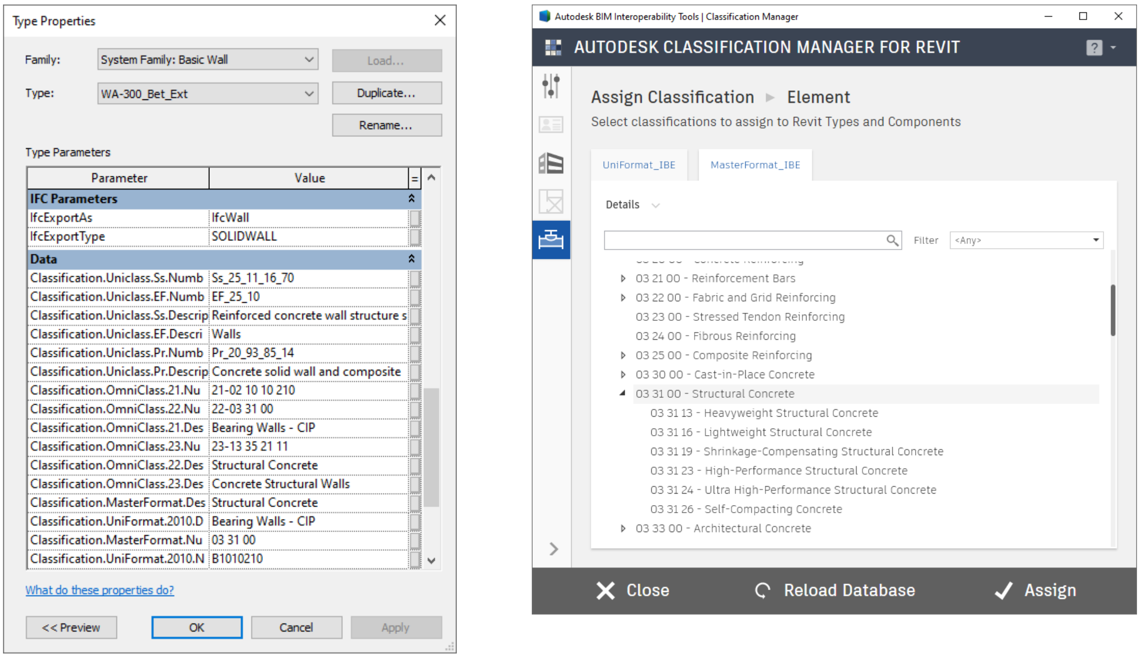


Figure 36: Type properties of an external structural concrete wall family type with the classifications assigned (left) and Autodesk Classification Manager for Revit (right).

To uniquely identify a type of BIM object, a keynote system was developed and implemented. The keynote system was similar to the Revit out-of-the-box keynote system, based on the MasterFormat classification system. The developments were made in the naming structure of individual elements to allow for a further breakdown of the element identification. Two more levels were added to the existing MasterFormat structure and a 4-digit number to uniquely identify the specific type of an object. A section of the keynote naming convention is given in Table 7.

Table 7: Section of keynote naming convention table concerning structural columns and structural walls.

03000	**Section 03: Concrete**		
03300	**Cast-in-Place Concrete**		
03310	**Structural Concrete**		
03310	**.SCO**	**Structural Columns**	
		.REC	Rectangular Structural Columns
		.CRC	Circular Structural Columns
03310	**.WLL**	**Structural Walls**	
		.INT	Internal Standard Structural Walls
		.EXT	External Standard Structural Walls
		.RET	Retaining Wall
		.COR	Load-Bearing Core Walls
		.PAR	Parapet Walls
		.FND	Foundation Walls

The Manage Keynotes tool (part of the pyRevit tools [40]) was used to implement the keynote system in Revit. The tool allows us to manage keynotes on a project level and a company level. The keynotes developed on a project level can be effectively imported into the central database. An example of a section of a keynote database (filtered to external structural concrete walls) is shown in Figure 37 below.

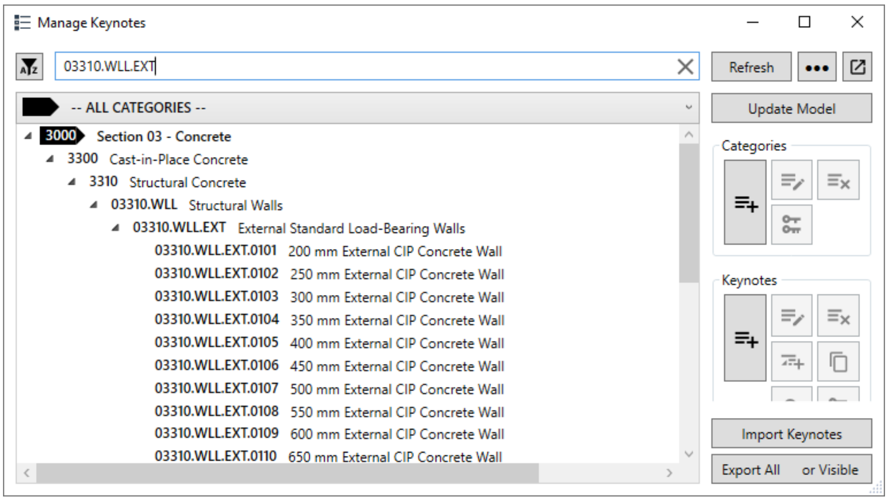


Figure 37: Section of the keynote database in Manage Keynotes tool (pyRevit tools [40]).

The keynotes were assigned to individual Revit family types within their type properties. An example is given in Figure 38 below. Because the keynote description is only available in the keynote file, a Dynamo script was developed to write the description of a keynote in the Description parameter of a family type in Revit (see section 3.7.7).

Keynote management system was an essential step towards standardized inputs and controlled vocabulary and was utilized in the BIM-based QTO process.

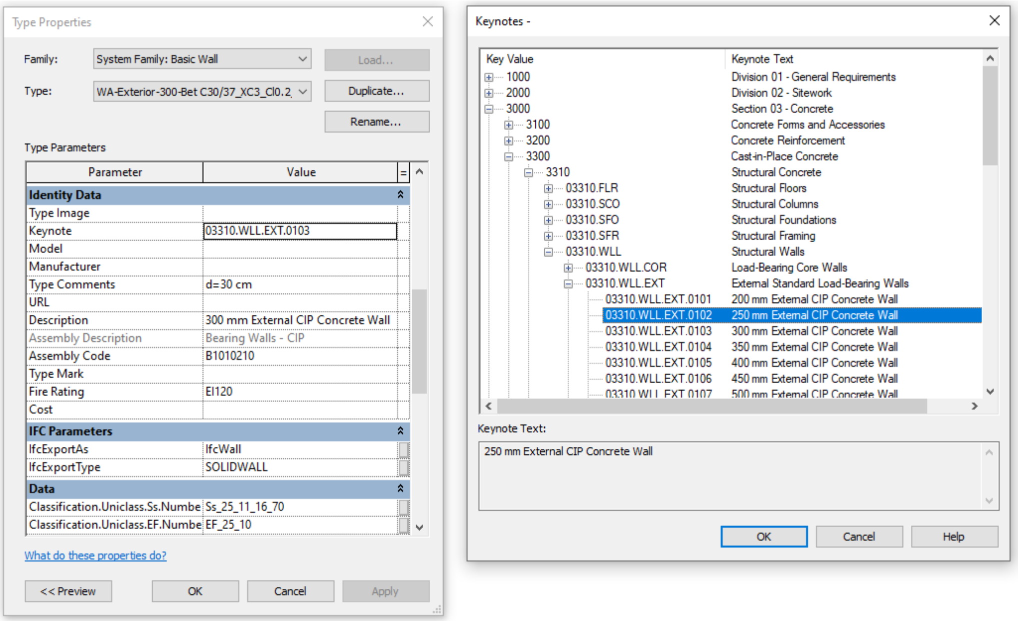


Figure 38: Assigning keynotes to individual Revit family types on an example of an external structural concrete wall.

3.7.4 Internal Data Dictionary

An essential step towards standardized inputs and controlled vocabulary in the BIM-based QTO process is developing and implementing an internal data dictionary. Generally, data dictionaries are collections of names, definitions, and attributes about data elements (for example, within a database or BIM models). The data dictionaries assist in avoiding data inconsistencies, help define conventions, enforce data standards and consequently make data easier to analyze (or use). In our case, the data dictionary also included a set of information requirements that have to be fulfilled across various project stages and BIM model uses. The information requirements are also the basis to define model checking criteria.

The development of the internal data dictionaries followed the standard for the level of information need (EN 17412-1:2020 - Building Information Modelling - Level of Information Need - Part 1: Concepts and principles, [41]).

The data dictionaries for BIM objects were made of the following sections:

- General information (name, Revit category, Revit family name, IFC parameters).
- Classifications.
- Labelling convention.
- Modelling guidelines across various project phases and BIM model uses.
- Information requirements across various project and BIM model uses:
  - Geometrical requirements (what is modelled and how).
  - Information (what information is required and through which parameters).
  - Documentation (how the object is documented in various types of documentation).

An example of a data dictionary documented for an interior load-bearing concrete slab is shown in Figure 39 below.

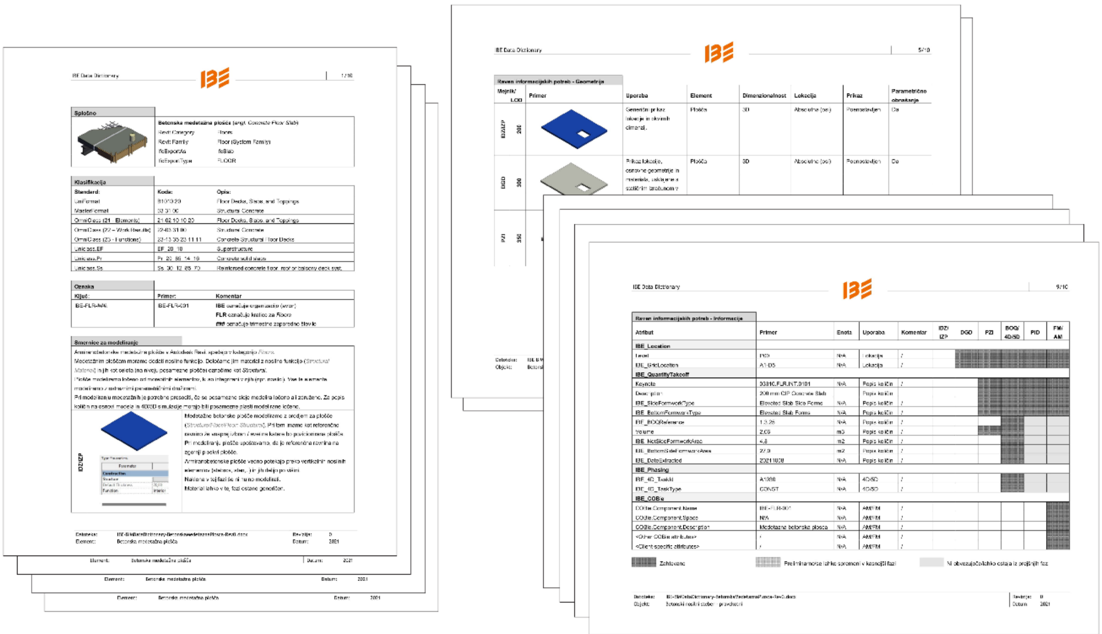


Figure 39: Example of a data dictionary (a document) for an interior load-bearing concrete slab.

The information requirements are divided into individual property sets. The user-defined property sets improve the control over the organization of information in a model exchange. The information requirements are listed in a tabular form, providing information about the attributes and the project phase or BIM model use for which the attributes have to be defined and included in a model exchange.

The information requirements included in the data dictionary are based on previous experience and the analysis of the AS-IS QTO process and existing BOQs. An example of information requirements relevant for quantity takeoff (*IBE_QuantityTakeoff* property set) of the interior load-bearing concrete slab is given in Figure 40.

IBE Data Dictionary 9/10

Raven informacijskih potreb - Informacije										
Atribut	Primer	Enota	Uporaba	Komentar	IDZ/ IZP	DGD	PZI	BOQ/ 4D/5D	PID	FM/ AM
IBE_Location										
Level	P00	N/A	Lokacija	/						
IBE_GridLocation	A1-D5	N/A	Lokacija	/						
IBE_QuantityTakeoff										
Keynote	03310.FLR.INT.0101	N/A	Popis količin	/						
Description	200 mm CIP Concrete Slab	N/A	Popis količin	/						
IBE_SideFormworkType	Elevated Slab Side Forms	N/A	Popis količin	/						
IBE_BottomFormworkType	Elevated Slab Forms	N/A	Popis količin	/						
IBE_BOQReference	1.3.25	N/A	Popis količin	/						
Volume	2,06	m3	Popis količin	/						
IBE_NetSideFormworkArea	4,8	m2	Popis količin	/						
IBE_BottomSideFormworkArea	27,0	m2	Popis količin	/						
IBE_DateExtracted	20211008	N/A	Popis količin	/						

Figure 40: Example information requirements for *IBE_QuantityTakeoff* property set.

As shown in Figure 40, the information contained within the *IBE_QuantityTakeoff* property set is not required unless a BIM-based QTO process is executed. Some information (for example, *IBE_BottomFormworkType*) is required in the detailed design (PZI) phase (the information is required for the execution of concrete works).

Additional examples of information requirements are given in Figure 41 below. The type of hatch in the cells indicates whether the information is a) required, b) preliminary or c) not required but can remain from previous phases.

IBE Data Dictionary 8/10

Raven informacijskih potreb - Informacije										
Atribut	Primer	Enota	Uporaba	Komentar	IDZ/ IZP	DGD	PZI	BOQ/ 4D/5D	PID	FM/ AM
IBE_Dimensions										
d	20	cm	Modeliranje	/						
IBE_Material										
Structural Material	IBE-Beton-C30/37_XC4_d32	N/A	Dobava	/						
IBE_General										
Mark	IBE-FLR-001	N/A	Identifikacija	/						
Description	Medetazna plosca	N/A	Metapodatek	/						
Type Comment	d=20cm	N/A	Metapodatek	/						
IBE_Structural										
IBE_ReinforcementGrade	B500B	N/A	Dobava	/						
IBE_ReinforcementRatio	120	kg/m3	Dobava	/						
Rebar Cover – Top Face	FLR: Concrete Floor Slab <>	/<mm>	Detajliranje	/						
Rebar Cover – Bottom Face	FLR: Concrete Floor Slab <>	/<mm>	Detajliranje	/						
Rebar Cover – Other Faces	FLR: Concrete Floor Slab <>	/<mm>	Detajliranje	/						
IBE_FireResistance	EI120	N/A	Zahteva	/						
IBE_Construction										
IBE_ConstructionProcess	InSitu	N/A	Izvedba	/						
IBE_SurfaceTreatment	VB2	N/A	Izvedba	/						
IBE_ExecutionClass	EXC2	N/A	Izvedba	/						
IBE_CuringClass	1	N/A	Izvedba	/						
IBE_ToleranceClass	1	N/A	Izvedba	/						
IBE_SideFormworkType	Elevated Slab Side Forms	N/A	Izvedba	/						
IBE_BottomFormworkType	Elevated Slab Forms	N/A	Izvedba	/						

Zahtevano Preliminarno/se lahko spremeni v kasnejši fazi Ni obvezujoče/lahko ostaja iz prejšnjih faz

Figure 41: Additional examples of information requirements for an interior load-bearing concrete slab.

It is important to note that the information requirements within the internal data dictionaries do not cover all information requirements on an actual project, but only the minimum requirements set within the organization to ensure consistency and enable specific BIM model uses (for example, BIM-based QTO). The information requirements on a specific project may exceed the information requirements specified within the internal data dictionary.

Various internal BIM data dictionaries were developed during the BPR process (and during this thesis). The developments were focused on BIM objects that were included and used in the case study. The development of the remaining data dictionaries will be done through continuous process improvement.

3.7.5 Model Checking Procedure

The model checking procedure ensures adequate quality and information content of the BIM models. Various model checks can be defined for various purposes (for example, an overall model "health" check, check and summary of model elements, check and summary of views and sheets, checks before a particular BIM model use or model exchange, and others). Therefore, we can define a model check to ensure that the exchanged model is adequate for the BIM-based quantity takeoff process. The bases are the information requirements (for example, the information requirements specified in internal BIM data dictionaries).

The model checks are performed using the Autodesk Model Checker for Revit add-in (part of Autodesk BIM Interoperability Tools). Multiple checks can be included in a check set. An example of a check set applicable to information requirements for the QTO process is given in Figure 42 below.

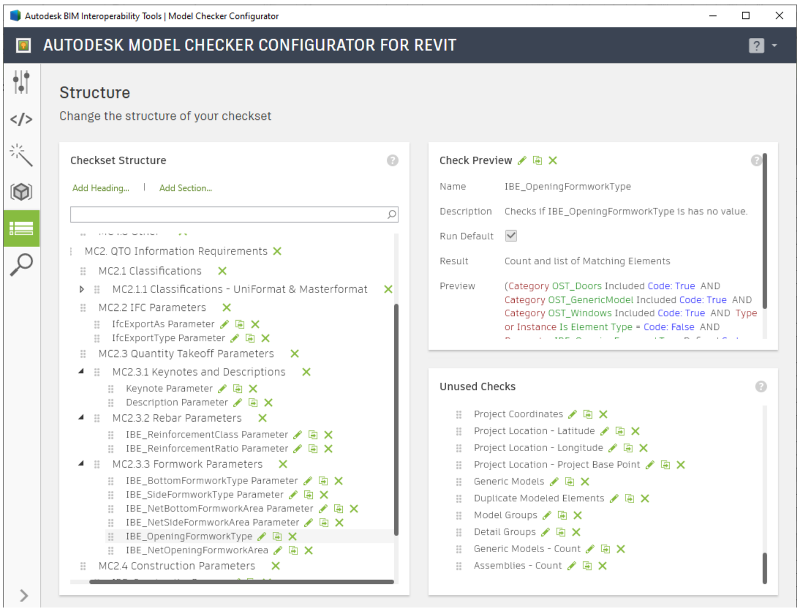


Figure 42: An example of a check set to check information requirements for the QTO process.

The checks are defined by check results (for example, count and list matching items) and filters. A model check that filters the doors, windows and generic models (Revit categories) that have no value assigned to the *IBE_OpeningFormworkType* parameter is given in Figure 43 below.

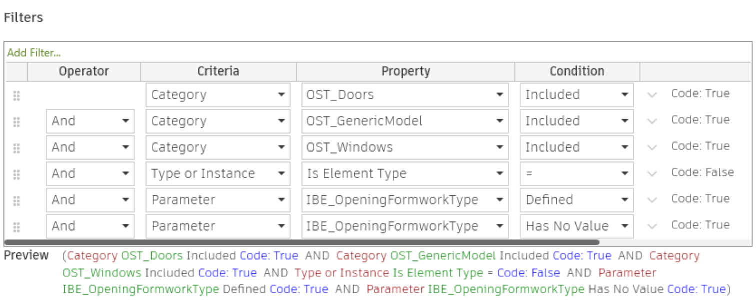


Figure 43: Check (an example) for windows, doors and generic models without formwork types defined.

3.7.6 Model Exchange for BIM-based QTO Process – User-defined Property Sets

For the re-engineered QTO process, downstream application software iTWO costX will be used. While the software supports proprietary Revit (.rvt) files, the models used for the QTO process will be exchanged in IFC (standard .ifc) file format. The use of IFC files gives us flexibility in how the property sets are defined and ensures that the models can be used regardless of the modelling software used. To provide well-structured input for the quantity surveyor, the (user-defined) property sets will follow the property sets defined in the internal BIM data dictionary, where the information requirements are specified. The parameters and their mappings are specified in a text file. An example of a definition of a user-defined property set (text file input) is given in Figure 44 below.

```
PropertySet:    IBE_QuantityTakeoff     I       IfcSlab, IfcWall, IfcColumn, IfcBuildingElementProxy,
IfcRoof, IfcFooting, IfcDoor, IfcOpeningElement, IfcBeam, IfcCovering, IfcRailing, IfcCurtainWall, IfcStair
        Keynote TEXT    Keynote
        Description     TEXT    Description
        Assembly Code   TEXT    Assembly Code
        Assembly Description    TEXT    Assembly Description
        IBE_BOQReference        TEXT    IBE_BOQReference
        Volume  VOLUME  Volume
        IBE_Area        AREA    IBE_Area
        Area    AREA    Area
        Length  LENGTH  Length
        IBE_SideFormworkType    TEXT    IBE_SideFormworkType
        IBE_BottomFormworkType  TEXT    IBE_BottomFormworkType
        IBE_OpeningFormworkType TEXT    IBE_OpeningFormworkType
        IBE_NetSideFormworkArea AREA    IBE_NetSideFormworkArea
        IBE_NetBottomFormworkArea       AREA    IBE_NetBottomFormworkArea
        IBE_NetOpeningFormworkArea      AREA    IBE_NetOpeningFormworkArea
        IBE_IBE_BOQReference    TEXT    IBE_IBE_BOQReference
        IBE_DateModified        TEXT    IBE_DateModified
        IBE_DateExtracted       TEXT    IBE_DateExtracted
        IBE_FormworkCalcTS      TEXT    IBE_FormworkCalcTS
```

Figure 44: An example of text file input for a user-defined property set.

The exchanged model can be viewed in various BIM model viewers. The mapped properties are available in separate tabs, named according to our input in the text file. For example, all information regarding the quantity takeoff of a particular strip footing is specified in one place. This proves helpful when creating model mappings and extracting quantities from the BIM models because the property set can be specified, reducing the chances of extracting the wrong property.

Footing

Summary | Location | Material | IBE_QuantityTa...

Property	Value
Assembly Code	A1010110
Assembly Description	Strip Footings
Description	2600 x 750mm Concrete Strip Footing
IBE_FormworkCalcTS	20210727144501
IBE_NetSideFormworkArea	21,82 m²
IBE_SideFormworkType	Strip Footing Side Forms
Keynote	03310.SFO.SF.0132
Volume	25,837 m³

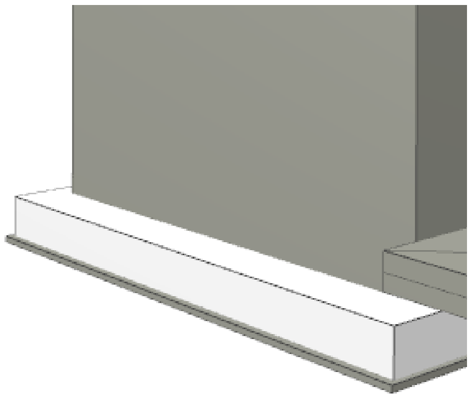


Figure 45: An example of user-defined property set in a model viewer (BIMcollab ZOOM).

3.7.7 REVIT API

Part of the re-engineered business process is also the development of custom-made solutions using Revit API to target specific challenges that occur in the BIM-based quantity takeoff process. Two of the challenges that occurred during the case study were:

- The calculation of accurate quantities of formwork areas – the net formwork areas for a specific structural element do not directly correspond to any of the quantities automatically calculated in the Revit model. Furthermore, the rules of measurement specify how the measurement should consider openings in concrete elements.
- The volumes of openings in structural elements by far exceed the volume of sealing material required to fill the space between the penetrant and the opening faces. Due to the specifics in the energy sector, the high number of penetrations on a project and demanding performance requirements for the sealing systems (fire resistance, water-tightness, air-tightness, and others) contribute significantly to the final construction costs. Thus, the volumes of sealants must be calculated accurately.

Both challenges were addressed and resolved by the development of Dynamo scripts (combination of DesignScript and Python syntax) that allow the end-user to automatically calculate the exact quantities based on the modelled BIM objects.

3.7.7.1 Formwork Area Calculators

Formwork area calculators (Dynamo scripts with GUIs) were developed for the formwork areas of:

- Concrete slabs.
- Concrete walls.
- Concrete columns.
- Concrete beams.
- Openings in concrete elements.

While the developed solutions are different for the different types of structural elements (slabs, beams, walls, and others), the solutions are conceptually and technically very similar. Therefore, only the development of the slab formwork area calculator will be presented in detail.

Some of the specifics of the floor slab formworks related to quantity surveying are:

- In most cases, bottom formwork and side formwork is required.
- Structural elements supporting the slab in the storey below are already cast, and the overlapping area has to be subtracted.
- Large shaft openings require side formwork, while small vertical openings ($< 1\ m^2$) are in most cases considered in the net area of the (bottom) formwork required.

The overall Dynamo graph of the solution is given in Figure 46 below.

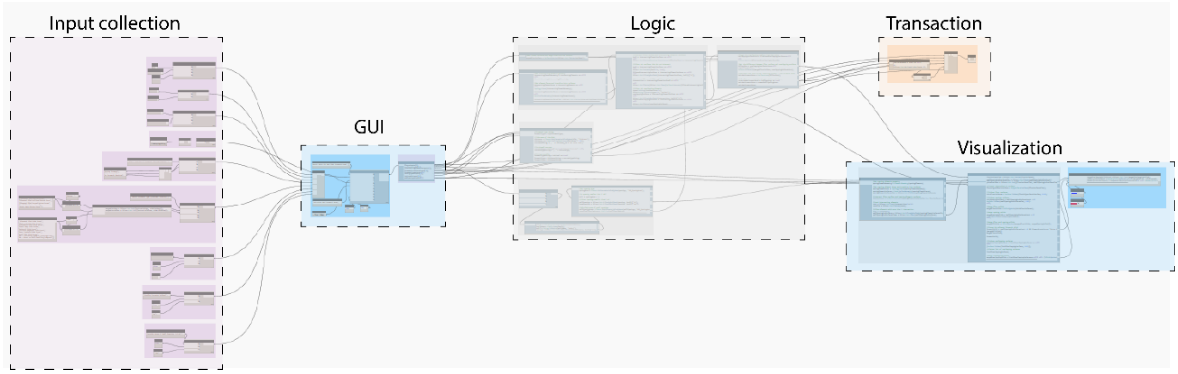


Figure 46: Dynamo graph for Slab Formwork Area Calculator with annotations.

The tasks executed in the individual steps within the script are:

1. **Input collection –** using a GUI, the user defines the inputs (selects the slab, the faces of contact with formwork sheets, intersecting elements, location of formwork, formwork type and others).
2. **GUI** – the script utilizes Data Shapes ([42]) Dynamo package to generate GUI for better user experience and control over the inputs.
3. **Logic** – considering the inputs, the script calculates the net area of the formwork required by transforming the selected elements and faces into surfaces and performing Boolean operations (union, difference, intersection). Additionally, the openings are considered, and output parameter values are generated.
4. **Transaction** – the values (formwork type and area for bottom or side formwork) are written into the parameters of the selected slab during the transaction. Additionally, the timestamp is written to an appropriate parameter.
5. **Visualization** – the geometries are visualized, and the net surfaces in contact with formwork sheets are coloured in blue, while the overlapping surfaces are coloured in red. The visualization is available when the script is run directly in Dynamo (and not using Dynamo Player, for example) and gives us a possibility to see the actual areas and evaluate if we had made a mistake. The latter is especially useful in cases where there are multiple openings and intersecting elements with overlapping areas.

The user interface with filled inputs (an example of a floor slab with multiple openings and intersecting elements) and annotations is shown in Figure 47.

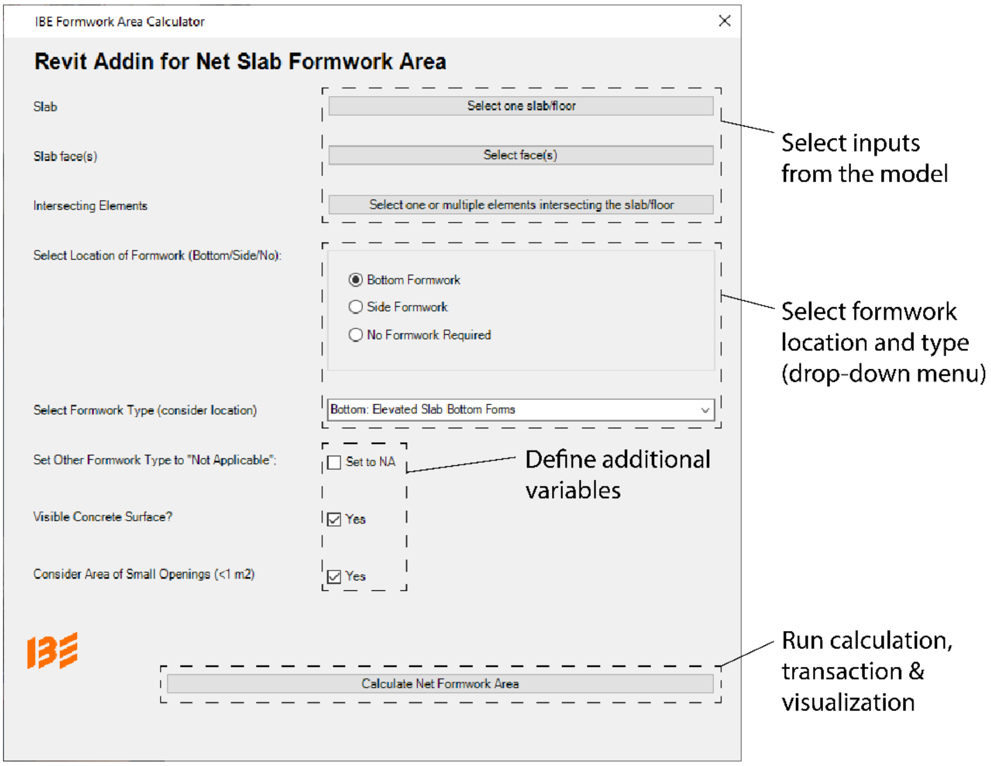


Figure 47: User interface for Slab Formwork Area Calculator.

DesignScript (Dynamo's programming language) was combined with standard Dynamo nodes and nodes containing Python scripts to make the script more manageable and organised. This way, it is easier to manage the information flow and understand the code. An example of a code block containing DesignScript code is shown in Figure 48 below.

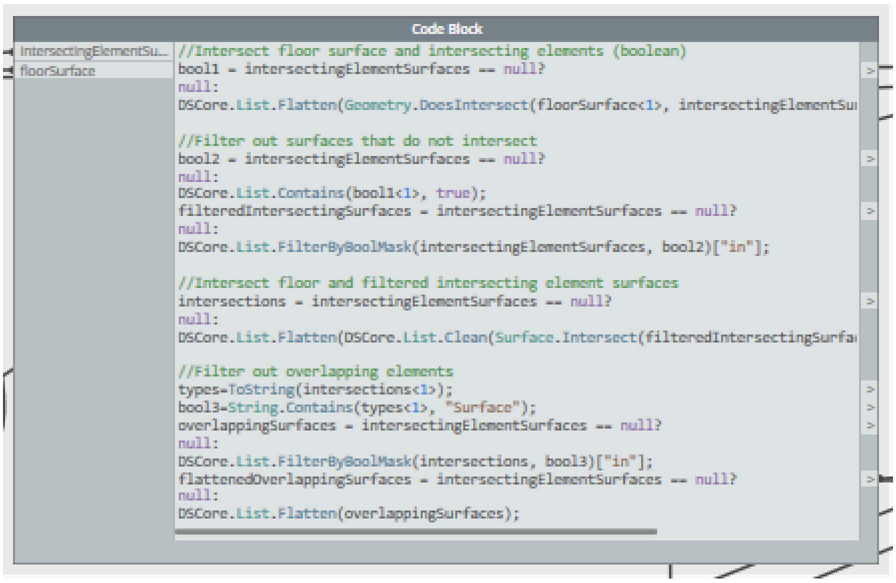


Figure 48: An example of a code block containing DesignScript code.

A node containing Python script was used to make a transaction between Dynamo script and BIM objects in Revit. This functionality allows us to access the Revit API directly and utilize the existing IronPython libraries by importing them into Dynamo. Part of the Python script in the node is shown in Figure 49 below.

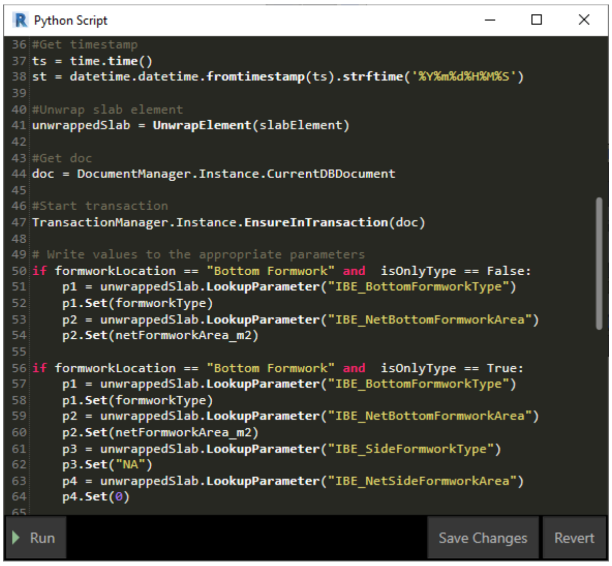


Figure 49: Part of the Python script used for the transaction – assigning the parameter values.

The Python script results in assigning the calculated values to the appropriate parameters of the chosen slab elements in Revit. Additionally, visualization is generated inside Dynamo, which enables the user to see the areas considered to be in contact with formwork sheets and the overlapping areas. The visualization also displays what openings were considered to be covered with formwork sheets. This reflects in accurately calculated formwork areas for bottom formwork, side formwork, and the formwork required to form openings in the next step.

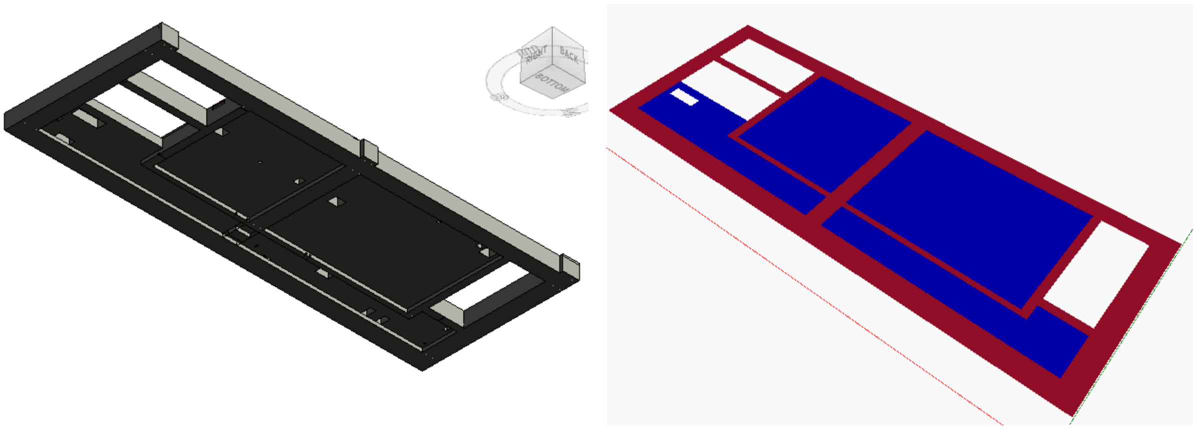


Figure 50: Floor slab in Revit (left) and visualization of surfaces in contact with formwork sheets and overlapping surfaces in Dynamo (right).

As we can see from the example in Figure 50, the larger openings (with areas exceeding 1 m^2) were not considered in the net formwork area for the host floor slab.

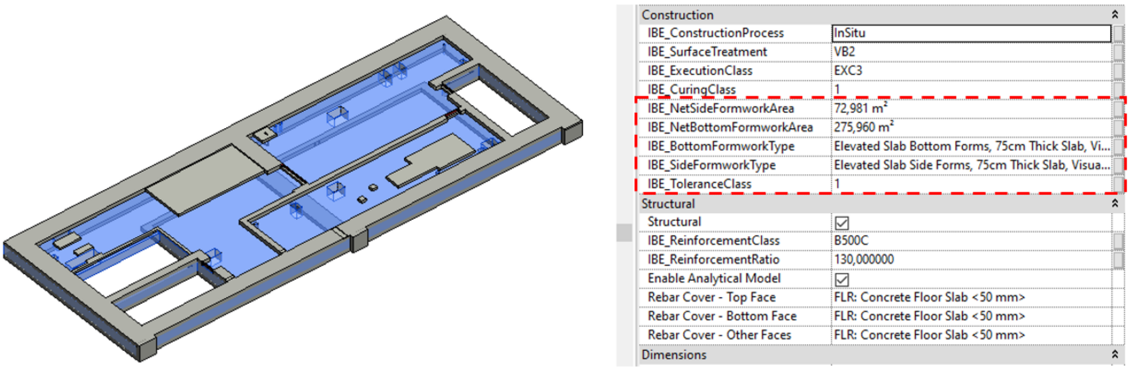


Figure 51: Assigned parameters to the floor slab.

Similar developments were made to calculate the net formwork areas for other types of structural elements (columns, beams, walls and footings). The developments followed the same logic and had the same workflow, but the functionality had to be adapted to suit the specifics of individual element types and construction technology foreseen. Additionally, a solution was developed for opening formworks. Since the openings often intersect with horizontal structural elements (for example, floor slabs), not all opening surfaces are in contact with formwork sheets. Furthermore, prefabricated solutions are often used (for example, for circular openings).

The user interfaces of individual solutions are shown in Figure 52 below.

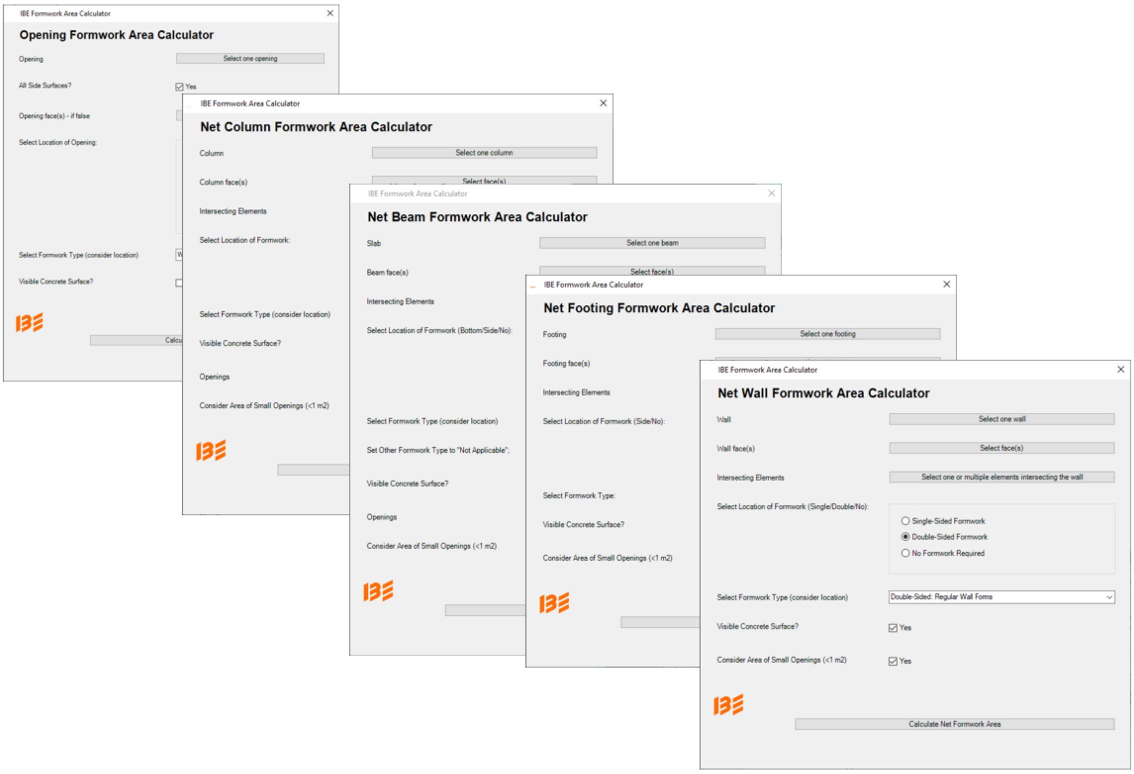


Figure 52: User interfaces for other formwork area calculators.

3.7.7.2 Penetration Sealant Generator

Similar to the net formwork area calculators, the penetration sealant generator was developed. DesignScript was combined with standard Dynamo nodes and nodes containing Python code. Compared to the formwork area calculators, where the script assigns the values to appropriate parameters, this solution generates a new model element representing a sealant. The geometry and of the sealant is generated based on the user inputs (geometry of the penetration and the penetrants, chosen sealing system, location and thickness of the applied sealant). Additionally, the material and other parameters are defined.

The overall Dynamo graph of the solution is given in Figure 53 below.

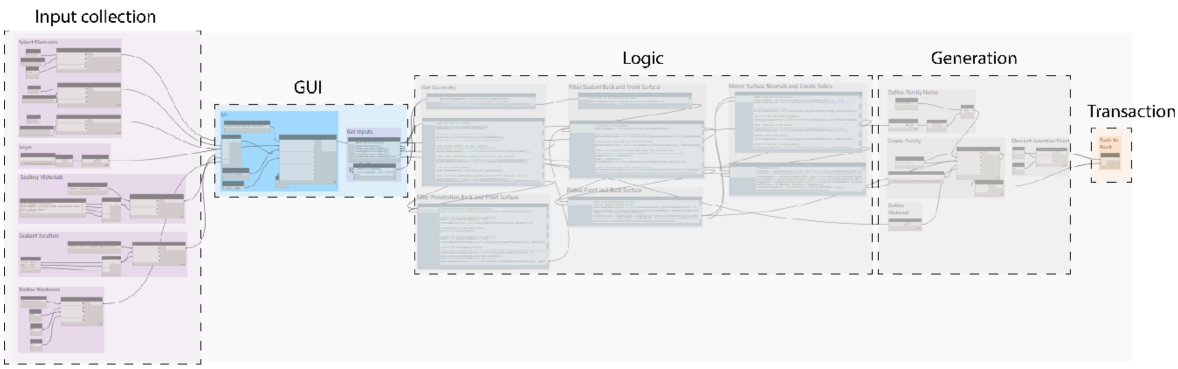


Figure 53: Dynamo graph for Penetration Sealant Generator with annotations.

The tasks executed in the individual steps within the script are:

1. **Input collection** – using a GUI, the user defines the inputs (penetration and penetrants, sealant type, its location and thickness).
2. **GUI** – the script utilizes Data Shapes ([42]) Dynamo package to generate GUI for better user experience and control over the inputs.
3. **Logic** – considering the inputs, the script first executes Boolean operations to define the net solids and their surfaces. To automatically determine the front and back surfaces, basic operations on vectors are used (cross-product and others). Finally, the solid representing the sealant volume is generated based on the remaining inputs (location, thickness and others).
4. **Generation** – the script generates the model element based on the solid generated in the previous step. A Revit family template specifically developed for this task is used as an input. Furthermore, material and other parameters are defines.
5. **Transaction** – the element is pushed to Revit within the transaction. The transaction plays an essential role as it breaks the connection (»*bakes*«) between the Dynamo script and element instance in the model.

The user interface for the Penetration Sealant Generator is shown in Figure 54. The figure also displays the practical application of the solution. The top and middle penetrations have the sealant already applied, while the inputs within the user interface are defined to generate the sealant for the bottom penetration.

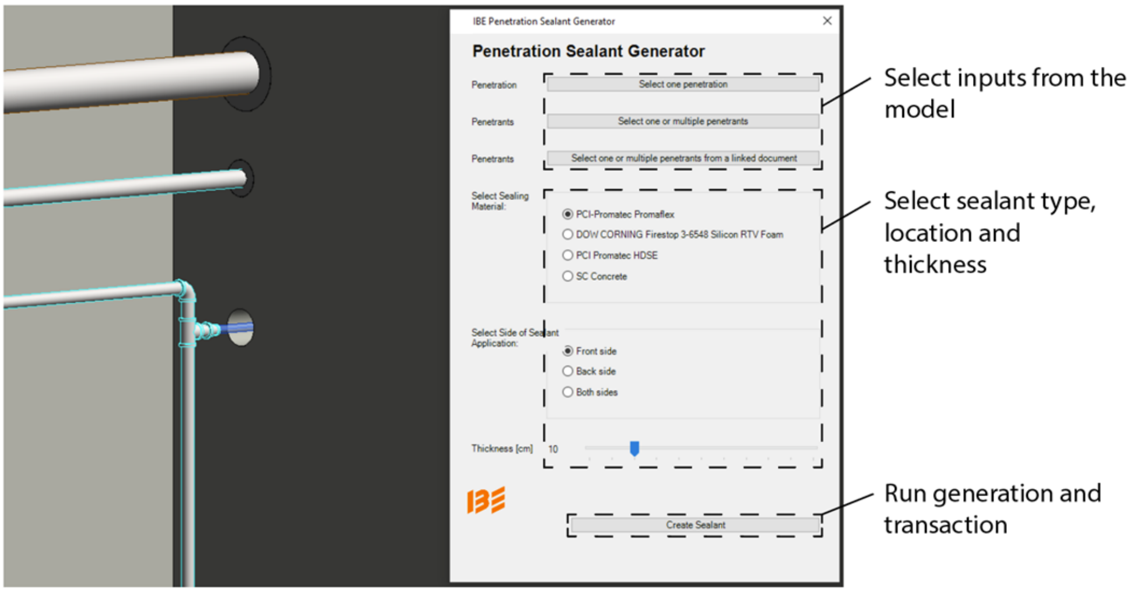


Figure 54: User interface for Penetration Sealant Generator.

As displayed in Figure 54 above, there is a big difference between the gross volume of the penetration and the net volume of the sealant needed (considering the product specification) to provide the performance required. Since the volume ratio can not be estimated accurately, the developed solution enables the quantity surveyor to extract the exact volume directly from the BIM model elements.

4 CASE STUDY

In the case study, an existing project was examined and used to execute the re-engineered business process. The analysis results for the existing BOQ are given in section 3.7.2 (Figure 33 and Figure 34). As reported in the analysis, approximately 20% of the BOQ items are model based in the AS-IS process, and approximately 80% of the BOQ items may be model-based in the re-engineered TO-BE process. The case study aimed to come close to this percentage.

4.1 Project Description

An existing project – a new power plant facility designed by IBE d.d. was used for the case study. In the project, BIM models were used to coordinate project solutions, exchange information and create project documentation. For quantity takeoff, the traditional method described in the AS-IS process was used. Although multiple disciplines were collaborating on the project, the scope of this case study is only the civil engineering and architectural part.

The power plant facility is a 3-storey building with a thick reinforced concrete structure. Two of the three storeys are below grade. The northern part of the building, where two water tanks are located, has only one continuous storey. The southern part of the building, where most of the mechanical and electrical equipment is located, has three storeys. There are two stair shafts with steel stairs connecting the three levels. While the main structure of the building is made of reinforced concrete, all secondary structures are made of structural steel. Because the building mainly serves as a protective envelope of its mechanical and electrical systems, it contains many anchoring elements and structures. The building has a flat roof with parapet walls at its perimeter. The façade of the building is made of prefabricated modular façade panels and is supported by a steel façade substructure.

The federated model of the building is shown in Figure 55 below. Existing BIM models from the project were used but were adapted to enable the execution of the TO-BE QTO process.

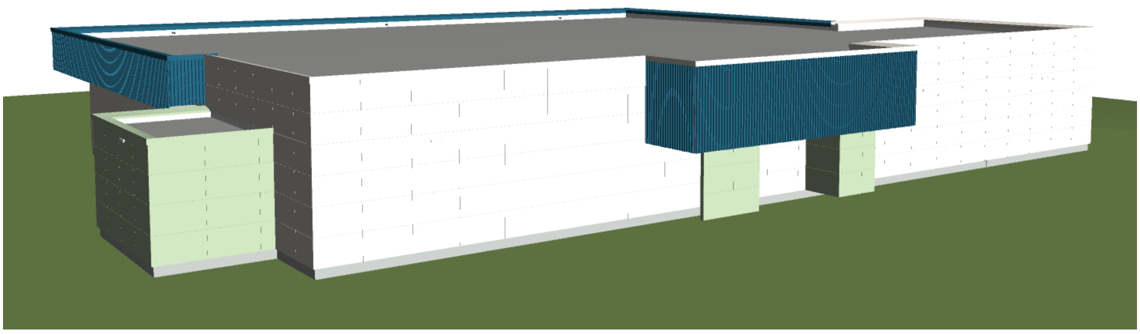


Figure 55: Model of the power plant facility in Navisworks.

The reinforced concrete structure of the power plant facility is shown in Figure 56 below.

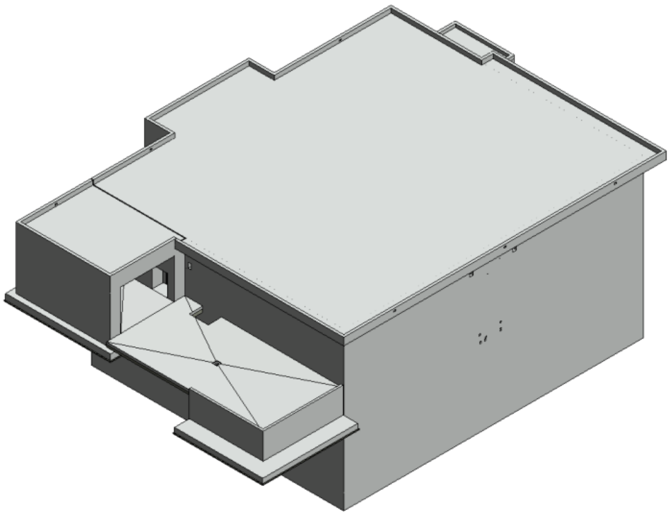


Figure 56: Model of the reinforced concrete structure in Revit.

4.2 Execution of the Re-engineered Quantity Takeoff Process

4.2.1 Preparation of the Model for BIM-based Quantity Takeoff

The preparation of the BIM models to execute the QTO process followed the steps defined in the TO-BE process model.

Firstly, since the model used was from an existing project (already built), the model already contained correct and complete design solutions. However, the model was not entirely aligned with the information requirements set in the internal data dictionary. Therefore, many adaptations had to be made. During the implementation and this case study, many existing libraries were further developed to meet the information requirements set in the internal data dictionary. The libraries, managed through a library management system (a combination of libraries separately stored on a server and in container files), replaced the existing libraries in the model. Additional information was assigned to the BIM model elements. Furthermore, the specific quantities were calculated with the Revit API tools developed in the implementation process. Some model elements had to be split or remodelled (for example, to consider the construction technology used correctly) to calculate their quantities accurately.

Secondly, the model was checked according to the model checking procedure defined for the QTO process. Inconsistencies and missing information were eliminated through several iterations of the model check. Once the information requirements were fulfilled, the model was considered ready for the exchange.

Finally, the model was exported to the IFC file format (IFC 2x3 Coordination View 2.0). User-defined property sets were used to map the information as specified in the internal data dictionary. In addition to the BIM models, some views (floor plans) were exported to CAD format. These were used to calculate the quantities in cases where BIM model elements were not available.

4.2.2 Preparation of Project Environment in iTWO costX

A new project was created in the iTWO costX application software, and general project information and units of measure were defined. The IFC models and CAD drawings were imported. Following the successful import, a visual check of the models and drawings was performed. The visual inspection examined if all model elements were successfully imported, if the imported model elements matched their IFC element types as defined in their IFC parameters, and if all information was available.

An example of an imported IFC model in iTWO costX is shown in Figure 57 below.

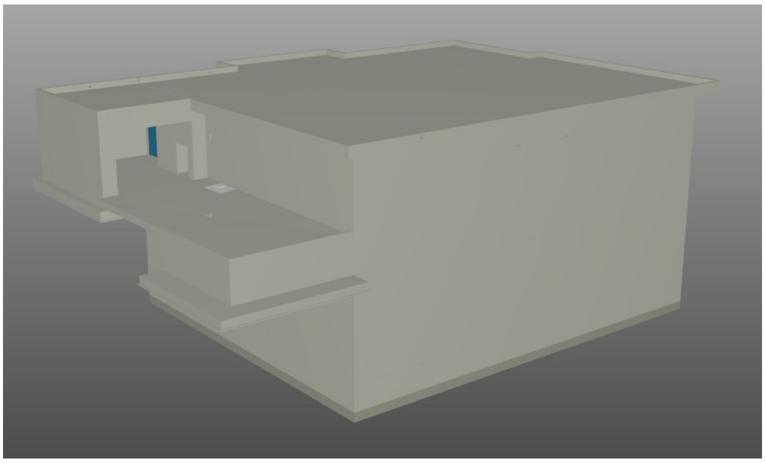


Figure 57: Model of the reinforced concrete structure imported in iTWO costX.

After the visual inspection of the imports, the *Dimensions View* inputs and *Workbook View* inputs are imported according to the TO-BE process model. Since this was the first time the application software was used to perform the BIM-based QTO process, there were no existing BIM templates, model maps, rate and code libraries and other inputs. Therefore, some libraries were developed during this case study, while others were left to be prepared in collaboration with the delegated quantity surveyor in the future and during the phase of continuous process improvement.

A model map in iTWO costX is a user-defined template which specifies how parametric model information contained within the BIM models is translated into dimension information within costX. Model maps allow the object property fields for groups of objects to be mapped to the fields of dimensions and dimension groups. Model maps are built to include map entries for the various nodes of the model tree (for example, different types or groups of objects can have different property fields specified). When dimensions are imported using the model map, the values for the model elements are read from the selected object property field, and a series of dimensions groups and dimensions are created containing the values. After extracting the quantities using model maps, the dimensions groups can be further organized in individual folders defined by the quantity surveyor (see Figure 58).

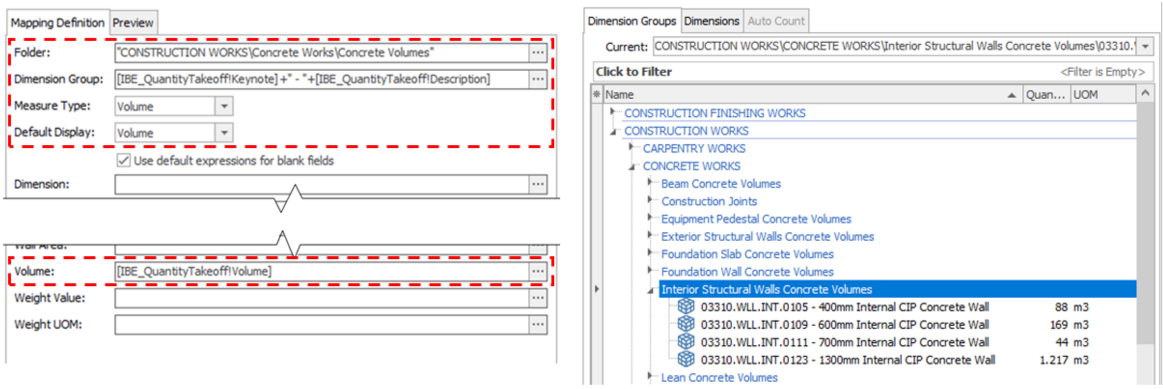


Figure 58: An example of model map definition to calculate concrete volumes (left) and dimension groups further organized in folders after the extraction (right).

A variety of model maps can be specified for different purposes and with different ways of grouping the dimensions into dimension groups. The model maps were used to extract the quantities for the majority of dimensions in the execution phase.

The workbook template used in the case study was developed based on an existing BOQ template (the .xlsx file). The existing template was imported to iTWO costX and adapted to the multi-level breakdown. The template may be exported, used on future projects and continuously developed.

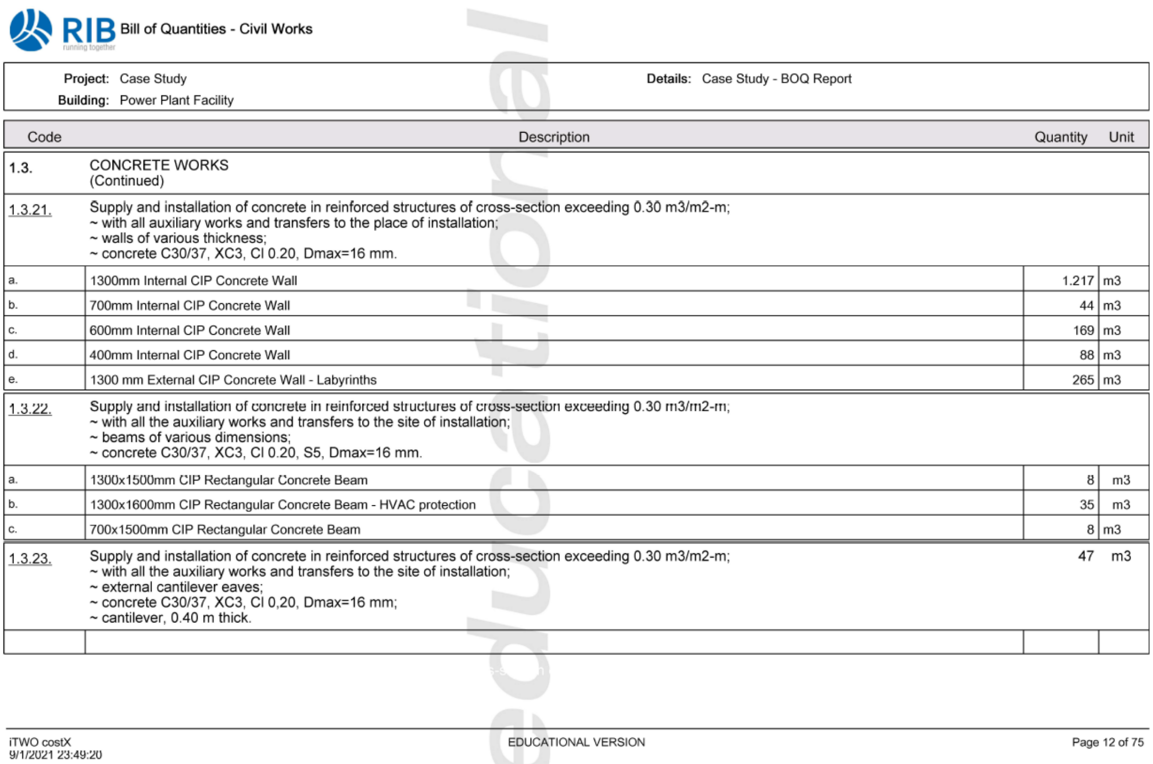
4.2.3 Execution of BIM-based Quantity Takeoff

The execution of the QTO process was done in several steps. In the beginning, the standards, procedures and guidelines were defined and written in general notes along with other general items. Then, the quantities were surveyed. As defined in the TO-BE process model, there are multiple steps to surveying all quantities in the BOQ.

Firstly, the quantities were extracted from the model using various model maps. The majority of the most common quantities (for example, concrete volumes) were extracted using model maps. Secondly, the custom quantities were extracted (for example, all quantities counted as individual items and had the dimension groups manually specified, items where model maps were not applicable because of the manual grouping required, and others). The custom quantities also included items where the measurement of a particular quantity was based on another element (for example, because the hydro insulation membranes were not modelled, the measurement considered the dimension of the element the membrane was applied to using a formula, for example, the perimeter of the model element multiplied by the height of the applied membrane layer). Thirdly, the remaining quantities were calculated based on the manual measurements from the model (for example, specific construction joints, specific detail elements that were not modelled) and model-based CAD drawings (for example, painting areas).

Following the extraction of the quantities, the workbook was populated with the BOQ items. The structure from the existing BOQ was adopted (to allow the comparison of the traditional and BIM-based approaches), and the individual quantities (dimension groups) were inserted into individual BOQ items. The item descriptions were taken from the existing BOQ. The development of phraseologies was outside of the scope of this case study.

Finally, the report was generated. There are many different options and functionalities iTWO costX offers to generate reports. In this case study, a basic report, similar to the existing BOQ report, was generated. Since the educational version of the application software was used, some of the functionalities were not available. As shown in Figure 59, the examples quantities from Figure 58 are shown in the report. The case study showed that the reporting functionality of the application software exceeds the functionality of basic spreadsheet tools (for example, MS Excel).



RIB Bill of Quantities - Civil Works

Project: Case Study **Details:** Case Study - BOQ Report
Building: Power Plant Facility

Code	Description	Quantity	Unit
1.3.	CONCRETE WORKS (Continued)		
1.3.21.	Supply and installation of concrete in reinforced structures of cross-section exceeding 0.30 m3/m2-m; ~ with all auxiliary works and transfers to the place of installation; ~ walls of various thickness; ~ concrete C30/37, XC3, Cl 0.20, Dmax=16 mm.		
a.	1300mm Internal CIP Concrete Wall	1.217	m3
b.	700mm Internal CIP Concrete Wall	44	m3
c.	600mm Internal CIP Concrete Wall	169	m3
d.	400mm Internal CIP Concrete Wall	88	m3
e.	1300 mm External CIP Concrete Wall - Labyrinths	265	m3
1.3.22.	Supply and installation of concrete in reinforced structures of cross-section exceeding 0.30 m3/m2-m; ~ with all the auxiliary works and transfers to the site of installation; ~ beams of various dimensions; ~ concrete C30/37, XC3, Cl 0.20, S5, Dmax=16 mm.		
a.	1300x1500mm CIP Rectangular Concrete Beam	8	m3
b.	1300x1600mm CIP Rectangular Concrete Beam - HVAC protection	35	m3
c.	700x1500mm CIP Rectangular Concrete Beam	8	m3
1.3.23.	Supply and installation of concrete in reinforced structures of cross-section exceeding 0.30 m3/m2-m; ~ with all the auxiliary works and transfers to the site of installation; ~ external cantilever eaves; ~ concrete C30/37, XC3, Cl 0,20, Dmax=16 mm; ~ cantilever, 0.40 m thick.	47	m3

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Figure 59: A page from the BOQ report generated in iTWO costX.

4.2.4 Control of the BIM-based Quantity Takeoff

Since the case study was done using an existing project, outside of everyday project work within the company, only part of the internal review of the BOQ was performed. The quantities in the generated BOQ were compared to the basic quantities in Revit. The quantities matched.

An official internal QA review and external review (according to the company's internal standards and project specifics) would follow on an actual project.

4.2.5 Close-out of the BIM-based Quantity Takeoff

Following the TO-BE process model, the Bill of Quantities (the generated report) was added to project documentation (thesis), and the files, inputs and outputs were archived. Since this was the first case study, the developed BIM libraries, custom Revit API solutions, model checking procedures and iTWO costX libraries will not be updated but will be used as a starting point for the actual pilot project or other actual projects in the future.

In this case study, the lessons learned were documented as a part of the thesis. This concludes the execution of the re-engineered business process.

4.3 Analysis of the Re-engineered Quantity Takeoff Process

4.3.1 Overall Analysis

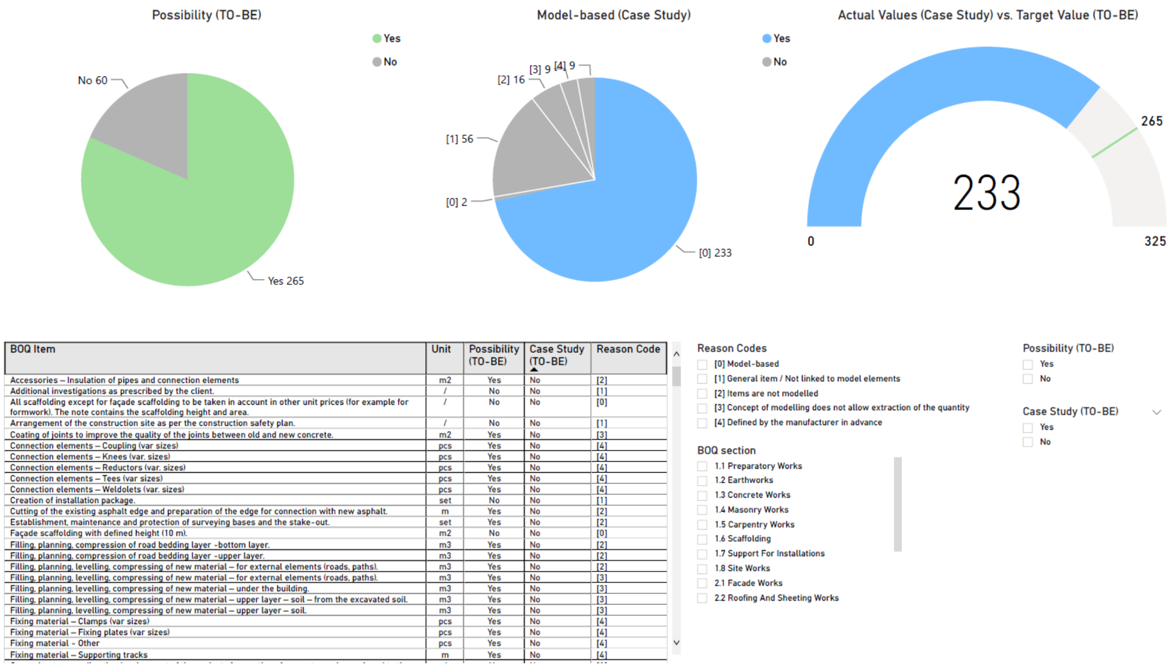
The analysis of the existing BOQ (see Section 3.7.2) was done for the BOQ used in this case study. Similar to the analysis of the existing BOQ, the items in the generated report were evaluated. For every item, it was determined if the measurement was model-based and what was the reason code. The final reason codes were:

0. Model-based.
1. General item / Not linked to model elements.
2. Items are not modelled.
3. The modelling does not allow extraction of the quantity (not modelled correctly).
4. Defined by the manufacturer in advance.

We can now compare the evaluations from the previous analysis with the analysis from the case study. As we can see from the Power BI dashboard (see Figure 60 below), the amount of model-based items in the BOQ increased significantly. Initially, approximately 20% of the items in the BOQ were model-based. In the case study, 233 (out of 325) or approximately 70% of the items were model-based. The target value was 265 (out of 325) or approximately 80%, representing an ideal value that was not fully reached.

Analysis shows that the BOQ items concerning preparatory works, earthworks and site works represent the majority of items that could be model-based but were not extracted from the model in the case study. The main reason for this is that the model for earthworks was not developed during the design, nor was it developed during this case study.

The overall analysis concludes that most of the items were successfully extracted from the model, while there is still some room for improvement on future projects, especially when it comes to earthworks, preparatory works, and site works.



BOQ Item	Unit	Possibility (TO-BE)	Case Study (TO-BE)	Reason Code
Accessories – Insulation of pipes and connection elements	m2	Yes	No	[2]
Additional investigations as prescribed by the client.	/	No	No	[1]
All scaffolding except for façade scaffolding to be taken in account in other unit prices (for example for formwork). The note contains the scaffolding height and area.	/	No	No	[0]
Arrangement of the construction site as per the construction safety plan.	/	No	No	[1]
Coating of joints to improve the quality of the joints between old and new concrete.	m2	Yes	No	[3]
Connection elements – Coupling (var sizes)	pcs	Yes	No	[4]
Connection elements – Knees (var. sizes)	pcs	Yes	No	[4]
Connection elements – Reductors (var. sizes)	pcs	Yes	No	[4]
Connection elements – Tees (var sizes)	pcs	Yes	No	[4]
Connection elements – Weldolets (var. sizes)	pcs	Yes	No	[4]
Creation of installation package.	set	No	No	[1]
Cutting of the existing asphalt edge and preparation of the edge for connection with new asphalt.	m	Yes	No	[2]
Establishment, maintenance and protection of surveying bases and the stake-out.	set	Yes	No	[2]
Façade scaffolding with defined height (10 m).	m2	No	No	[0]
Filling, planning, compression of road bedding layer -bottom layer.	m3	Yes	No	[2]
Filling, planning, compression of road bedding layer -upper layer.	m3	Yes	No	[2]
Filling, planning, levelling, compressing of new material – for external elements (roads, paths).	m3	Yes	No	[2]
Filling, planning, levelling, compressing of new material – for external elements (roads, paths).	m3	Yes	No	[3]
Filling, planning, levelling, compressing of new material – under the building.	m3	Yes	No	[3]
Filling, planning, levelling, compressing of new material – upper layer – soil – from the excavated soil.	m3	Yes	No	[3]
Filling, planning, levelling, compressing of new material – upper layer – soil.	m3	Yes	No	[3]
Fixing material – Clamps (var sizes)	pcs	Yes	No	[4]
Fixing material – Fixing plates (var sizes)	pcs	Yes	No	[4]
Fixing material - Other	pcs	Yes	No	[4]
Fixing material – Supporting tracks	m	Yes	No	[4]

Figure 60: Overall Power BI dashboard with analysis results from the case study.

4.3.2 Critical Success Factors (CSFs)

After the case study was completed, the critical success factors were evaluated. The TO-BE process is fully digitalized in all steps within the process. The QTO process is BIM-based, and the case study proved that more than 70% of the BOQ items are model-based. The overall time spent was decreased since the time required to measure the quantities was significantly reduced. The workload and responsibilities were distributed across the project team, similar to the AS-IS process. The QTO process was executed in a single environment (iTWO costX) and had advanced changed management. Many of the inputs were already standardized, and many more will become through future CPI. Lessons learned were documented and will improve the process. A high potential for further automation was exhibited.

Table 8: Evaluation of CSFs after completion of the case study.

Critical Success Factor	**Case Study (TO-BE process)**
TO-BE process fully digitalized.	✓
BIM-based QTO process.	✓
Reduction in time spent and increase in profit.	✓
Workload and responsibilities distributed across the project team.	✓
Single environment.	✓
Change management.	✓
Standardized inputs and automation.	✓
Lessons learned and CPI.	✓

4.3.3 Key Performance Indicators (KPIs)

Finally, we can evaluate the key performance indicators for this case study. Since working on a case study based on an existing project is not equivalent to actual project work, the KPIs may be evaluated only partially. In some cases, KPIs may only be estimated.

The number of model-based BOQ items was already evaluated in the overall analysis. However, now we are interested in the number of model-based BOQ items compared to the number of BOQ items that may be model-based in an ideal scenario. There will always be a certain number of items in the BOQ that can not be associated with any model elements. Therefore, the performance of the executed process is evaluated based on the items that may be associated with model elements. The number in this case study is 233 (out of 265). Approximately 88% of the BOQ items were successfully extracted/measured from the model.

Since no cost estimation was made in the case study, the ratio between the summed cost of the model-based BOQ items and total costs can not be calculated. However, the ratio may be conservatively estimated. Since 70% of all BOQ items were model-based and all major works (except for earthworks, preparatory works, and site works) were covered in those items, the conservative estimation would be that at least 90% of all costs were covered with model-based items.

Similarly, the number of person-hours spent on the project may not be calculated since the basis for the case study was a complete BOQ with complete design solutions. However, because of the significant improvements in the execution of the BOQ process and change management, we can estimate that the number of person-hours is reduced by at least 30%. The same applies to the time required to implement changes. If the changes cause the affected BOQ items to be redone from scratch, the time required to implement them is reduced by at least 30%. If the changes mean only automatic recalculation of the quantities, the implementation time is reduced significantly, in some cases by even more than 90%.

The whole BIM-based quantity takeoff process is standardized (internally). Some individual activities (for example, BIM modelling to enable BIM-based QTO process, model checking, model exchange, extraction of quantities, QA procedures, and others) are standardized and documented, while others are not yet (for example, change management). There are no standards for the QTO process on a national or international level yet, but the guidelines used are standardized within the company.

The BIM object libraries used in the case study were developed according to the internal data dictionary (also mainly developed during the case study). Similarly, the keynote library was populated. In iTWO costX, many model maps were developed, while rate and code libraries, phraseologies and others were outside the scope of this thesis. Generally, the overall control of the process was significantly improved.

5 CONCLUSION

The main goal of this thesis was to re-engineer the quantity takeoff process for and in collaboration with the engineering and consulting company IBE d.d. Considering the re-engineered process will be adopted on future projects, the highest priority was to develop a solution that would be reliable and would ultimately succeed given the characteristics of the company, its structure, employees, established workflows, market segments and also the level of BIM adoption. Therefore, the re-engineering of the business process had to be planned and executed thoroughly and very carefully. Considering the above, the existing publications on business process re-engineering were studied, and the methodologies, guidelines and recommendations from the experts in the field were adopted. Furthermore, the articles and dissertations on the efforts to implement the BIM-based quantity takeoff process were researched, the existing solutions were analyzed, and the found setbacks and challenges were acknowledged. The research resulted in the BPR process following recommendations and methodologies from the studied literature and considering the examples of implementation of BIM-based QTO and their lessons learned.

By interviewing the employees using questionnaires, the information regarding the current quantity takeoff process was collected, and the current process was captured and documented through analysis and AS-IS process modelling. The analysis displayed many gaps, bottlenecks and weaknesses of the AS-IS process, including the time spent manually measuring the quantities, the fact that the process is error-prone, the difficulty of change management, the compromised accuracy of the measured quantities, little potential for automation and also limited possibilities of improvement through lessons learned. To bridge those gaps, three alternatives for the BIM-based quantity takeoff were proposed and analyzed. The analysis determined that relying on the development and maintenance of an application software internally may result in ultimate failure because of the time required to develop it, the indefinite maintenance of the solution, and the limited quality. Furthermore, evaluating critical success factors determined that two of the proposed alternatives can not accommodate all CSFs. The analysis showed that in this specific case, the best solution would be to buy specific software from the market (iTWO costX) and target domain-specific challenges with APIs. Finally, this was the chosen solution.

The chosen solution for the re-engineered TO-BE process was defined in detail, the TO-BE process model was created, and the key performance indicators were identified. The implementation followed, and it consisted of assigning roles and responsibilities, developing a system for management of classification systems and keynotes, developing internal data dictionaries containing information requirements and modelling guidelines for the BIM models to allow successful quantity takeoff in iTWO costX. A model checking procedure was defined to ensure the model meets the specified requirements. The model exchange for the BIM-based QTO process was defined using user-defined property sets to exchange the required information. Finally, custom solutions for calculating net formwork areas of various reinforced concrete structural elements and generating sealants for the penetrations were developed using Revit API through Dynamo (Dynamo nodes, DesignScript and Python).

In the final part of the thesis, the re-engineered process was executed on a case study (an existing project). The BIM-based quantity takeoff was successfully executed following the steps defined in the TO-BE process model. In the case study, the analysis determined that approximately 70% of the BOQ items were model-based, compared to approximately 20% from the AS-IS process (analysis was made on the same project). The evaluation of the existing BOQ determined that approximately 80% of the items could potentially be model-based. Therefore, we can conclude that we came close to reaching the target but still have some room for improvement, especially for the BOQ items concerning preparatory works, earthworks, and site works. All critical success factors were accommodated. In analysing key performance indicators, we estimated that the number of person-hours required to execute the process is reduced by at least 30% and that the time required to implement the changes that only require recalculation may be reduced even more significantly. We can also conclude that the BIM-based quantity takeoff process is now internally standardized and, for the most part, documented. Many developments were made in various types of libraries. Of course, there are still some existing limits, which. The BIM models used for the QTO process will never have all building elements modelled, which means that these items can either be manually inserted into the BOQ or can be calculated based on some modelled elements (for example, the number of ventilation duct supports corresponds to the number of duct segments and their lengths) or can be included in the BOQ item as a package (for example, all fastening connecting material included to the item). Additionally, the compound elements (for example, facades) were considered as an assembly in the BOQ, meaning that the individual layers were not separated and had the same quantity (for example, area) measured, which is not entirely accurate.

We can conclude that the existing quantity takeoff process was successfully re-engineered and that the new BIM-based quantity takeoff process was successfully implemented, applied on a case study and is very likely to succeed in the future. One of the key and possibly most essential improvements recognized was the improved overall control of the process.

5.1 Future Developments

After its re-engineering, the quantity takeoff process will enter the phase of continuous process improvement. Many developments are still to be made to libraries, data dictionaries, BIM models, and other aspects of the QTO process. Using the re-engineered process on future projects and documenting and implementing the lessons learned will continuously improve it as new challenges arise and resolve. Additionally, some functionalities of the iTWO costX application software were not yet fully explored and will be in the future, for example, the use of phraseologies, code libraries and others. This will even further improve the process and reduce the time required to execute it. One of the remaining tasks is also to define, document and standardize the change management procedure.

Furthermore, the re-engineered BIM-based quantity takeoff process was only used for construction and construction finishing works, that is, within the company's architectural and civil engineering sector. The scope of use will be extended to other areas, for example, MEP.

Finally, the Revit API developments were done in Dynamo (using Dynamo nodes, DesignScript and Python). The developments will be further tested on future projects and will eventually be developed as a Revit add-in (the programming will be made in an external editor through textual programming). This will give us more flexibility and control in developing the solutions, especially with the user interface.

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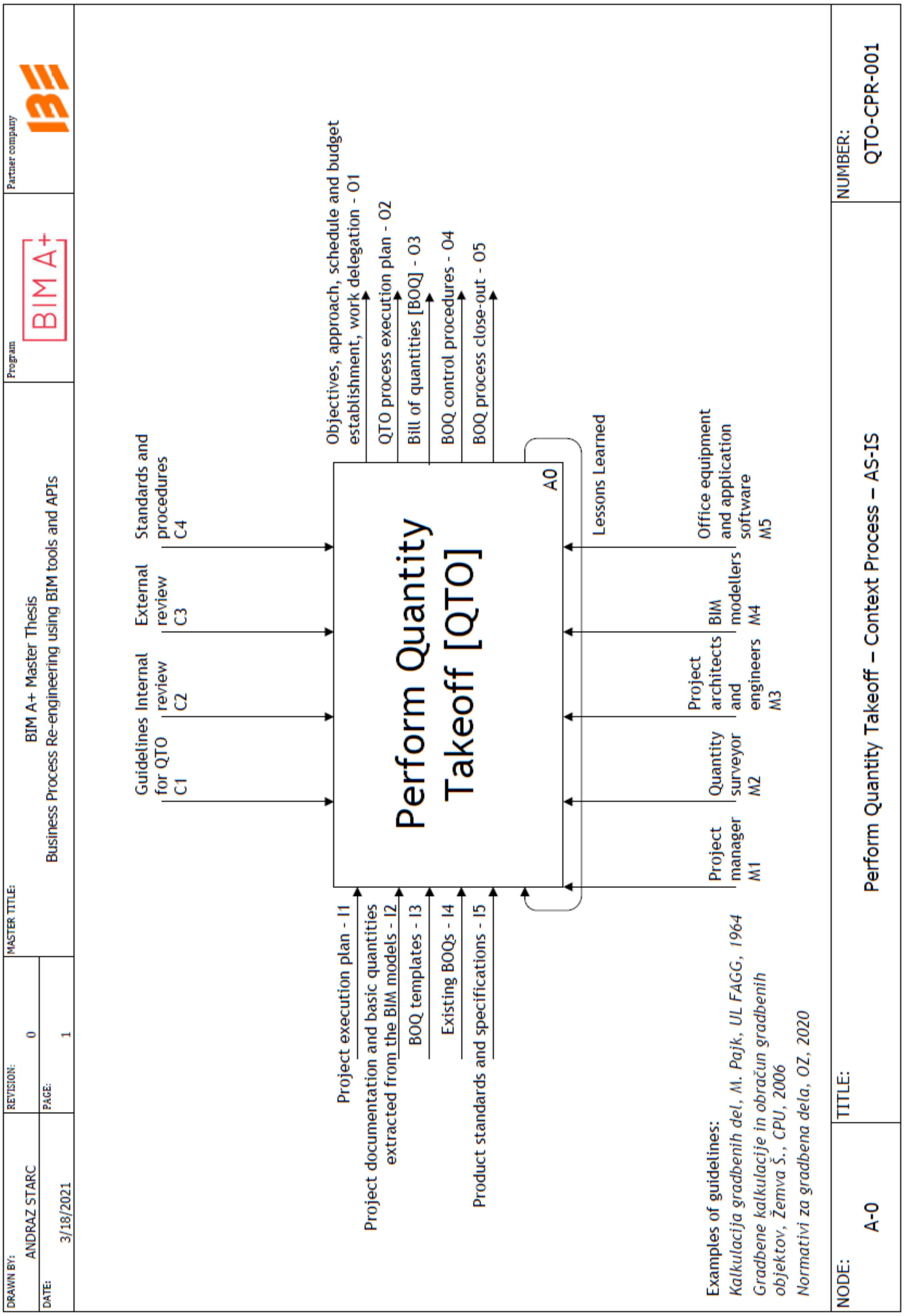
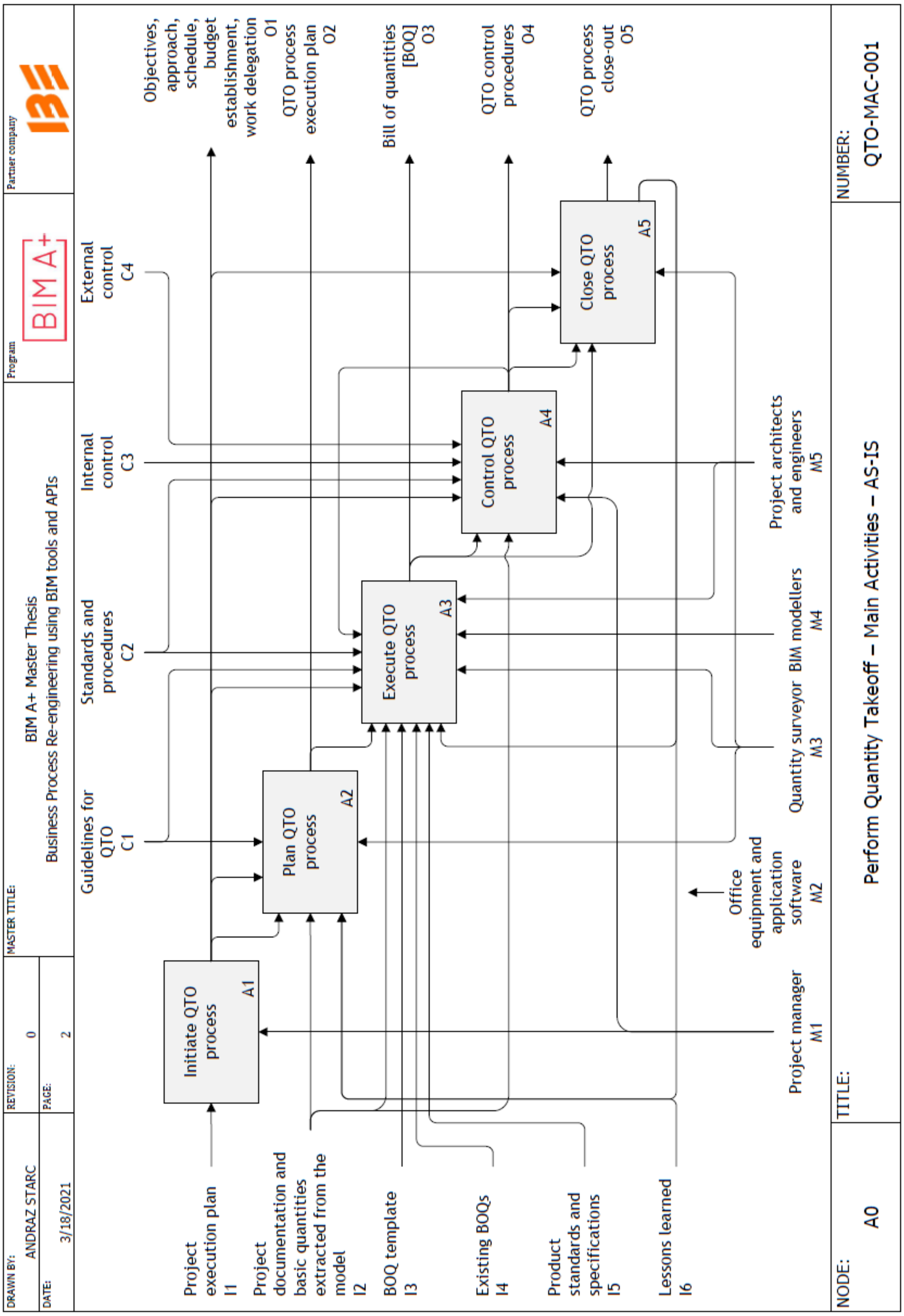
LIST OF APPENDICES

APPENDIX A: AS-IS PROCESS MODEL

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Program
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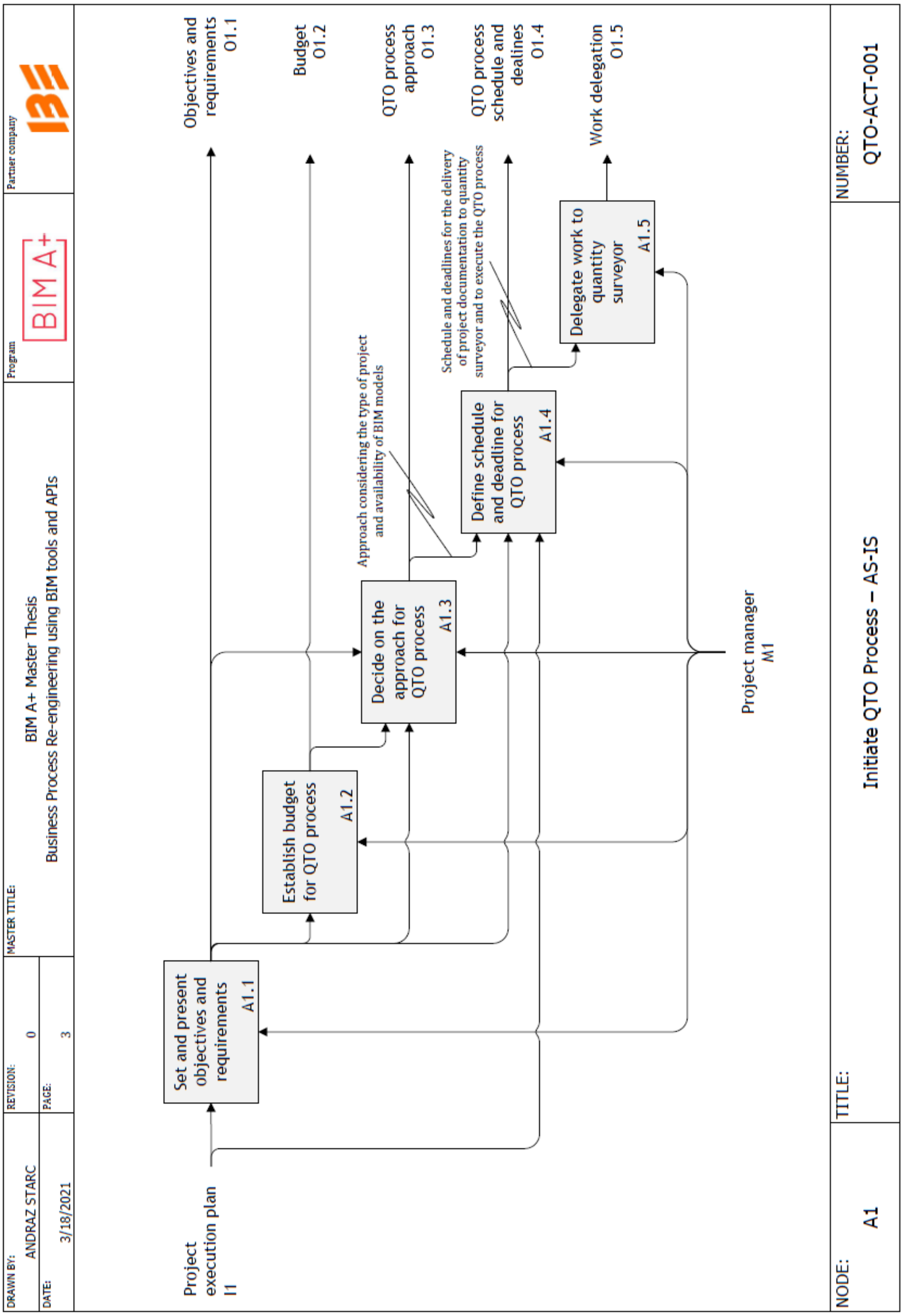
Partner company
Guidelines for QTO
C1
Standards and procedures
C2
Internal control
C3
External control
C4
Initiate QTO process
A1
Plan QTO process
A2
Execute QTO process
A3
Control QTO process
A4
Close QTO process
A5
Project execution plan
I1
Project documentation and basic quantities extracted from the model
I2
BOQ template
I3
Existing BOQs
I4
Product standards and specifications
I5
Lessons learned
I6
Objectives, approach, schedule, budget establishment, work delegation
O1
QTO process execution plan
O2
Bill of quantities [BOQ]
O3
QTO control procedures
O4
QTO process close-out
O5
Project manager
M1
Office equipment and application software
M2
Quantity surveyor
M3
BIM modellers
M4
Project architects and engineers
M5
NODE:
A0
TITLE:
Perform Quantity Takeoff – Main Activities – AS-IS
NUMBER:
QTO-MAC-001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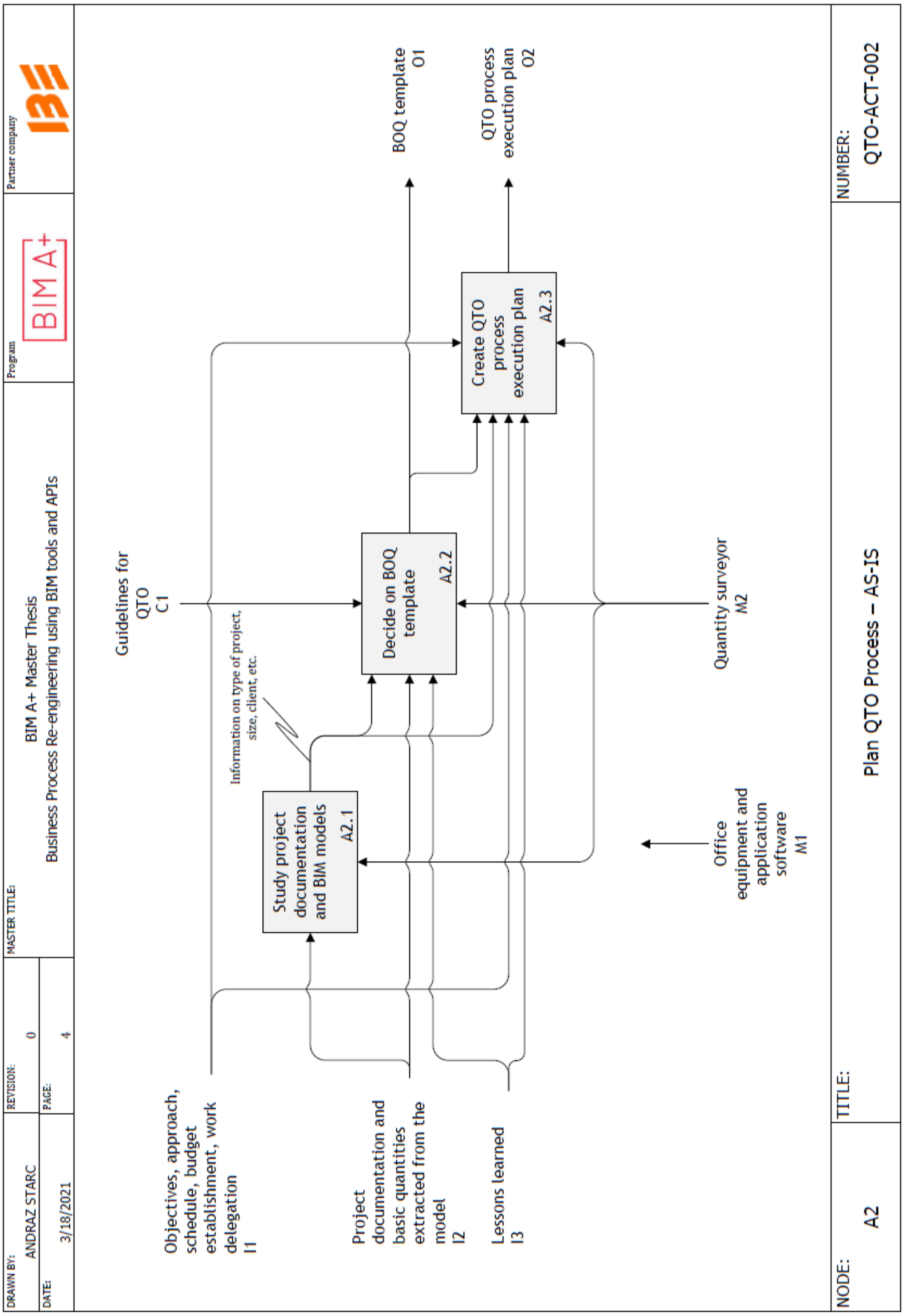
Partner company
Project execution plan
I1
Set and present objectives and requirements
A1.1
Establish budget for QTO process
A1.2
Decide on the approach for QTO process
A1.3
Define schedule and deadline for QTO process
A1.4
Delegate work to quantity surveyor
A1.5
Approach considering the type of project and availability of BIM models
Schedule and deadlines for the delivery of project documentation to quantity surveyor and to execute the QTO process
Objectives and requirements
O1.1
Budget
O1.2
QTO process approach
O1.3
QTO process schedule and dealines
O1.4
Work delegation
O1.5
Project manager
M1
NODE:
A1
TITLE:
Initiate QTO Process – AS-IS
NUMBER:
QTO-ACT-001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Program
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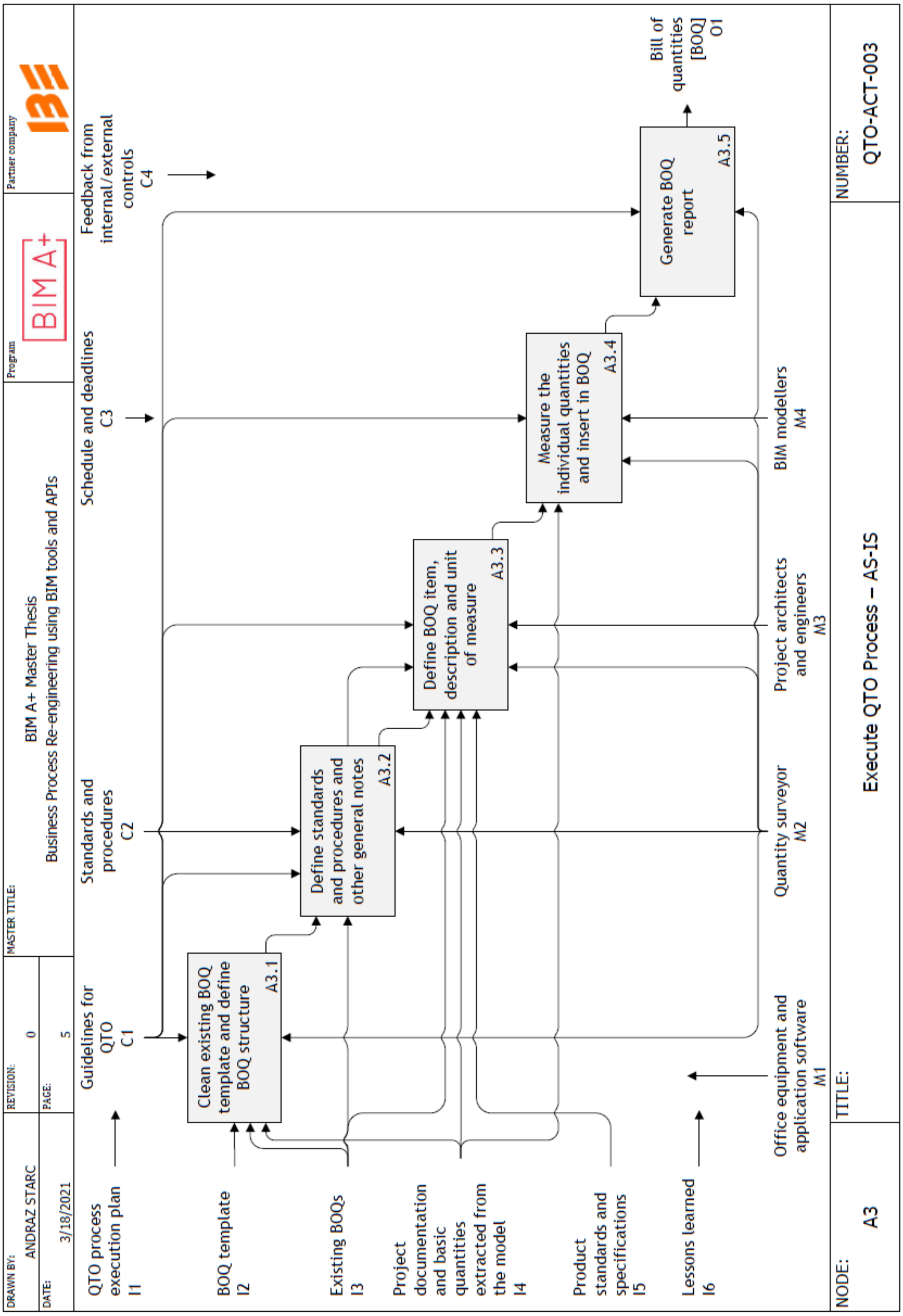
Partner company
Guidelines for QTO
C1
Information on type of project, size, client, etc.
Study project documentation and BIM models
A2.1
Decide on BOQ template
A2.2
Create QTO process execution plan
A2.3
BOQ template
O1
QTO process execution plan
O2
Objectives, approach, schedule, budget establishment, work delegation
I1
Project documentation and basic quantities extracted from the model
I2
Lessons learned
I3
Quantity surveyor
M2
Office equipment and application software
M1
NODE:
A2
TITLE:
Plan QTO Process – AS-IS
NUMBER:
QTO-ACT-002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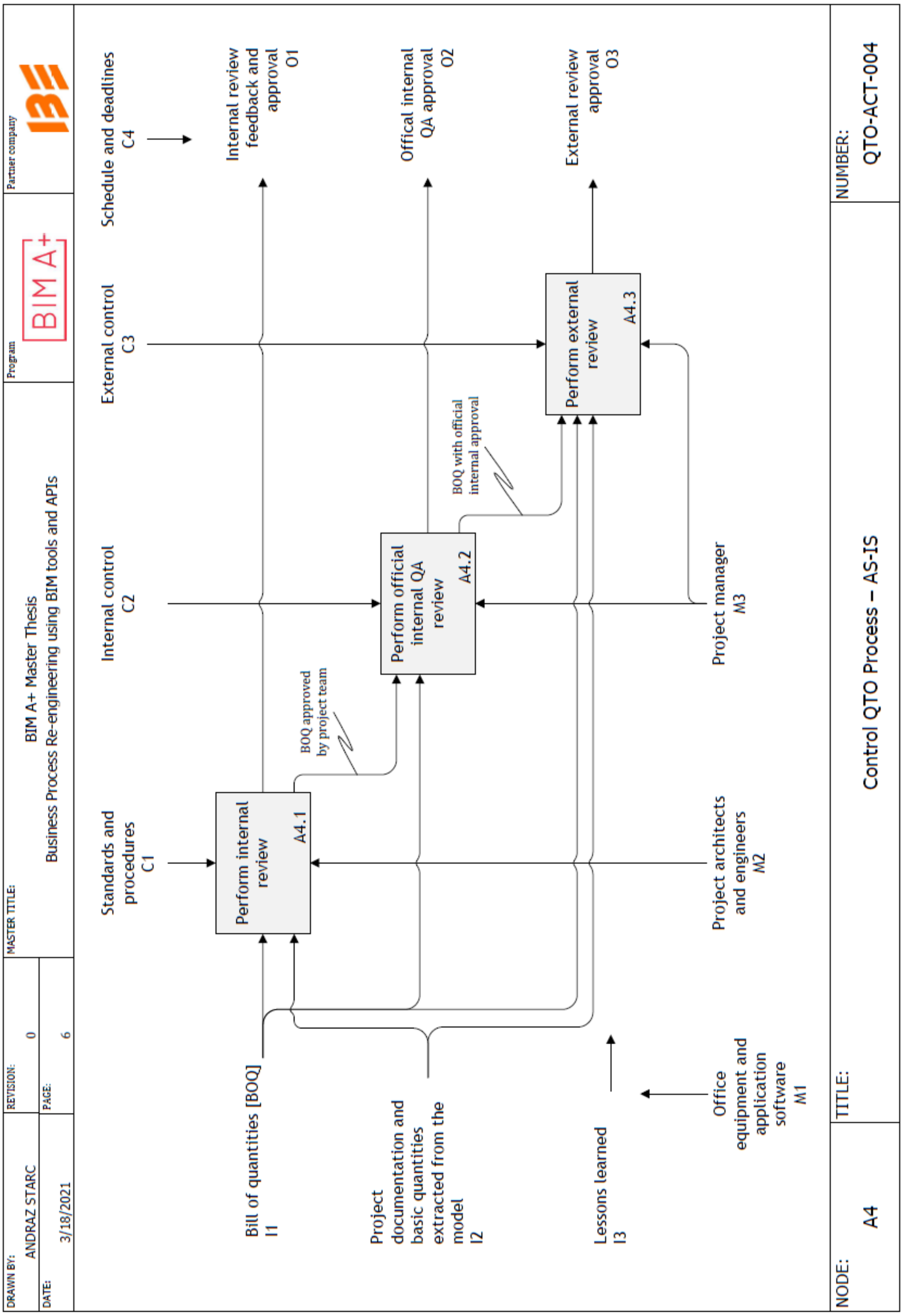
QTO process execution plan I1
BOQ template I2
Existing BOQs I3
Project documentation and basic quantities extracted from the model I4
Product standards and specifications I5
Lessons learned I6
Guidelines for QTO C1
Standards and procedures C2
Schedule and deadlines C3
Feedback from internal/external controls C4
Clean existing BOQ template and define BOQ structure
A3.1
Define standards and procedures and other general notes
A3.2
Define BOQ item, description and unit of measure
A3.3
Measure the individual quantities and insert in BOQ
A3.4
Generate BOQ report
A3.5
Bill of quantities [BOQ] O1
Office equipment and application software M1
Quantity surveyor M2
Project architects and engineers M3
BIM modellers M4
NODE: A3
TITLE: Execute QTO Process – AS-IS
NUMBER: QTO-ACT-003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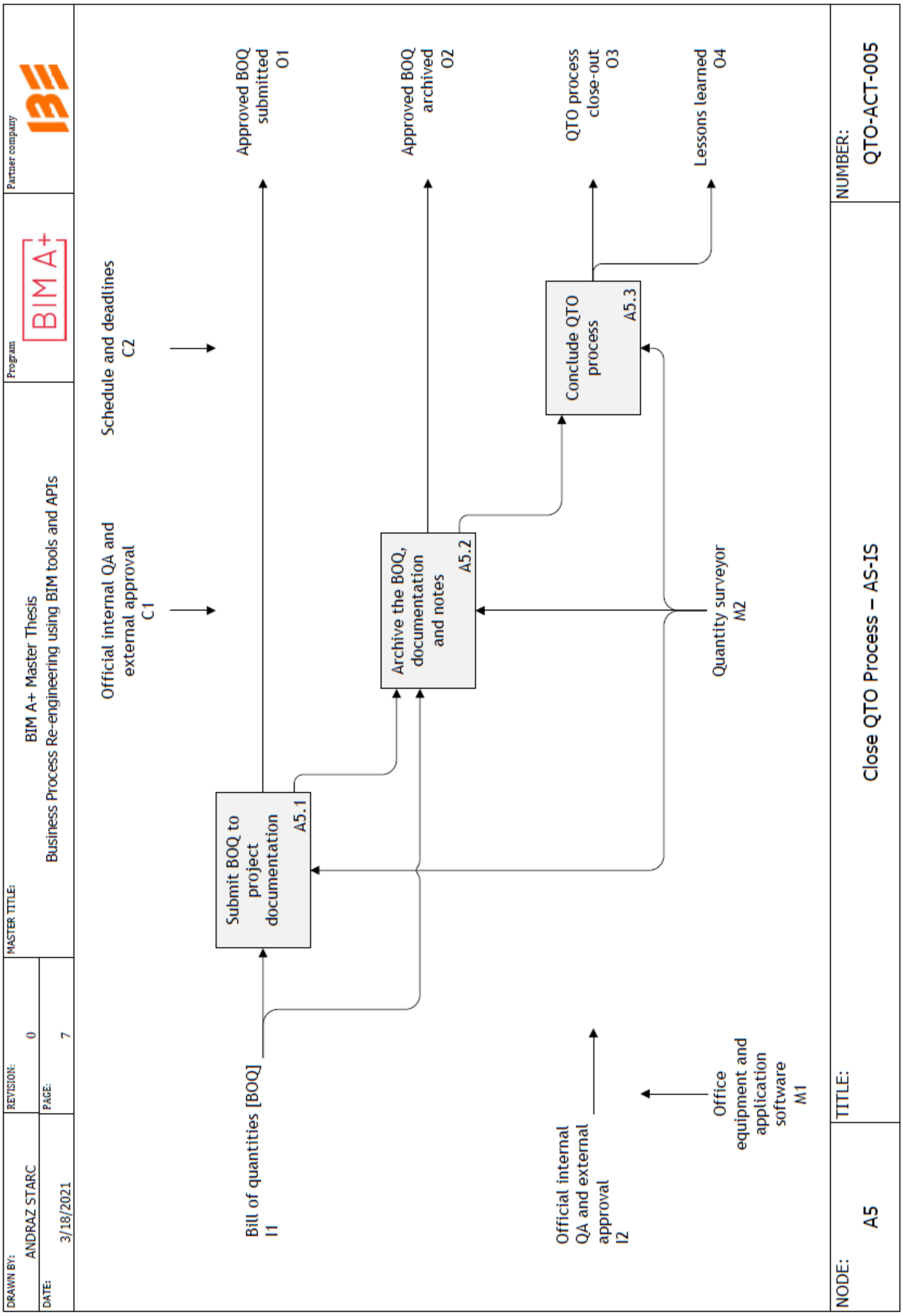
Standards and procedures C1
Internal control C2
External control C3
Schedule and deadlines C4
Internal review feedback and approval O1
Offical internal QA approval O2
External review approval O3
Perform internal review A4.1
Perform official internal QA review A4.2
Perform external review A4.3
BOQ approved by project team
BOQ with official internal approval
Bill of quantities [BOQ] I1
Project documentation and basic quantities extracted from the model I2
Lessons learned I3
Office equipment and application software M1
Project architects and engineers M2
Project manager M3
NODE: A4
TITLE: Control QTO Process – AS-IS
NUMBER: QTO-ACT-004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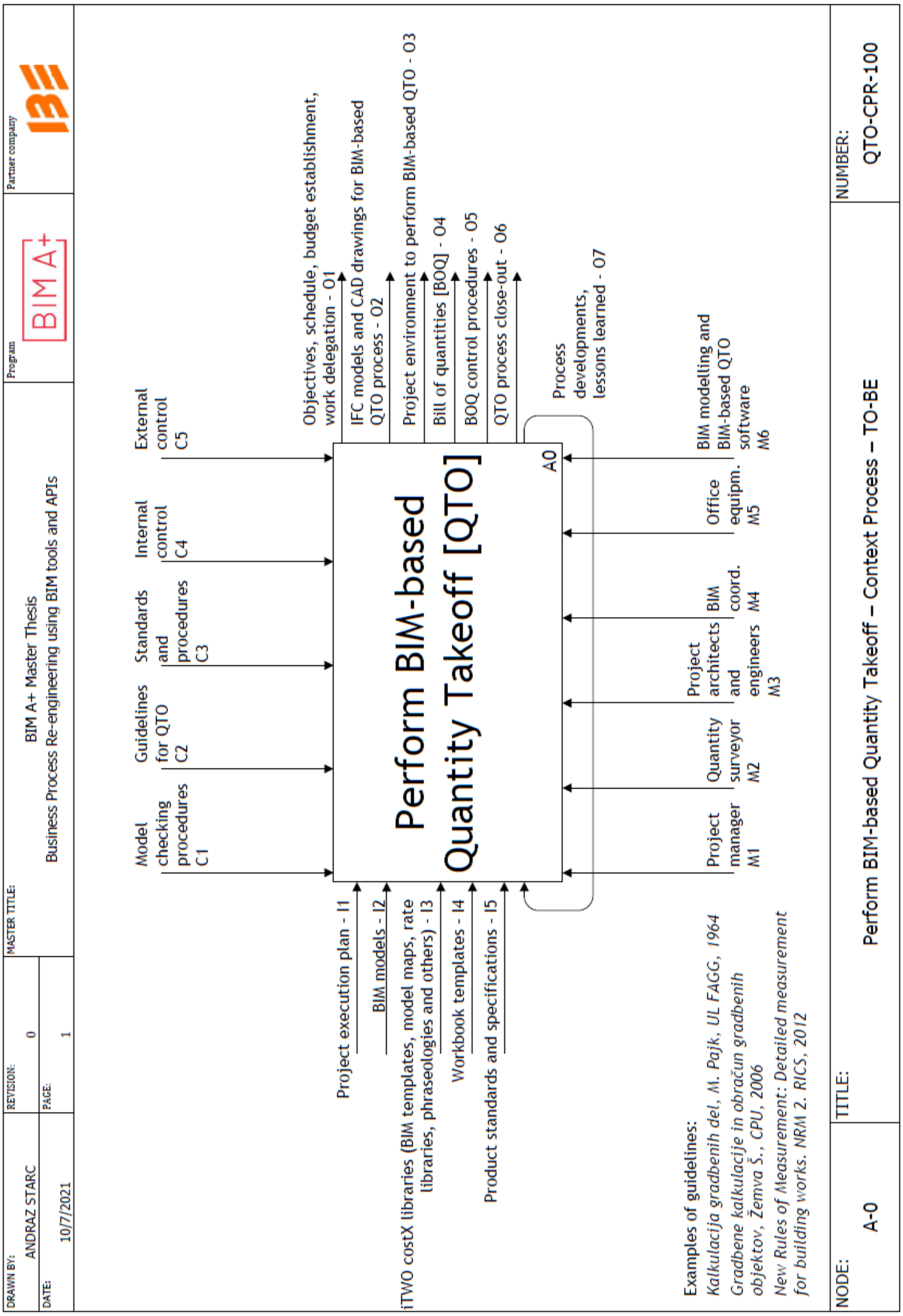
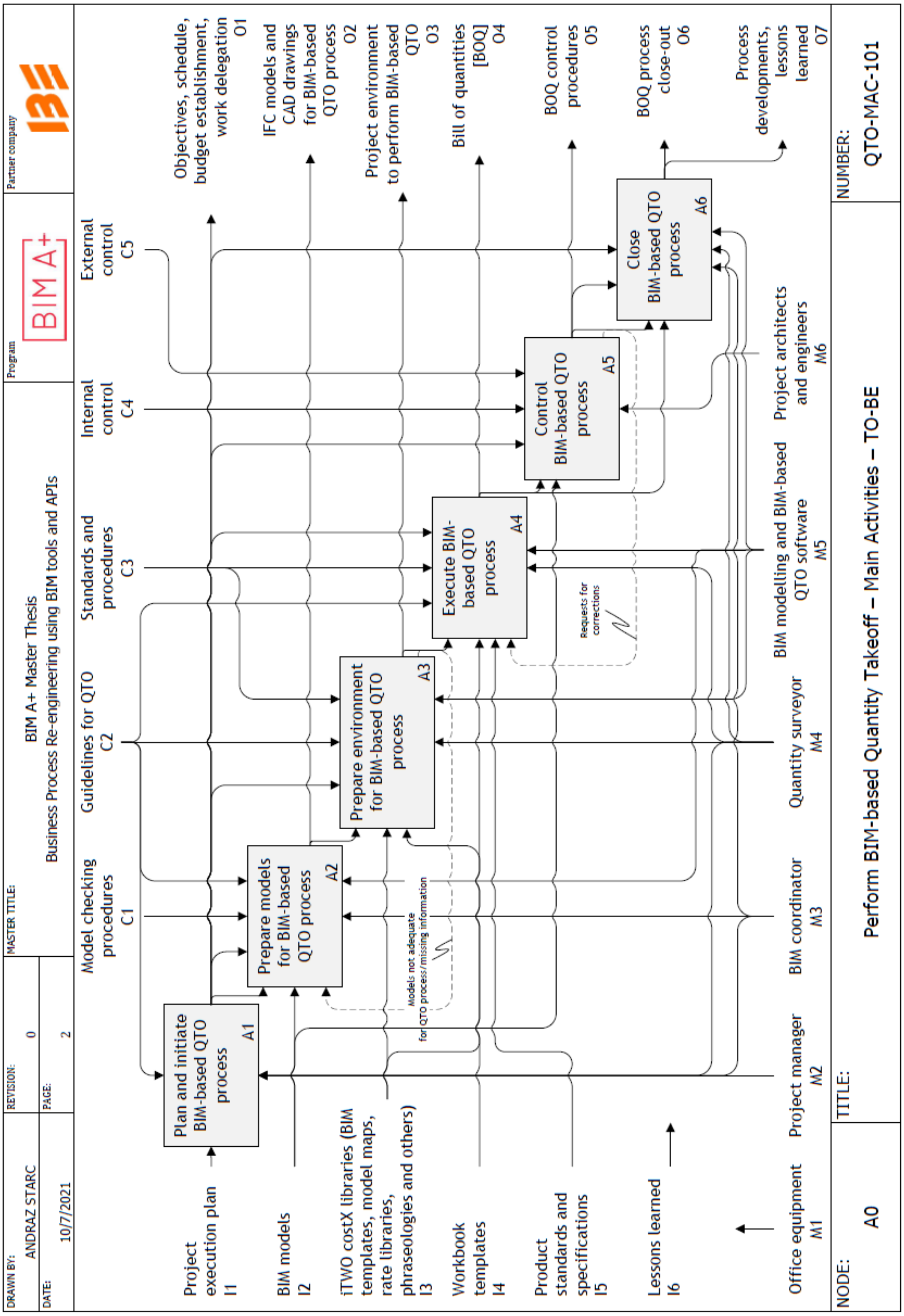
Partner company
Official internal QA and external approval C1
Schedule and deadlines C2
Bill of quantities [BOQ] I1
Official internal QA and external approval I2
Submit BOQ to project documentation A5.1
Archive the BOQ, documentation and notes A5.2
Conclude QTO process A5.3
Approved BOQ submitted O1
Approved BOQ archived O2
QTO process close-out O3
Lessons learned O4
Office equipment and application software M1
Quantity surveyor M2
NODE: A5
TITLE: Close QTO Process – AS-IS
NUMBER: QTO-ACT-005

APPENDIX B: TO-BE PROCESS MODEL

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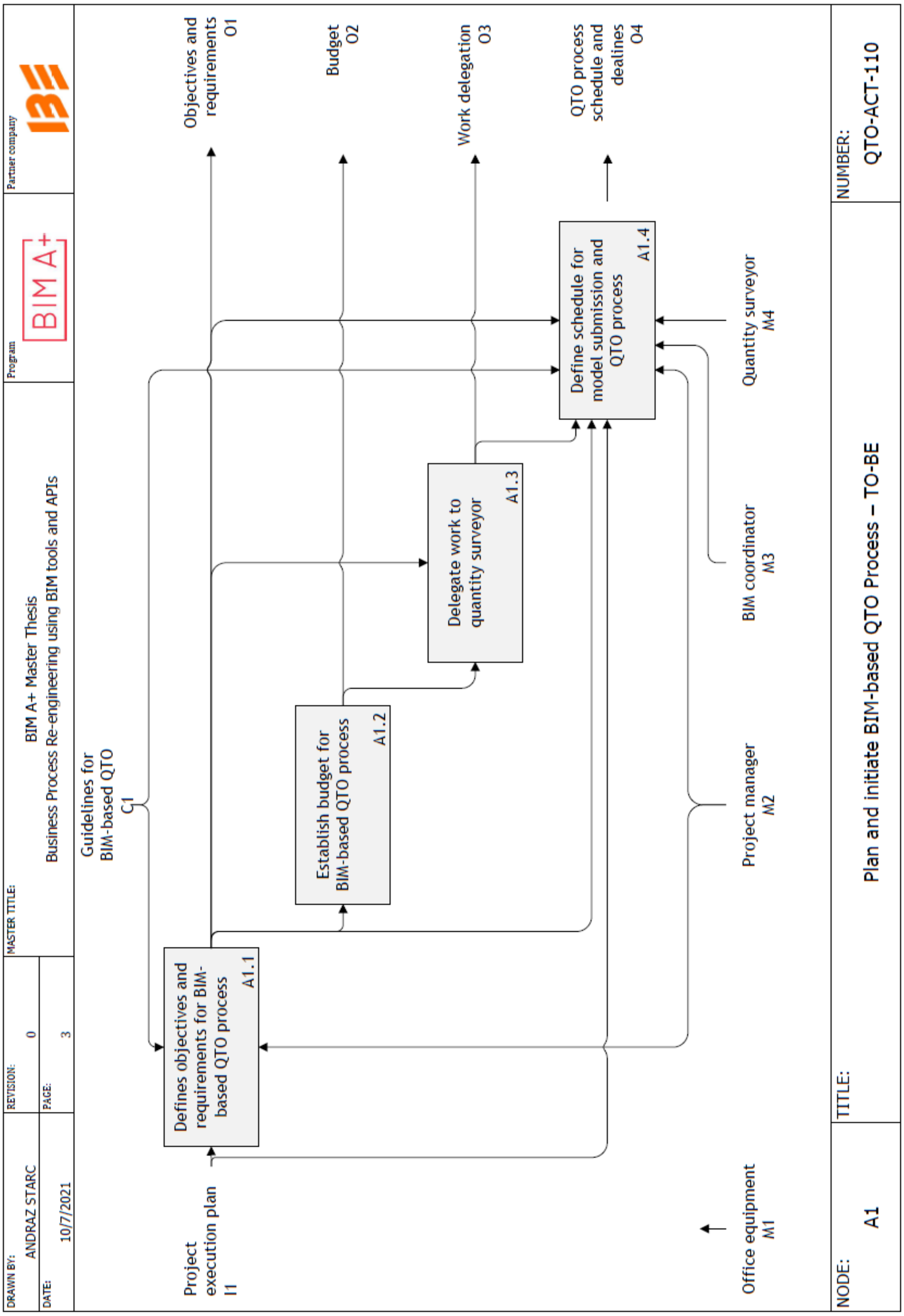
Model checking procedures C1
Guidelines for QTO C2
Standards and procedures C3
Internal control C4
External control C5
Project execution plan I1
BIM models I2
iTWO costX libraries (BIM templates, model maps, rate libraries, phraseologies and others) I3
Workbook templates I4
Product standards and specifications I5
Lessons learned I6
Plan and initiate BIM-based QTO process A1
Prepare models for BIM-based QTO process A2
Prepare environment for BIM-based QTO process A3
Execute BIM-based QTO process A4
Control BIM-based QTO process A5
Close BIM-based QTO process A6
Models not adequate for QTO process/missing information
Requests for corrections
Objectives, schedule, budget establishment, work delegation O1
IFC models and CAD drawings for BIM-based QTO process O2
Project environment to perform BIM-based QTO O3
Bill of quantities [BOQ] O4
BOQ control procedures O5
BOQ process close-out O6
Process developments, lessons learned O7
Office equipment M1
Project manager M2
BIM coordinator M3
Quantity surveyor M4
BIM modelling and BIM-based QTO software M5
Project architects and engineers M6
NODE: A0
TITLE: Perform BIM-based Quantity Takeoff – Main Activities – TO-BE
NUMBER: QTO-MAC-101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Program
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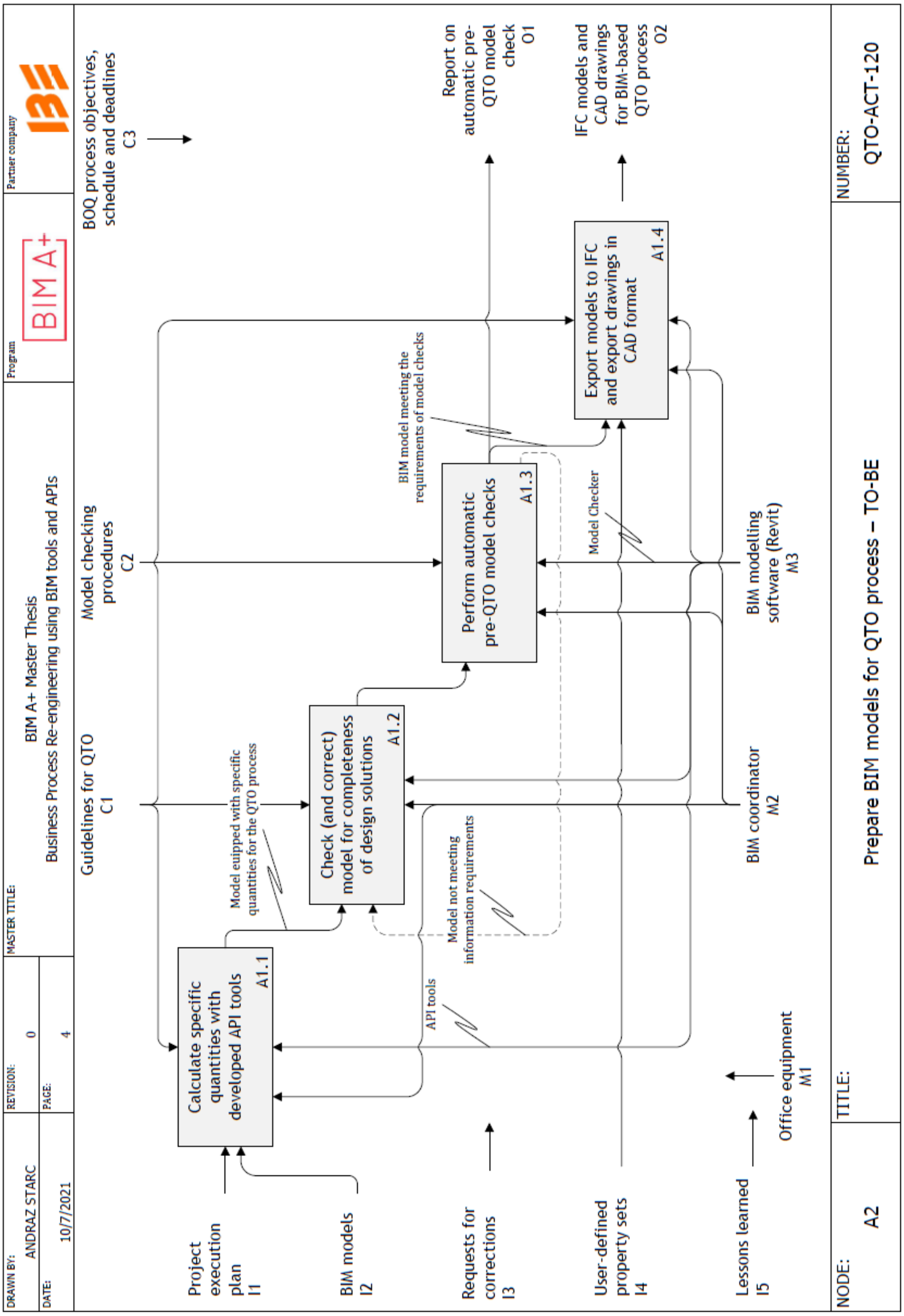
Partner company
Guidelines for BIM-based QTO C1
Project execution plan I1
Defines objectives and requirements for BIM-based QTO process A1.1
Establish budget for BIM-based QTO process A1.2
Delegate work to quantity surveyor A1.3
Define schedule for model submission and QTO process A1.4
Objectives and requirements O1
Budget O2
Work delegation O3
QTO process schedule and dealines O4
Office equipment M1
Project manager M2
BIM coordinator M3
Quantity surveyor M4
NODE: A1
TITLE: Plan and initiate BIM-based QTO Process – TO-BE
NUMBER: QTO-ACT-110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Program
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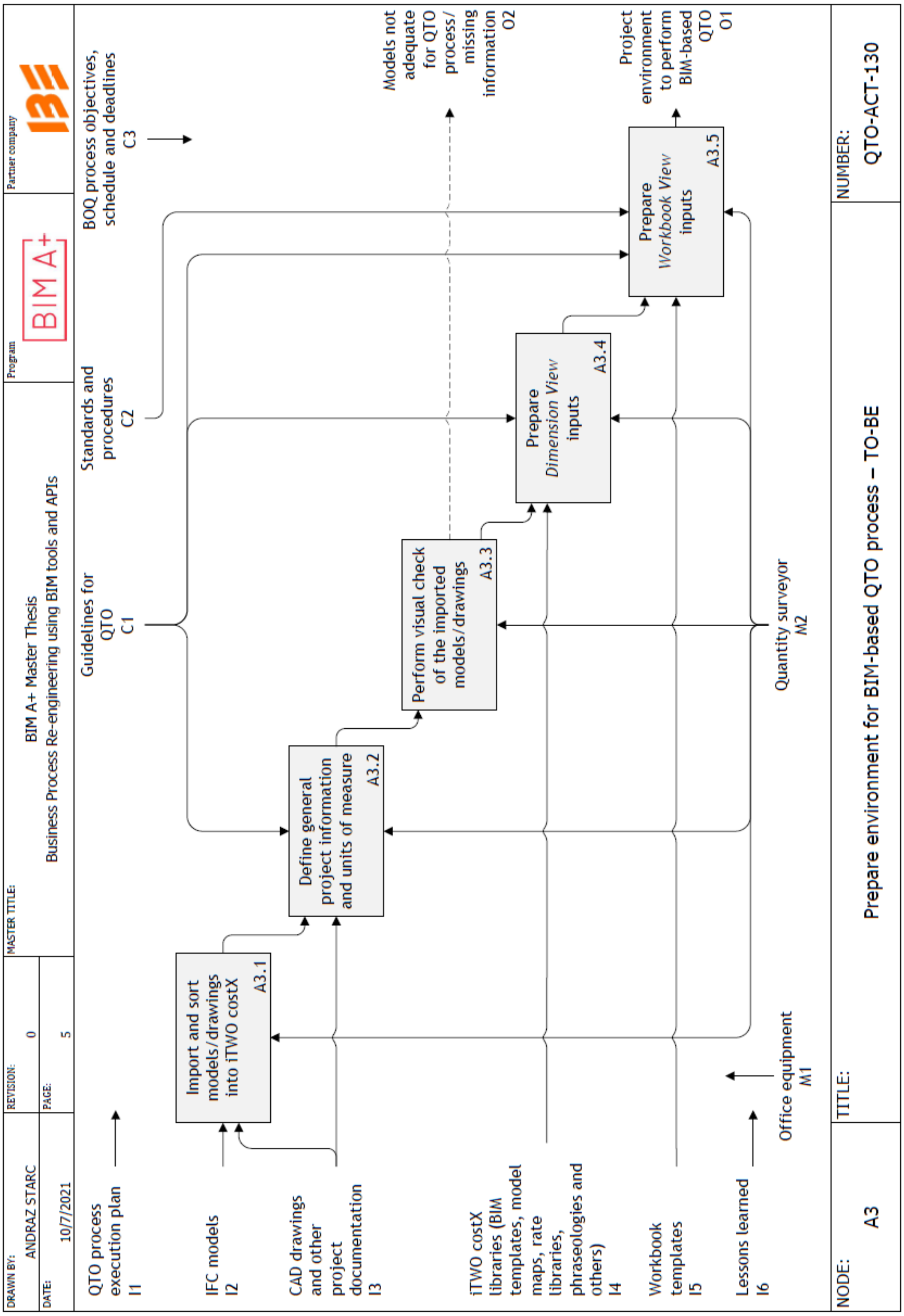
Guidelines for QTO C1
Model checking procedures C2
BOQ process objectives, schedule and deadlines C3
Project execution plan I1
BIM models I2
Requests for corrections I3
User-defined property sets I4
Lessons learned I5
Calculate specific quantities with developed API tools A1.1
Check (and correct) model for completeness of design solutions A1.2
Perform automatic pre-QTO model checks A1.3
Export models to IFC and export drawings in CAD format A1.4
Model euipped with specific quantities for the QTO process
Model not meeting information requirements
BIM model meeting the requirements of model checks
API tools
Model Checker
Report on automatic pre-QTO model check O1
IFC models and CAD drawings for BIM-based QTO process O2
Office equipment M1
BIM coordinator M2
BIM modelling software (Revit) M3
NODE: A2
TITLE: Prepare BIM models for QTO process – TO-BE
NUMBER: QTO-ACT-120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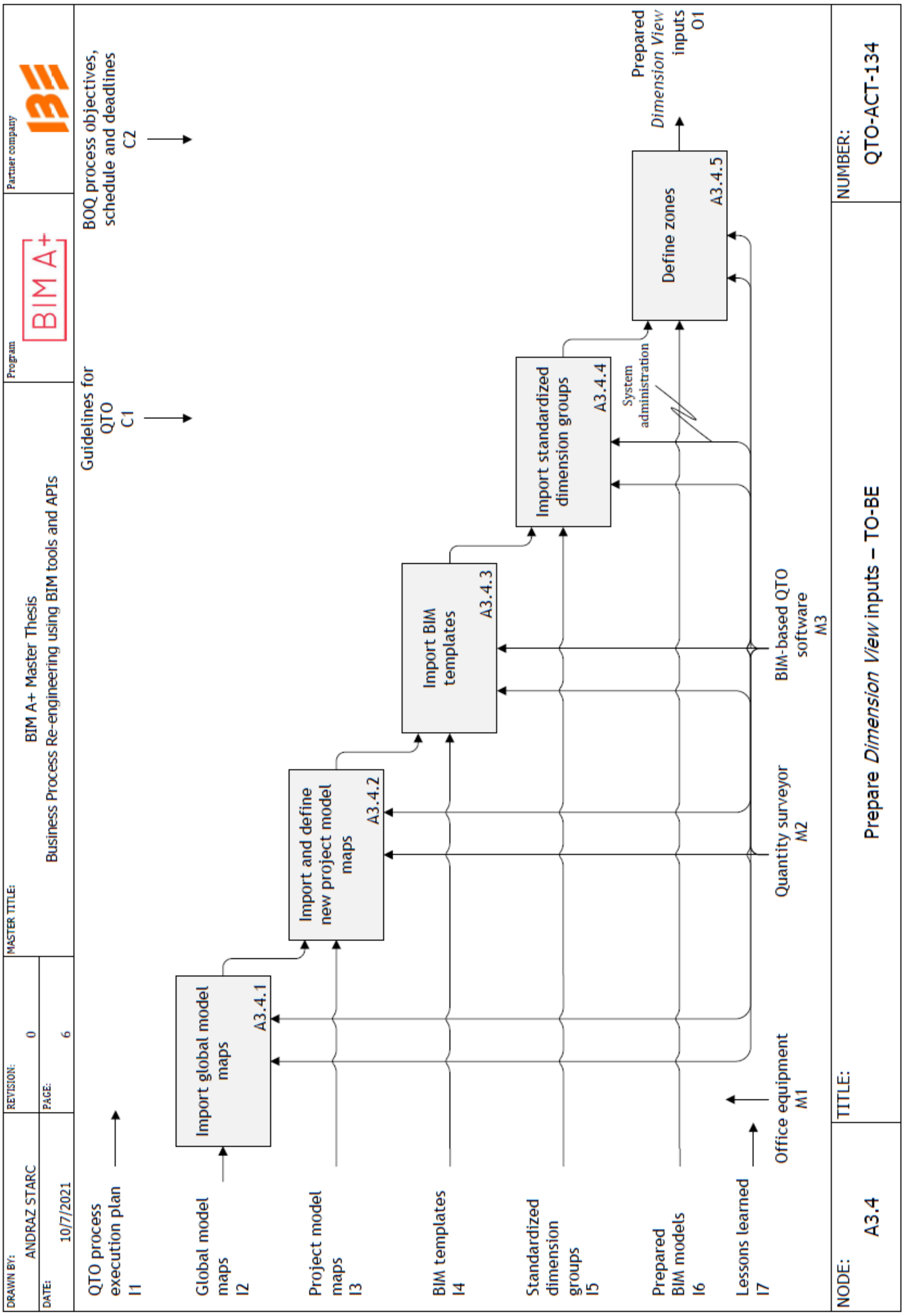
Guidelines for QTO C1
Standards and procedures C2
BOQ process objectives, schedule and deadlines C3
QTO process execution plan I1
IFC models I2
CAD drawings and other project documentation I3
iTWO costX libraries (BIM templates, model maps, rate libraries, phraseologies and others) I4
Workbook templates I5
Lessons learned I6
Office equipment M1
Quantity surveyor M2
Import and sort models/drawings into iTWO costX A3.1
Define general project information and units of measure A3.2
Perform visual check of the imported models/drawings A3.3
Prepare Dimension View inputs A3.4
Prepare Workbook View inputs A3.5
Models not adequate for QTO process/ missing information O2
Project environment to perform BIM-based QTO O1
NODE: A3
TITLE: Prepare environment for BIM-based QTO process – TO-BE
NUMBER: QTO-ACT-130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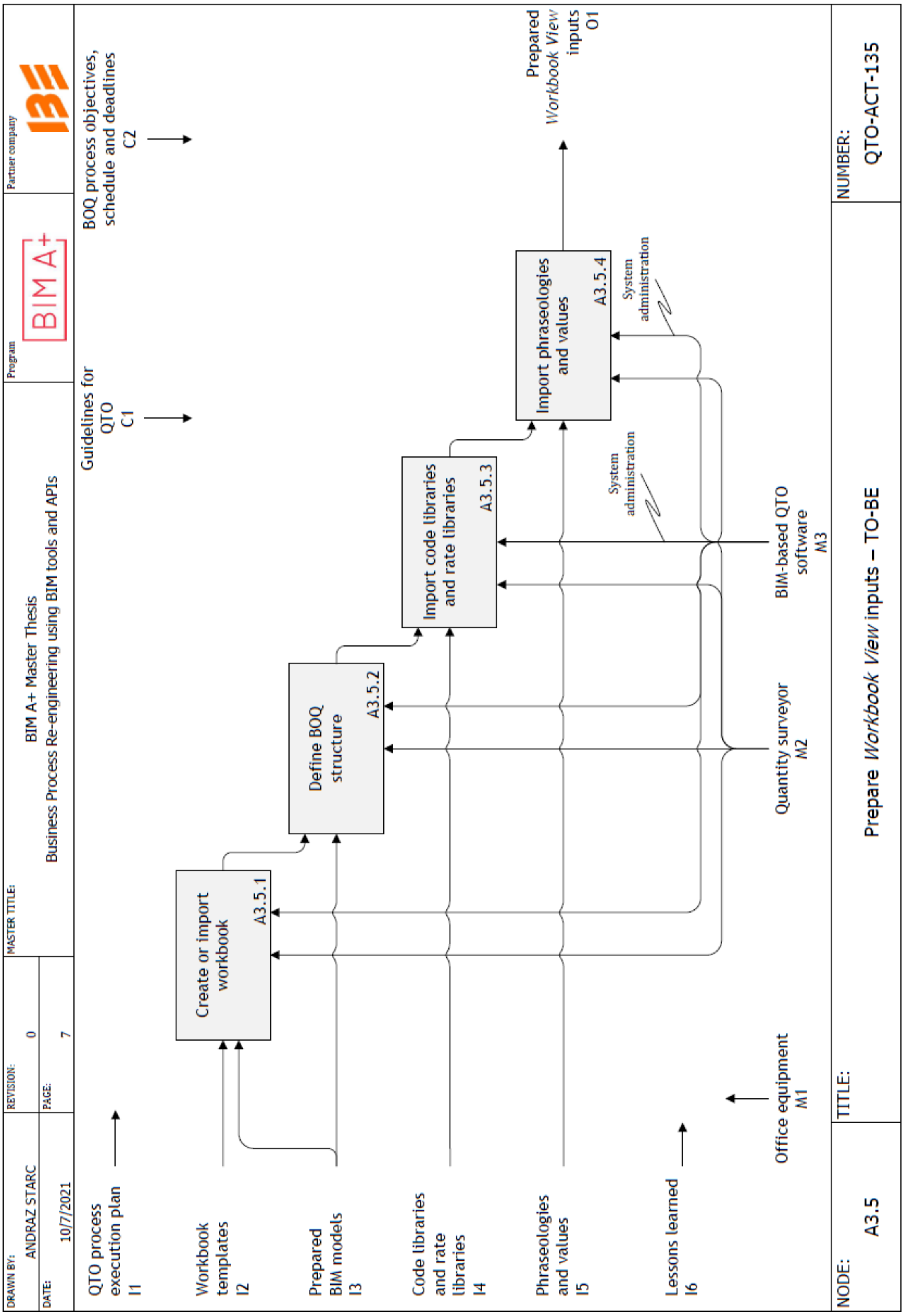
Business Process Re-engineering using BIM tools and APIs
Program
BIM A+
Partner company
QTO process execution plan I1
Global model maps I2
Project model maps I3
BIM templates I4
Standardized dimension groups I5
Prepared BIM models I6
Lessons learned I7
Guidelines for QTO C1
BOQ process objectives, schedule and deadlines C2
Import global model maps A3.4.1
Import and define new project model maps A3.4.2
Import BIM templates A3.4.3
Import standardized dimension groups A3.4.4
Define zones A3.4.5
System administration
Prepared Dimension View inputs O1
Office equipment M1
Quantity surveyor M2
BIM-based QTO software M3
NODE: A3.4
TITLE: Prepare Dimension View inputs – TO-BE
NUMBER: QTO-ACT-134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MASTER TITLE:
BIM A+ Master Thesis
Business Process Re-engineering using BIM tools and APIs
Program
BIM A+
Partner company
QTO process execution plan
I1
Workbook templates
I2
Prepared BIM models
I3
Code libraries and rate libraries
I4
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I5
Lessons learned
I6
Guidelines for QTO
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C2
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A3.5.2
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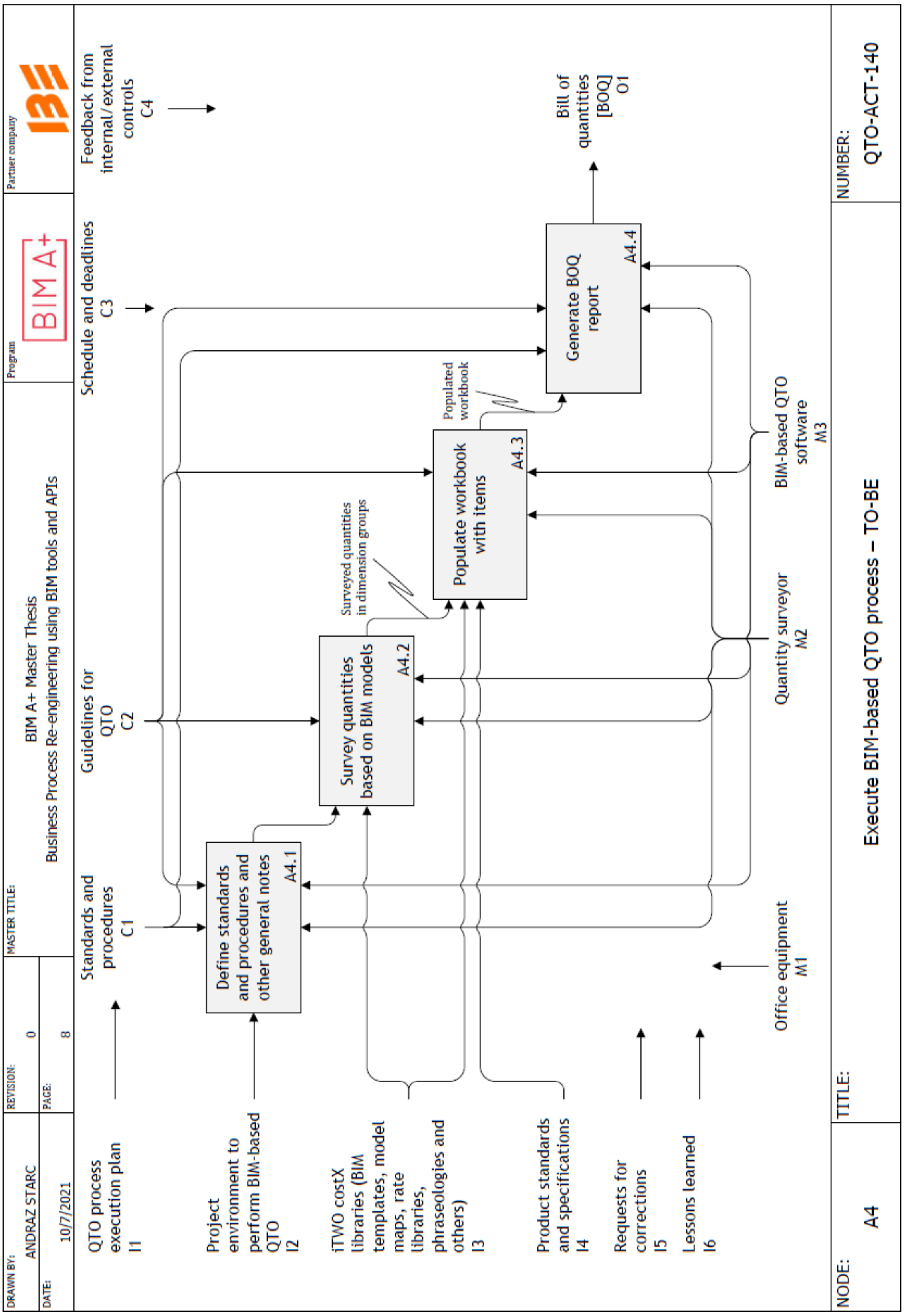
A3.5.4
System administration
System administration
Prepared Workbook View inputs
O1
Office equipment
M1
Quantity surveyor
M2
BIM-based QTO software
M3
NODE:
A3.5
TITLE:
Prepare Workbook View inputs – TO-BE
NUMBER:
QTO-ACT-135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MASTER TITLE:
BIM A+ Master Thesis
Business Process Re-engineering using BIM tools and APIs
Program
BIM A+
Partner company
QTO process execution plan I1
Project environment to perform BIM-based QTO I2
iTWO costX libraries (BIM templates, model maps, rate libraries, phraseologies and others) I3
Product standards and specifications I4
Requests for corrections I5
Lessons learned I6
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Surveyed quantities in dimension groups
Populate workbook with items
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Populated workbook
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A4.4
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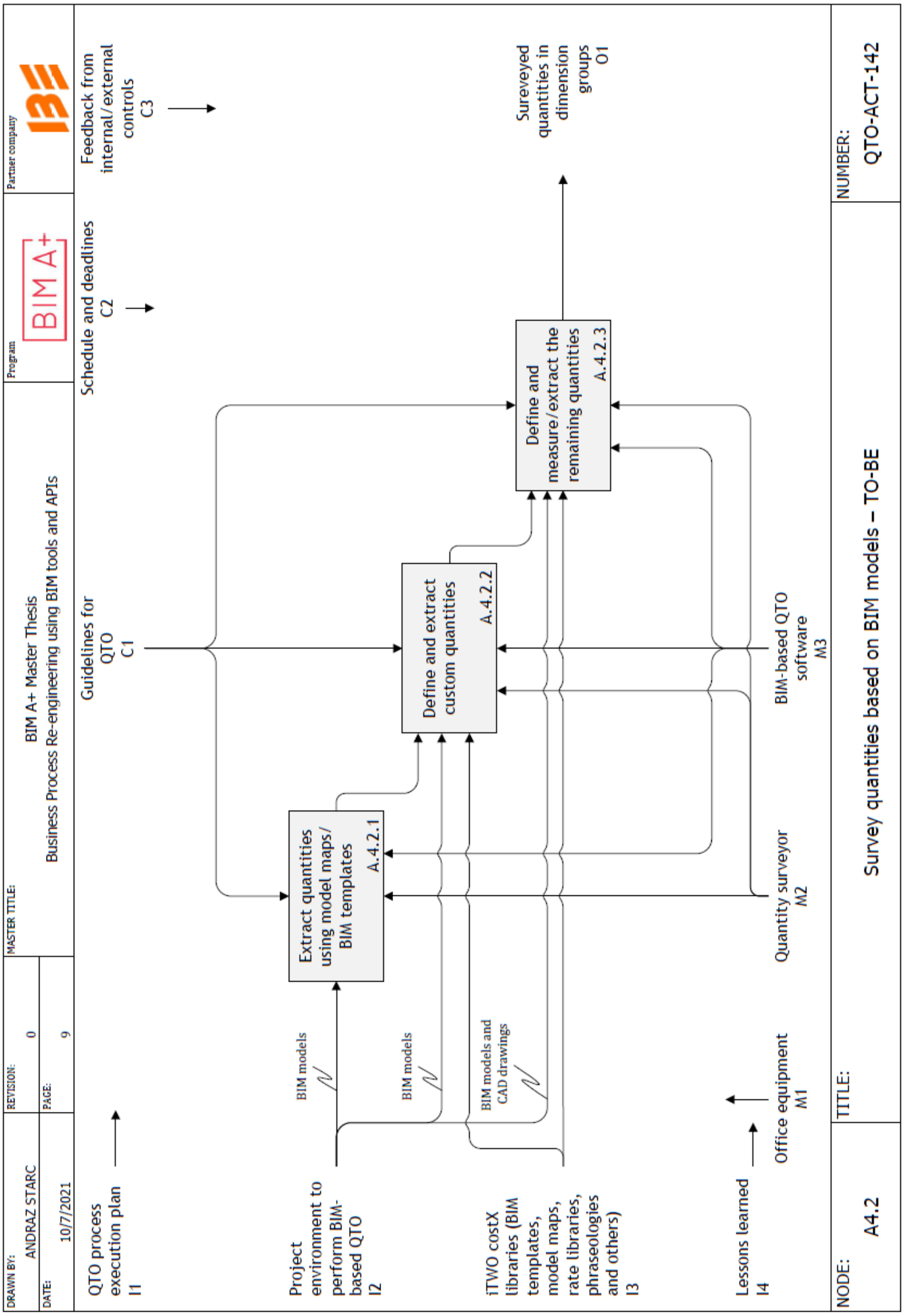
Office equipment M1
Quantity surveyor M2
BIM-based QTO software M3
NODE:
A4
TITLE:
Execute BIM-based QTO process – TO-BE
NUMBER:
QTO-ACT-140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MASTER TITLE: BIM A+ Master Thesis
Business Process Re-engineering using BIM tools and APIs
Program
BIM A+
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QTO process execution plan I1
Project environment to perform BIM-based QTO I2
iTWO costX libraries (BIM templates, model maps, rate libraries, phraseologies and others) I3
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Feedback from internal/external controls C3
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BIM models
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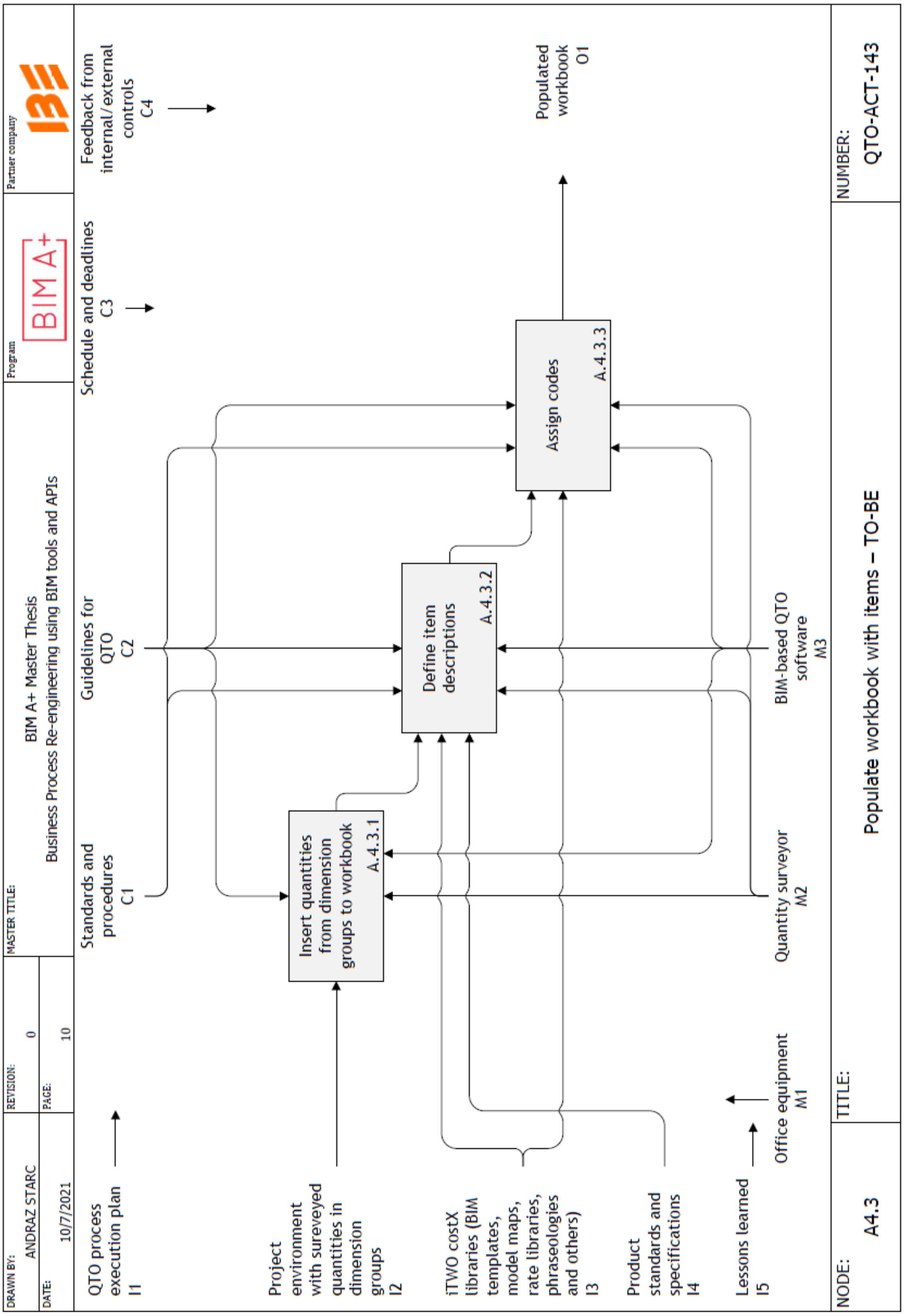
TITLE: Survey quantities based on BIM models – TO-BE
NUMBER: QTO-ACT-142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Business Process Re-engineering using BIM tools and APIs
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Project environment with surveyed quantities in dimension groups I2
iTWO costX libraries (BIM templates, model maps, rate libraries, phraseologies and others) I3
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Lessons learned I5
Standards and procedures C1
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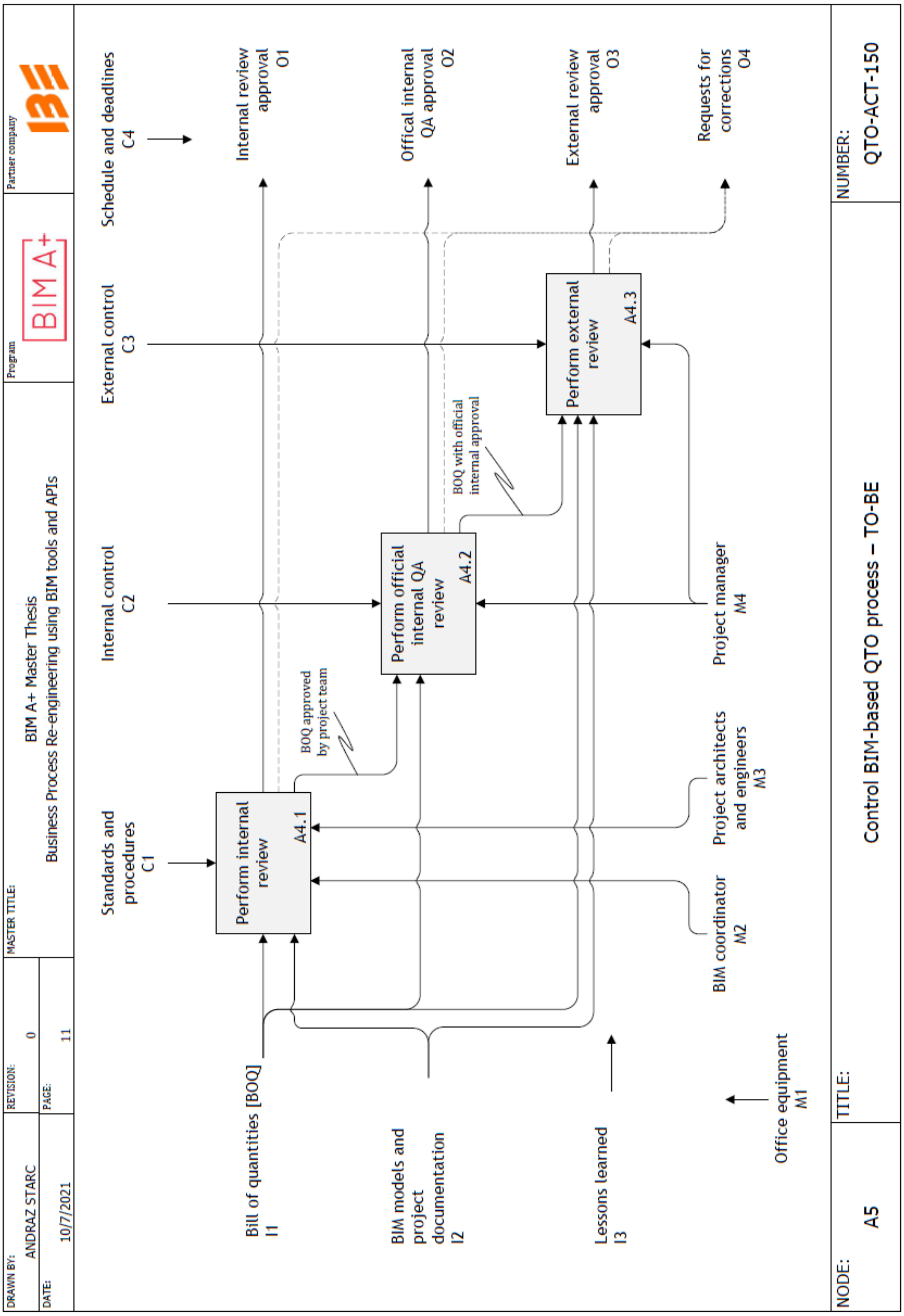
TITLE: Populate workbook with items – TO-BE
NUMBER: QTO-ACT-143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MASTER TITLE: BIM A+ Master Thesis
Business Process Re-engineering using BIM tools and APIs
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Standards and procedures C1
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Office equipment M1
BIM coordinator M2
Project architects and engineers M3
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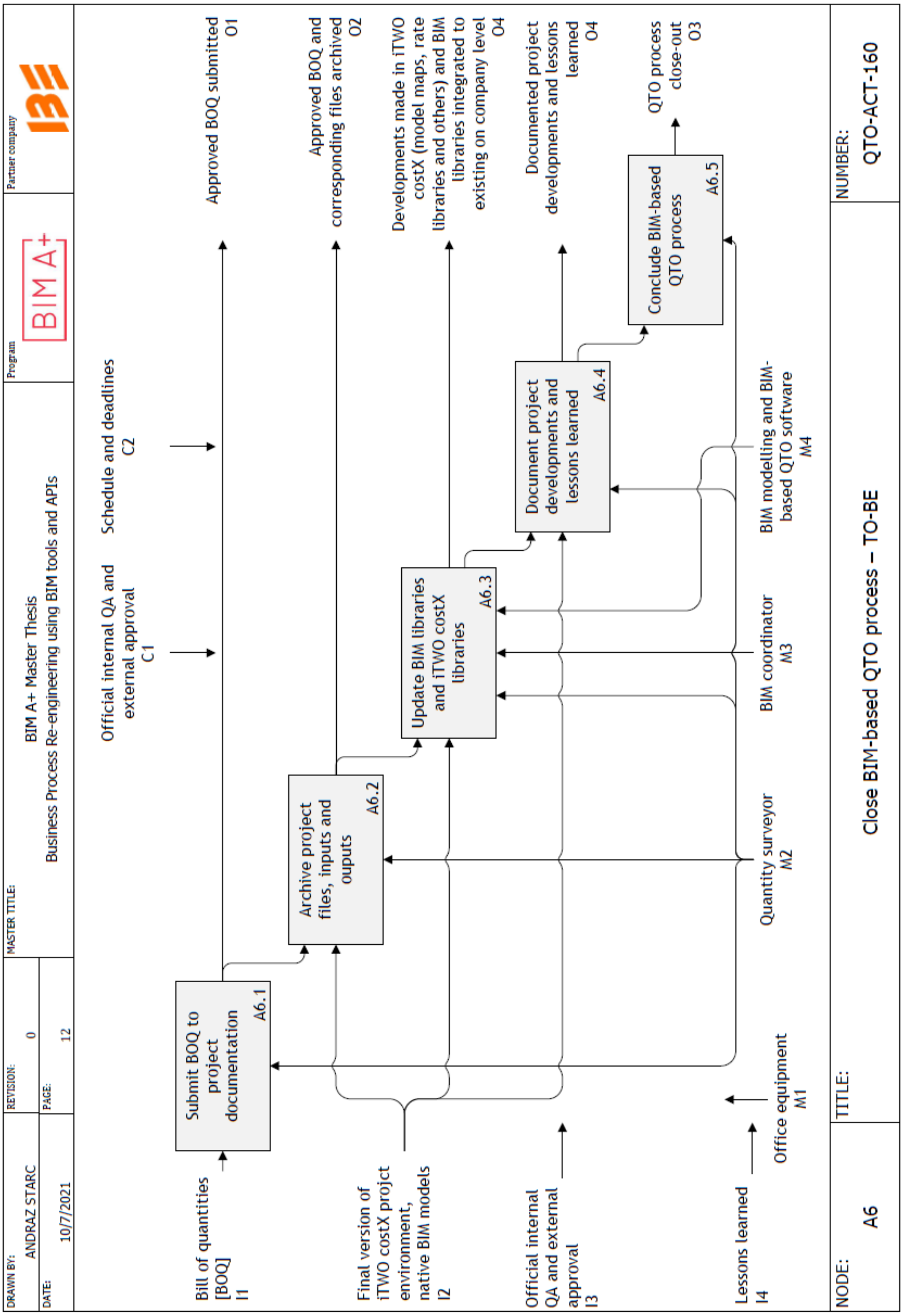
NODE: A5
TITLE: Control BIM-based QTO process – TO-BE
NUMBER: QTO-ACT-150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MASTER TITLE: BIM A+ Master Thesis
Business Process Re-engineering using BIM tools and APIs
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BIM A+
Partner company
Official internal QA and external approval C1
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Bill of quantities [BOQ] I1
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BIM coordinator M3
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TITLE: Close BIM-based QTO process – TO-BE
NUMBER: QTO-ACT-160