Optimal Construction Management & Production Control

D 7.1
System Design – Requirements and Specifications for Simulation and Prediction

WP7 – Production Planning

Version 2.1

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BIM2TWIN Consortium Partners

	Partner	Country
1	CSTB: CENTRE SCIENTIFIQUE ET TECHNIQUE DU BATIMENT	FR
2	TECHNION: ISRAEL INSTITUTE OF TECHNOLOGY	IL
3	UNIVERSITY OF CAMBRIDGE	UK
4	TUM: TECHNISCHE UNIVERSITAET MUENCHEN	DE
5	INRIA: INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE	FR
6	FIRA GROUP OY	FI
7	INTSITE LTD	IL
8	FUNDACION TECNALIA RESEARCH & INNOVATION	ES
9	ACCIONA CONSTRUCCTION SA	ES
10	RUHR-UNIVERSITAET BOCHUM	DE
11	SPADA CONSTRUCTION	FR
12	UNIVERSITA POLITECNICA DELLE MARCHE	IT
13	UNISMART – FONDAZIONE UNIVERSITÀ DEGLI STUDI DI PADOVA	IT
14	ORANGE SA	FR
15	SIEMENS AKTIENGESELLSCHAFT	DE
16	IDP INGENIERIA Y ARQUITECTURA IBERIA SL	ES
17	AARHUS UNIVERSITET	DK

DISCLAIMER

Executive Summary

In the BIM2TWIN project, we aim to apply the digital twin concept to the building construction process through a complete and holistic approach. This requires the design and creation of a digital twin platform of the construction process that will have a set of applications that allow management of the construction and provide complete knowledge of the real situation of the work at any time. The BIM2TWIN platform will bring together multiple data sources from the construction site to provide information on the status of the construction process. Knowing what is really happening on site will allow optimizing construction management. The development of the Digital Twin of the construction process on site will focus on the most relevant activities for the construction phase, such as the control of the execution and quality of the works, the planning and control of the necessary equipment and resources, and the safety of the workers.

With respect to the planning process, WP7 is developing procedures and a software prototype for optimization of construction planning subject to lean principles. The approach is to predict possible outcomes of changes to design or plan, using simulations based on the situational awareness provided by the digital building twin. To accomplish this, it is necessary at the outset to determine what information is needed to begin the simulation process, i.e. to specify the requirements for the Project Status Model (PSM) and the BIM2TWIN platform as a whole, and to define how the simulation results are to be stored in the digital twin data structure, including generation of new future state model versions.

This report focuses on the system design and the definition of the requirements and specifications for simulation and prediction. The first step was to determine and analyze the scope, or freedom of action, of future potential users when making decisions about possible changes to production plans during a project on the basis of the situational awareness provided by the Digital Building Twin Platform (DBTP). This was accomplished through semi-structured interviews with different actors involved in construction projects. On the basis of the use case results and an extensive literature review, a BPMN diagram that depicts the overall system architecture was proposed. After defining the system architecture, the input and output requirements for the simulation were specified. Finally, the DBTP functionality and data schema were developed with the aim of determining the information requirements from the PSM and the Project Intent Model (PIM), as well as the functions needed in the Application Programming Interface (API) of the DBTP to communicate that information.

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Abbreviations

AP	Alternative Plan
API	Application Programming Interface
B2T	BIM2TWIN
BIM	Building Information Model
BP	Base Line Plan
BPMN	Business Process Model and Notation
CBA	Choosing by Advantages
CPM	Critical Path Method
DBT	Digital Building Twin
DBTP	Digital Building Twin Platform
KPI	Key Performance Indicator
LPS	Last Planner System
PII	Project Intent Information
PIM	Project Intent Model
PSK	Project Status knowledge
PSM	Project Status Model
TRL	Technology Readiness Level
WP	Work Package

1 INTRODUCTION

The digital twin construction system's prediction module implements the 'ACT' step of the 'Plan-Do-Check-Act' cycle of production planning and execution. As such, it draws heavily on the project status information (PSI) and project status knowledge (PSK) components of the overall system design. These are kept separately from the project intent information (PII), to ensure that the past (status) and future (intent) can always be readily compared. The prediction module is forward looking, and its primary function is to forecast the likely outcomes of the current baseline plan and of any possible alternative plans, with the goal of providing planners with the necessary information to select an optimal construction plan at the start of every planning cycle through the life of a construction project.

1.1 Objective of the deliverable

This technical report presents the system design and the definition of the requirements and specifications for simulation and prediction. It is intended to serve as a blueprint for the development of a suite of software applications that will enable operators to

- generate alternative production plans in response to the current status production of a construction project,
- evaluate the alternative plans by simulating their likely outcomes, and
- receive recommendations concerning possible courses of action.

The report provides the information needed to align all the project actors who will work together to design, implement and test the software. As such, it provides a high-level design of the system.

1.2 Structure of the deliverable

The report is composed of five sections that describe the following topics:

(1) *Uses case results:* The use cases section summarizes the results obtained through the application of semi-structured interviews to production planners. The main objective of the application of this instrument was to define the operational decisions that production planners take during a construction project. The section also contains information regarding production planners' degree of freedom, limitations, and constraints they faced during the decision-making process as well as the outcomes of these decisions.

(2) *System objectives*: This section explains in detail the general objective of the system, as well as the methods and tools that will be used for its design.

(3) *BPMN overall system architecture:* This section presents information regarding the system architecture in order to provide the basis for defining the requirement specification for the DBTP and conceptualize the workflow and dependencies between the user, the DBTP, and the simulation software developed by WP7.

(4) *Input and output requirements:* This section provides an overview of the input and output information required or generated by the simulation process. The input requirements refer to information retrieved from the DBTP, user targets, constraints, and simulation parameters. On the other hand, the output requirements refer to the information displayed in the system dashboard such as KPIs and decision-making aids

(5) *DBTP functionality and data schema requirements:* This section presents a detailed description of the information that must be stored in the DBT platform, as well as the functionalities that the platform needs to provide to the simulation software.

1.3 Contribution of partners

This Deliverable is a collaborative effort among the consortium partners. The breakdown of the contribution of the involved partners to the various sections is:

Chapters	Main authors	Contributors
Background	Technion	
Case studies	Technion	Fira, Spada and Acciona
Use cases	Technion	Fira, Spada and Acciona
System objectives	Technion	
Overall system architecture	Technion	
User inputs and generation of alternative plans	Technion	IDP
System input and output requirements	Technion	
DBT functional and data schema requirements	Technion	TUM
Summary and discussion	Technion	

1.4 Relations to other activities

This deliverable considers the global end-user requirements, the overall workflow needs, and KPIs for the construction process specified in Task 1.1, 1.2, and 1.3, respectively. It also takes into account the solutions to be developed under Work Packages 3, 4, 5, and 6 in terms of the information they will provide to Work Package 7 through the Digital Building Twin Platform (DBTP) to be developed by Work Package 2.

The proposed data schema was developed in conformance to the core process model proposed by Task 2.1. This deliverable also specifies the frontend and backend functionality requirements for the DBTP to be considered during the development of the platform under Task 2.5. The user input and output requirements are relevant to Task 1.4 and Task 2.6, which concern the user interface of the DBTP. The use cases of the Work Package 7 software solution can guide Task 8.1 in the planning of the demonstration activities.

2 BACKGROUND

In the construction industry, many decisions are made according to the construction companies' expectations and goals. These decisions and actions can be categorized into two levels. From one side, business decisions are intended to determine what products and in which markets the construction company will offer or act [3]. On the other hand, operational decisions frame how operations should be conducted to support the business strategy [4]. A typical example of an operation strategy is the Lean construction implementation. Lean construction is defined as a relationship-focused production management system that aims to eliminate waste from the entire construction process and deliver greater value to clients [5]. Lean construction encourages accomplishing six principles to achieve the project goals successfully: (1) Define the value stream, (2) Eliminate waste, (3) Work to achieve smooth flow of work processes, (4) Implement Pull Planning and Scheduling, and (5) strive for continuous improvement [6]. This philosophy uses various tools such as 5S, Concurrent engineering, Six Sigma, Poka-yoke, Kaizen, Kanban, and Last Planner System (LPS) to guarantee its proper implementation. At the production planning level, the LPS plays a vital role in the shot -term decision-making process. The LPS process enables those who execute the work to make detailed work plans. It requires the team to review the plan near its execution specifically for collaborative planning to remove constraints and to verify that the promises made are tied to milestones and that these commitments are firm, timely, and unambiguous [7]. The last planner is characterized by the involvement of production planners in the decision-making process, specifically those who are required to implement short-term strategies to correct any project deviations [8].

According to lean construction and LPS principles, various researchers have identified production planners' main actions and decisions during the course of a construction project. Lidelöw and Simu [9] explored construction companies' emergent operations strategies and contrasted these with existing research on decision categories. The authors categorized the operational decisions according to lean construction principles: standardization, capacity/organization in projects, work environment, supply chain, work environment, human resources, continuous improvements, production planning, long-term perspective, process vs. project, and performance measurement. Pikas et al. [10] studied different decisions that production planners make based on their perceptions of the state of readiness or maturity of the work. These decisions can result in abandoning (or stopping) the planned work or improvisation and making-do.

Simu and Lidelöw [3] investigated how the perception of operations strategy in construction practice aligns with existing theories of operations strategy. The research result showed that there are two alternative sets of operations strategies: (1) resource efficiency and (2) flow efficiency. Furthermore, the study found that standardization, supply chain, and organization are perceived as structural decision categories, and human resources, continuous improvements, long-term perspective, process vs. project, and performance management are perceived as infrastructural decision categories in construction. Based on the findings of the previous researches, the main decisions or changes in the production system that production planners might make are as follows:

a) Standardize the construction activities to reduce waste and enhance the flow of activities.
b) Divide the jobsite into locations for measuring its performance (location-based method)
c) Reduce the batch size in order to decrease the work-in-progress (WIP)
d) Balance the capacity of the resources (labor and machinery) to minimize the non-value added time

A field study with different construction planners from various countries was conducted to contrast the abovementioned findings and enrich the decision set. The results and methodology are presented in Section 3.

3 CASE STUDIES

3.1 Introduction

In construction projects many actors, including production planners, are involved in making design and planning decisions that affect project outcomes. Decisions are made whenever planners determine that the current product designs or process plans can be improved upon. This may be in response to measured deviations from the designs or plans, or they may be proactive steps that result from review of progress and performance to date. Production planners' decisions are implemented in the form of revised or new production plans. Thus, in this step of the research, we seek to document and understand their behaviors, actions, and degrees of freedom. The method adopted to gain precise understanding of the aforementioned factors was to formulate several uses cases on the basis of a series of semi-structured interviews that elicited case studies and the literature review (chapter 2). The case studies were documented to provide a clear perspective of the context for production planners involved in the construction decision-making process. It is important to note that the use cases listed in Chapter 4 were derived from the case studies obtained in the interview process.

A use case is an engineering term that describes how a user utilizes a system to accomplish a particular goal. A use case acts as a modeling technique that defines the features to be implemented and the resolution of any errors that may be encountered [1]. The following subsections present in detail the methodology used, descriptions of the case studies, consolidated results, and the conclusions obtained.

3.2 Methodology

Eighteen (18) semi-structured interviews (see annex 1) were performed to gather information directly from production planners working in the architecture, engineering, and construction domain (AEC). A semi-structured interview consists of a meeting in which the interviewer does not precisely follow a formal list of questions. Instead, they will ask more open-ended questions, allowing for a discussion with the interviewee rather than a straightforward question and answer format [2]. The instrument was implemented with a variety of production planners, including site managers, project managers, foremen and supervisors. The semi-structured interview template contained ten (10) relevant questions that aimed to identify the production planners' degree of freedom in decision-making when faced with the need for product or process changes. The technical sheet of this instrument is shown in

Table *1*. Th case studies themselves are documented in Annex I, starting on page 63.

After implementing the instrument, a meticulous analysis of the operational decisions made by production planners during a construction project was carried out. Later, limitations that production planners faced during the decision-making process were systematized and analyzed. Finally, production planners' degree of freedom was defined according to their roles. Figure 1 depicts the methodology used for this task:

Table 1. Semi-structured interviews technical sheet

Technical sheet	
Method:	Semi-structured interview
Approximated duration:	1 hour
Population:	Site manager, project manager, foreman, supervisor
Number of interviews conducted:	18
Countries of implementation:	Finland, Spain, Colombia and Panama
Period of implementation:	April to June 2021
Interview content:	
1. Interviewee general information 2. Main decisions or actions performed to accomplish the construction project goals 3. Case study description 4. Decisions 5. Responsible person – decision makers 6. Degrees of freedom 7. Limitations 8. Information needed and updated 9. KPIs 10. Information needed/desired	
Data analysis	Qualitative

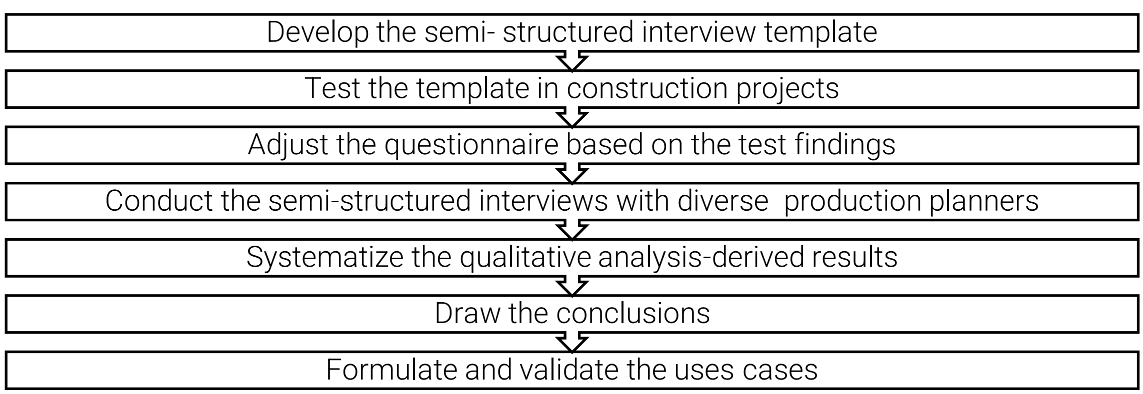

Figure 1. Use cases methodology

3.3 Case studies systematization

The semi-structured interview results were consolidated for further analysis. Aspects such as type of project, interviewee role, location of the work (interior or exterior), nature of the problem, and its category were useful for structuring and analyzing the case studies results. Production planners' degrees of freedom in the process of making decisions or changes to the construction plan were categorized into three types, according to the number of actors involved and the time required to implement these decisions:

- *High Level:* production planners only require authorization from the site manager
- *Medium Level:* production planners require authorization from the project manager and other field professionals (e.g., geotechnical engineer, structural engineer)
- *Low Level:* production planners require authorization from several parties involved such as the owner, project manager, site manager and other field professional

3.4 Conclusions

In total, 18 case studies were documented with the aim of understanding the operational decisions that production planners make during the course of construction projects (see annex 1). To achieve this goal, semi-structured interviews were applied with different construction planners pertaining to the ACE domain. Semi-structured interview results were meticulously systematized and categorized by the nature of the problem, production planners' role, decisions considered to mitigate problems, changes in the production system, production planner's degree of freedom, and limitations and constraints. In general, seven (7) case studies corresponded to interior work and eleven (11) to structural work. In total 18 production planners were interviewed. More specifically, nine site managers, one project manager, three supervisors, one superintendent, one foreman, and three support staff. To complement the findings obtained through the field study, an extensive literature review was carried out to understand the main decisions and actions that production planners make according to lean construction principles.

Based on the field study findings and the literature review, we conclude that the main changes in the production system that production planners made to accomplish the project's objectives were: (1) add, reduce, or allocate resources (labor, material, and machinery), (2) change the original design, (3) incorporate new subcontractors, (4) reschedule some construction activities, (5) modify construction methods (6) standardize the construction activities to reduce waste and enhance the production flow, (7) divide the jobsite into locations for measuring its performance (location-based method), (8) reduce the batch size in order to decrease the work-in-progress (WIP) and, (9) balance the capacity of the resources (labor and machinery) to minimize the non-value added time. According to the nature of the change, production planners involved in both structural and interior work required authorization to make decisions that could affect the project cost and duration. More specifically, decisions that needed design changes demanded a higher level of authorization when compared to those that required changes in the construction method. Thus, modifications in the original design led to requesting the owner's approval, hindering the production planners' degree of freedom. On the other hand, changes in construction methods or rescheduling construction activities required approval from site managers and other field professionals. However, despite the large number of people involved in the decision, these changes needed less time to be implemented when compared to design changes.

The primary limitations that affected the decision-making process of production planners were: (1) lack of information concerning the current status of both interior and structural work (e.g., tile installation on bathrooms, floors, excavation, among others), (2) absence of real-time information about subcontractors (e.g., crews productivity rate, number of workers by crew and subcontractor, workers location and subcontractor schedule), (3) excessive number of people participating during the decision-making process (chain of command), (4) legal limitations concerning the scope of the subcontractor's assignments and (5) technical limitations that hindered the implementation of the proposed solution (e.g., soil studies, specification of the concrete among others). More specifically, production planners claimed that the lack of real-time information with respect to the construction project status hampered the decision-making process of production planners. Indeed, manual data capture is error-prone and time-consuming, affecting production planners' response to any change in the production system. For instance, the absence of real-time information on project resources status led production planners to manually gather and analyze these values from the jobsite, affecting the decision-making process and increasing uncertainty.

Production planners also relied heavily upon KPIs capable of accounting for the project cost and duration. The majority of the proposed changes were assessed by comparing the actual cost and duration against the planned ones. In most cases, production planners could not determine the root causes of delays and cost overruns for each proposed change. Nevertheless, some production planners, especially those associated with structural work, implemented KPIs related to resource productivity, allowing their optimization and continuous improvement. For interior work, various production planners computed the number of defects observed during the finishing work. More concretely, they compared the number of defects identified and fixed by each workers' crew to determine non-conformities per trade crew.

Plan and schedules were the most frequent data sources utilized, especially for structural work changes, concerning the information or documents used and updated during the decision-making process. This could be associated with the impact of the proposed solutions on the project's cost and duration. The most common data source for interior work was productivity rates, mainly used to assign work crews to certain activities depending on their skills. Finally, production planners emphasized the need for real-time information related to production rates, workers' locations and assignments, material inventory, and project progress status.

4 USE CASES

4.1 Use cases definition

Using the case studies and literature review results, it can be inferred that the main changes that production planners make for reducing the project cost, time, and waste are (1) add, reduce, or allocate resources (labor, material, and machinery), (2) change the original design, (3) incorporate new subcontractors, (4) reschedule some construction activities, (5) modify construction methods (6) standardize the construction activities to reduce waste and enhance the production flow, (7) divide the jobsite into locations for measuring its performance (location-based method), (8) reduce the batch size in order to decrease the work-in-progress (WIP) and, (9) balance the capacity of the resources (labor and machinery) to minimize the non-value added time . For each case, production planners' degree of freedom varies according to the impact on the project cost and duration. It implies that different actors may influence the decision-making process and delay the proposed solution implementation, affecting the fulfillment of the intended objectives. According to their nature and the people involved, the changes mentioned above were formulated and presented as use cases intended to establish user inputs and requirements for the simulation and prediction software.

The proposed use cases were validated with appropriate field management personnel at all three construction companies (Fira, Spada and Acciona) participating in task 7.1. Tables 2 to 10 describe the use cases for each change in the production system, degree of freedom, and KPIs utilized to measure the feasibility of the changes.

Table 2. Use case # 1. Resources modification

Use case # 1	
Category	Process change
Production system change	Add, reduce, or re-allocate resources (labor, material, and machinery)
Responsible for the decision	Superintendent and/or supervisor
Decision-makers	Site manager
Level of authority	High
Information required to take the decision	Construction schedule, budget, resources productivity rate.
KPIs used	Resources productivity rate and utilization rate, activity total cost and duration
Case study associated	1-16, 18

Table 3. Use case # 2. Design changes

Use case # 2	
Category	**Product change**
Production system change	Change the original design
Responsible for the decision	Site manager
Decision-makers	Owner's representative, external stakeholders (community or public institutions), and other field professionals (e.g., geotechnical engineer, structural engineer, and electromechanical engineer)
Level of authority	Low
Information required to take the decision	Plans, budget, contract and schedule
KPIs used	Resources productivity rate, activity total cost and duration
Case study associated	2, 5, 9, 10, 12, 15-17

Table 4. Use case # 3. Subcontractors incorporation

Use case # 3	
Category	Process change
Production system change	Incorporate new subcontractors and crews or remove existing subcontractors or crews
Responsible for the decision	Site manager
Decision-makers	Project manager
Level of authority	Medium
Information required to take the decision	Project schedule and budget
KPIs used	Resources productivity rate
Case study associated	1, 7, 11

Table 5. Use case # 4. Construction activities rescheduling

Use case # 4	
Category	Process change
Production system change	Reschedule some construction activities
Responsible for the decision	Site manager and/or superintendent
Decision-makers	Project manager
Level of authority	High
Information required to take the decision	Project schedule and resources productivity rate
KPIs used	Activity total cost and duration
Case study associated	2, 3, 5, 11,18

Table 6. Use case # 5. Construction methods modification

Use case # 5	
Category	**Product change**
Production system change	Modify construction methods
Responsible for the decision	Site manager
Decision-makers	Project manager and other field professionals (e.g., geotechnical engineer, structural engineer, and electromechanical engineer)
Level of authority	Medium
Information required to take the decision	Technical specifications, budget, resources productivity rate and schedule
KPIs used	Activity total cost and duration and resources utilization rate
Case study associated	2, 5, 6, 9, 10, 13, 14, 16, 18

Table 7. Use case # 6. Resources utilization rate, productivity rate, no-value added time, and cycle time

Use case # 6	
Category	**Process change**
Production system change	Standardize the construction activities to reduce waste and enhance the production flow
Responsible for the decision	Site manager
Decision-makers	Foreman
Level of authority	High
Information required to take the decision	Technical specifications, budget, resources productivity rate, and schedule
KPIs used	Resources utilization rate, productivity rate, non-value-added time, and cycle time
Case study associated	From the literature

Table 8. Use case # 7. Divide the jobsite into locations for measuring its performance (location-based method)

Use case # 7	
Category	**Process change**
Production system change	Divide the jobsite into locations for measuring its performance (location-based method)
Responsible for the decision	Site manager
Decision-makers	Project manager
Level of authority	High
Information required to take the decision	Resources productivity and utilization rate and project schedule
KPIs used	Resources utilization rate, productivity rate, non-value-added time, and cycle time
Case study associated	From the literature

Table 9. Reduce the batch size in order to decrease the work-in-progress (WIP)

Use case # 8	
Category	**Process change**
Production system change	Reduce the batch size in order to decrease the work-in-progress (WIP)
Responsible for the decision	Site manager
Decision-makers	Foreman
Level of authority	High
Information required to take the decision	Resources productivity and utilization rate, and project schedule
KPIs used	Resources utilization rate, productivity rate, non-value-added time, and cycle time
Case study associated	From the literature

Table 10. Balance the capacity of the resources (labor and machinery) to minimize the no-value added time

Use case # 9	
Category	**Process change**
Production system change	Balance the capacity of the resources (labor and machinery) to minimize the no-value added time
Responsible for the decision	Site manager
Decision-makers	Foreman
Level of authority	High
Information required to take the decision	Resources productivity and utilization rate, and schedule
KPIs used	Resources utilization rate, productivity rate, non-value adding time, and cycle time
Case study associated	From the literature

5 SYSTEM OBJECTIVES

5.1 Proposal

The overarching objectives defined for the BIM2TWIN project (section 1 of Part B of the grant agreement) are to a) provide construction designers and planners with complete situational awareness, thus b) enabling them to “implement lean construction principles through PDCA cycles, thus reducing operational waste of all kinds, including energy consumption.”

WP 7 focuses on the second aspect, that is to leverage the situational awareness to improve production planning and execution. It addresses the quality of workflow on a construction project, primarily on-site, through simulation, prediction, formulation and recommendation of proposed changes to construction plans and/or building designs to improve performance. Evaluation of future outcomes for proposed changes will use agent-based simulations (for an explanation of agent-based simulation, see [11]), enabling identification of alternatives to optimize resource flow and minimize waste.

The state-of-the-art in this area is to use scheduling tools based on the Critical Path Method (CPM), but these are not efficient and co-dependencies with external factors are not considered. These tools are at the highest technology readiness level (TRL), i.e. TRL 9. The innovation proposed in BIM2TWIN within the context of WP 7 consists of a holistic approach to predict outcomes of design and plan alternatives using agent-based simulations and applying machine learning to historical data. This technology has been explored up to TRL 3, and the objective is to attempt to bring this technology to TRL 6.

5.2 System objectives

Specifically, the system objectives that define WP 7 activity are the following (from chapter 1.1 Objectives of the grant agreement Part B):

SO4: Optimise work planning and use of equipment

SO4.1: Design, prototype and validate a set of innovative AI-based methods and tools for optimal short- and medium-term operational planning and control of the equipment on construction sites

SO4.3: Design, prototype and validate a set of agent-based methods and tools to optimize construction planning from situational awareness provided by BIM2TWIN.

SO4.4: Interoperate the tools with the BIM2TWIN Platform

Fulfillment of these system objectives requires development of software in three distinct modules: first, for proposing candidate alternate production plans (AP); second, for evaluating those plans; and third, for optimization of production planning.

The **proposal module** should apply artificial intelligence techniques to derive meaningful adaptations to the baseline plan (BP). As can be seen from the use cases derived in the previous chapter, adaptations may include: addition, removal and/or re-allocation of resources (material, crews, equipment); design changes, i.e. changes to the construction product designs; incorporation of new subcontractors and/or removal of others; re-scheduling construction activities; modification of construction methods; and, of course, any combination of these.

The **evaluation module** should determine the most likely outcomes from implementation of any given AP. This module must support simulation of future states based on the current as-built/as-performed state and any given alternative future state as-designed/as-planned. Simulations are essential for prediction of possible outcomes, which informs managers' decision-making, allowing them to select some optimal future design/plan for delivery to the construction team for execution from any given time forward.

The **optimization module** should apply a genetic algorithm or other techniques to progressively improve alternate plans with respect to their predicted outcomes, thus leading to the identification of optimal plan alternatives at any given time.

Three targets were set for validating the outcomes of WP 7, as follows:

- Unitary testing and assessment of the tools in two ways: lab tests and demo on construction sites of partners ACCIONA, FIRA, SPADA.
- Testing and assessment of the tools when integrated with the BIM2TWIN platform
- Demonstrate the use of the CFI as a KPI of flow at the demonstrator projects and evaluate its effectiveness as a measure of the impact of the WP7 solution

6 OVERALL SYSTEM ARCHITECTURE

6.1 Introduction

6.1.1 Objectives

The overall system architecture provides the basis for defining the requirement specification for the DBT and for conceptualizing the workflows and the dependencies between the user, the DBTP, and the simulation software developed by WP7. Once the key components and functionalities of the overall simulated-based production planning system were identified, a list of input information requirements was detailed based on understanding what information is needed to achieve the expected output of the component or functionality. Detailing the workflow of the system also enables the identification of potential interactions and dependencies between WP7 and other WPs.

6.1.2 Definitions

The **Baseline Plan (BP)** in the DBT is the current as-planned construction plan stored in the **Project Intent Information** (**PII)**. It consists of the work breakdown schedule (a hierarchy of work packages, activities, tasks that capture the construction methods and group the building product element parts that are constructed in each one), the location breakdown schedule (a hierarchy of zones and locations in which work is assigned), a planned construction and material delivery time schedule, labor assignments, equipment utilization, product information requirements, and site safety information.

An **Alternative Plan (AP)** in the DBT is any proposed alternative construction plan to be investigated. An AP can be generated in three possible ways:

- a user can modify the current BP directly
- a user can compile an AP from scratch
- the system can automatically generate an AP subject to constraints defined by users

The user input of the WP7 system can be generalized to three categories: targets, constraints, and simulation parameters. **Targets** are user-defined objectives to evaluate the performance of an **AP**. These can be construction milestones such as the handover date of a building or KPIs such as the cycle time. **Constraints** in the context of the simulation software refer to the scope of modification the user can make to the **BP**. For example, the subcontractor may increase the size of its concrete crew by a maximum of 5 workers. These **constraints** define the set of **APs** which the software should simulate and evaluate. Finally, **simulation parameters** are performance indicators which the user can adjust to better conform the simulation to the reality on the construction site. An example of such parameters is the production rate of a concrete crew. These parameters can also be derived based on historical DBT data from past construction projects and the **Project Status Knowledge (PSK)** of the current project.

We adopt the **Business Process Model and Notation (BPMN)**, a graphical representation standard, to capture the overall information flow within the simulation, prediction, and evaluation process. **BPMN** is based on a flowcharting technique similar to activity diagrams from Unified Modeling Language (UML). A **BPMN** diagram comprises four basic element categories: flow objects, connecting objects, swim lanes, and artifacts.

6.2 Methodology

Backward design, or backward planning, was performed to devise the overall system architecture. Based on the consolidated output requirements from use cases derived from Section 2 and the proposed **KPIs** from T1.3, a preliminary mock-up of the **Recommendation Dashboard** for production planning was constructed and presented to the construction partners in the project. According to the information requirements of the dashboard, a list of system functionality requirements is consolidated, and the system components (**BPMN flow objects**) for simulation, prediction, and evaluation of **APs** are proposed. Finally, these system components are linked by connecting objects and data artifacts in the BPMN according to the information flows identified.

6.3 System Functionality

The resulting BPMN diagram of the overall system architecture is presented in **Erreur ! Source du renvoi introuvable.**. It comprises three swim lanes representing the three elements in the simulation process: the user, the simulation software, and the DBTP.

6.3.1 User

The **Start** event is defined as the instance when the user has entered into the user interface of the simulation software. It is the beginning of a **simulation cycle**. At this moment, the user has already reviewed the current site conditions as provided by the Situational Awareness Dashboard in the core DBT platform and made an informed decision to explore **APs** using the simulation software. The **User Inputs** module contains a user interface through which the user can define the inputs of **targets**, **constraints**, and **simulation parameters**. These user inputs are then compiled into a data file called **User Targets and Constraints**, which is transferred into the simulation software. The user is led to the **Recommendation Dashboard** once the simulation process is complete. This dashboard allows the user to interactively select an **AP** out of all **APs** generated based on the user input and compare it against the **BP** on various aspects of production planning such as **KPIs**, schedules, resource utilization, and safety. If a desirable **AP** is identified, the user can accept this proposed **AP** as the new **BP**.

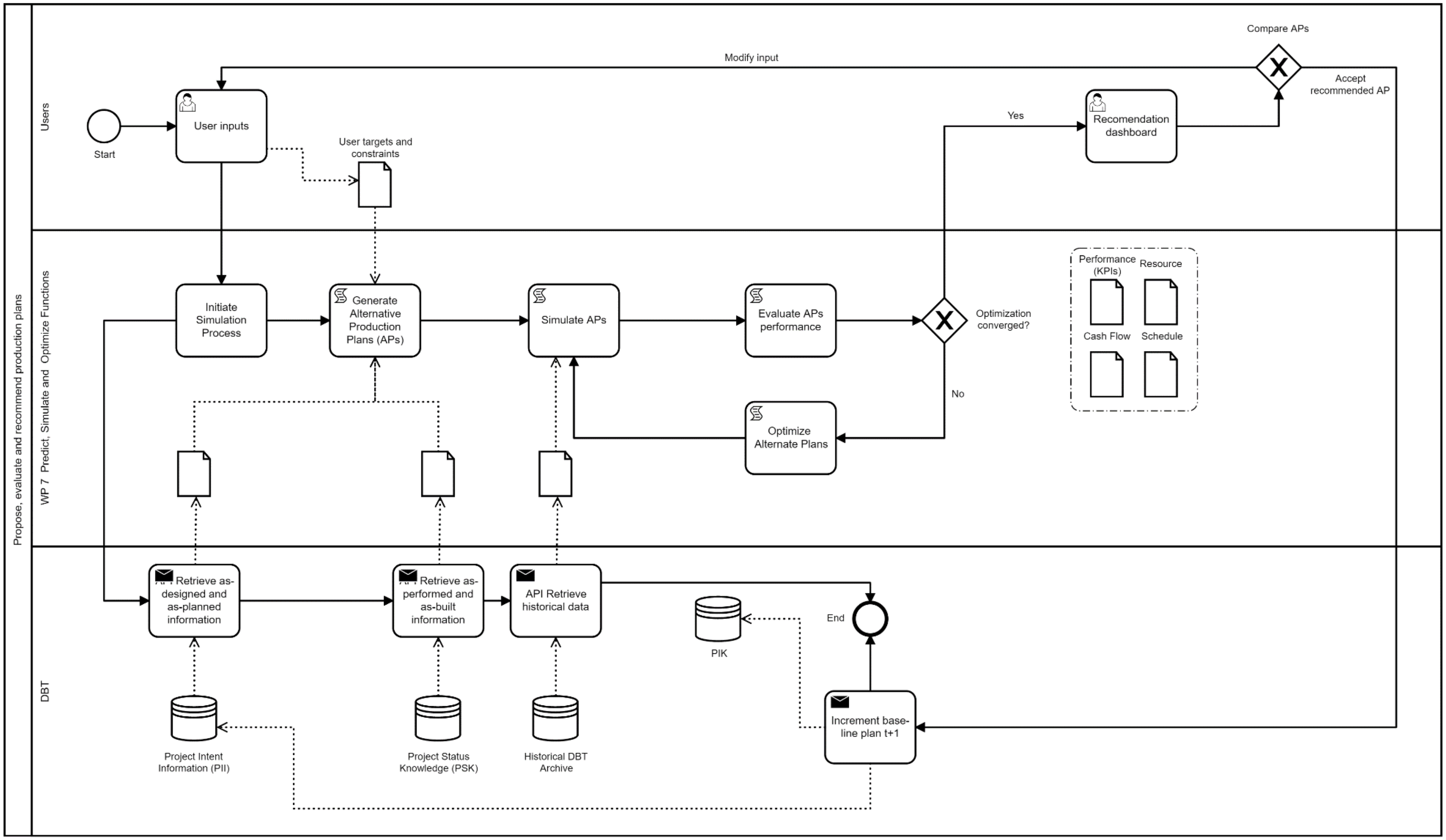

Figure 2. Overall system architecture

6.3.2 DBTP

According to the simulation software's information requirement for performing the simulation process, information is retrieved from the DBTP through the **Application Programming Interfaces (APIs)**. The as-performed and as-built information will be retrieved from the **Project Status Knowledge** database. The as-planned and as-designed information will be retrieved from the **Project Intent Information**. Historical data for deriving simulation parameters will also be extracted from the **Historical DBT Archive** database through the **APIs**.

When the user has selected a desirable **AP**, the **Increment Baseline Plan t+1** converts the **AP** output into a DBT database compatible format and updates it as the new **BP** before arriving at the **End** event, signifying the end of the **simulation cycle**.

The **Process Intent Knowledge (PIK)** module stores the entire **simulation cycle**, from **User Input** to **Increment Baseline Plan** at ***t+1***, allowing the user to review the decision-making process and to revert any changes as needed.

6.3.3 WP7 predict, simulate and optimize functions

Once all the information required has been received, the **Generate Alternative Production Plans** module enumerates a batch of **APs** derived from combinations of feasible actions according to the degrees of freedom defined by the user **constraints**. This batch of **APs** is inserted into the agent-based simulation engine contained in the **Simulate APs** module, which also utilizes the current project status to generate simulation parameters. The raw simulation data generated from the simulations is transferred into the **Evaluate APs** module. It is interpreted, evaluated by KPIs and utility functions, and compared against the user targets. If the **AP** batch is deemed undesirable by the evaluation, it is fed into the **Optimize AP** module. This module optimizes the **AP** batch using a **Genetic Algorithm**. If the AP batch is deemed desirable, the simulated **APs** are sent to the **Recommendation Dashboard** and presented in the forms such as **KPIs**, **Resource Histograms**, **Cash Flows**, and **Schedule**.

7 USER INPUTS & GENERATION OF ALTERNATIVE PLANS

We envision three possible cases for the flow from User Inputs to Generate APs:

- A user imports custom APs into the DBT core platform
- A user manually formulates specific APs from the BP
- APs are automatically generated based on the BP and the degrees of freedom defined by the user

The process and information flow of the above cases are detailed in the following sections.

7.1 User-defined APs

The **Start** event is defined as the instance when the user selects the functionality of importing custom APs in the DBT core platform's user interface (see Figure 3). The user then goes through the procedures to **Import User-Defined APs**. This results in one or more **User-Defined APs** stored temporarily in the DBT database. A module will **Check the Conformance** of the APs against the structure and information requirements for a DBT AP. This check may also entail evaluating the APs' feasibility based on previously defined degrees of freedom. If conformance is achieved, the user is led to the simulation software's user interface to **Confirm the APs** before the AP generation process begins. Meanwhile, the user-defined APs are appended to the PIK before being transmitted to the simulation software along with the BP. Once confirmed, the software takes the BP and APs and makes them simulation-ready in the **Compile APs** module. Finally, the information is sent back to the DBT core platform and appended to the **PIK**.

7.2 Modifying the BP Manually

The user begins this scenario in the DBT core platform's user interface, where the user reviews the project status and assesses whether an evaluation of APs is needed based on the situational awareness provided by the dashboard (see Figure 4). If the evaluation is indeed needed, the user is directed to the simulation software's user input interface, where the user **defines** the AP Configurations of interest. AP configurations are incremental changes to the BP, and a specific set of AP configurations applied to the BP constitutes an AP. These sets of AP configurations are interpreted in the **Compile APs** module to generate the BP and APs batch. Finally, this batch is appended to the PIK in the core DBT platform.

7.3 Modifying the BP Automatically

This case begins with the user assessing the project status as in the previous section. Once the user reaches the simulation software's interface, however, they are asked to define their **Targets** and **Degree of Freedom** instead of defining specific AP configurations (see Figure 5). The definitions of targets and degree of freedom are discussed in detail in Section 8. The defined degrees of freedom are then used to **Generate AP Configurations**. Since the time and computing resource needed to generate and simulate all combinatorial possibilities of AP configurations for a construction project is impractical for the scope of this work, this generation process is expected to be selective, either through random selection or other more intelligent means such as rules, algorithms, or artificial intelligence. The AP configurations are compiled and transferred back to the **PIK** as in the previous section.

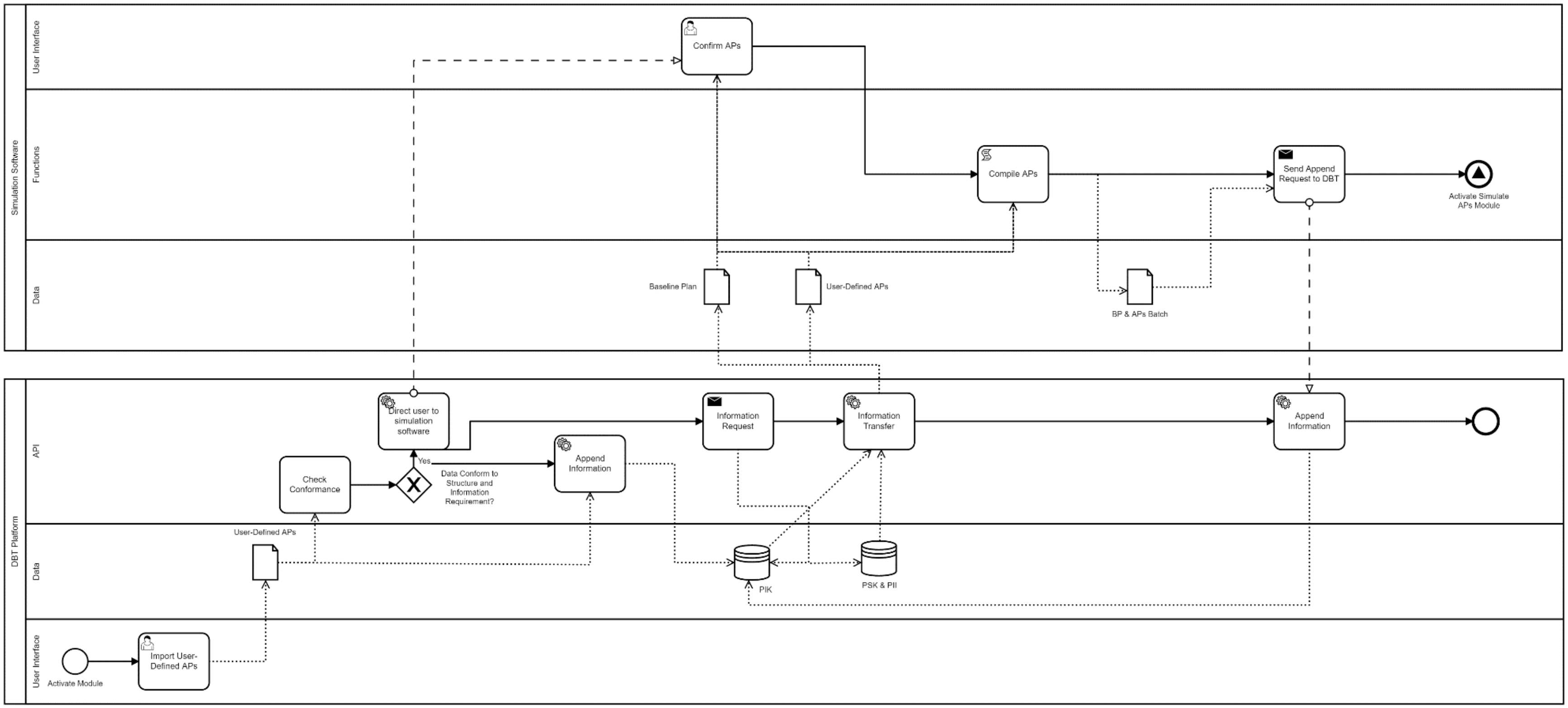

Figure 3. User-defined APs.

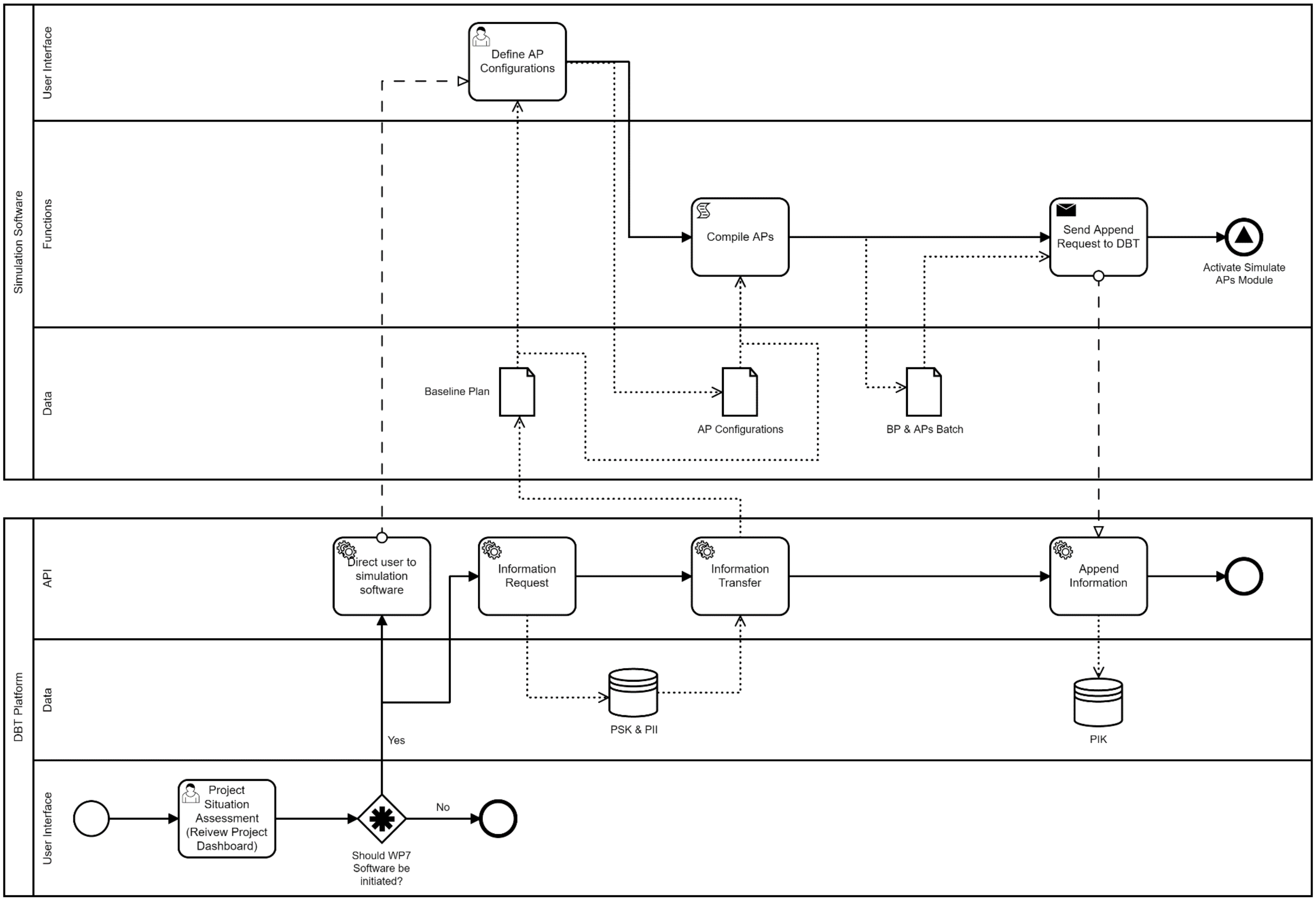

Figure 4. BP manually modified

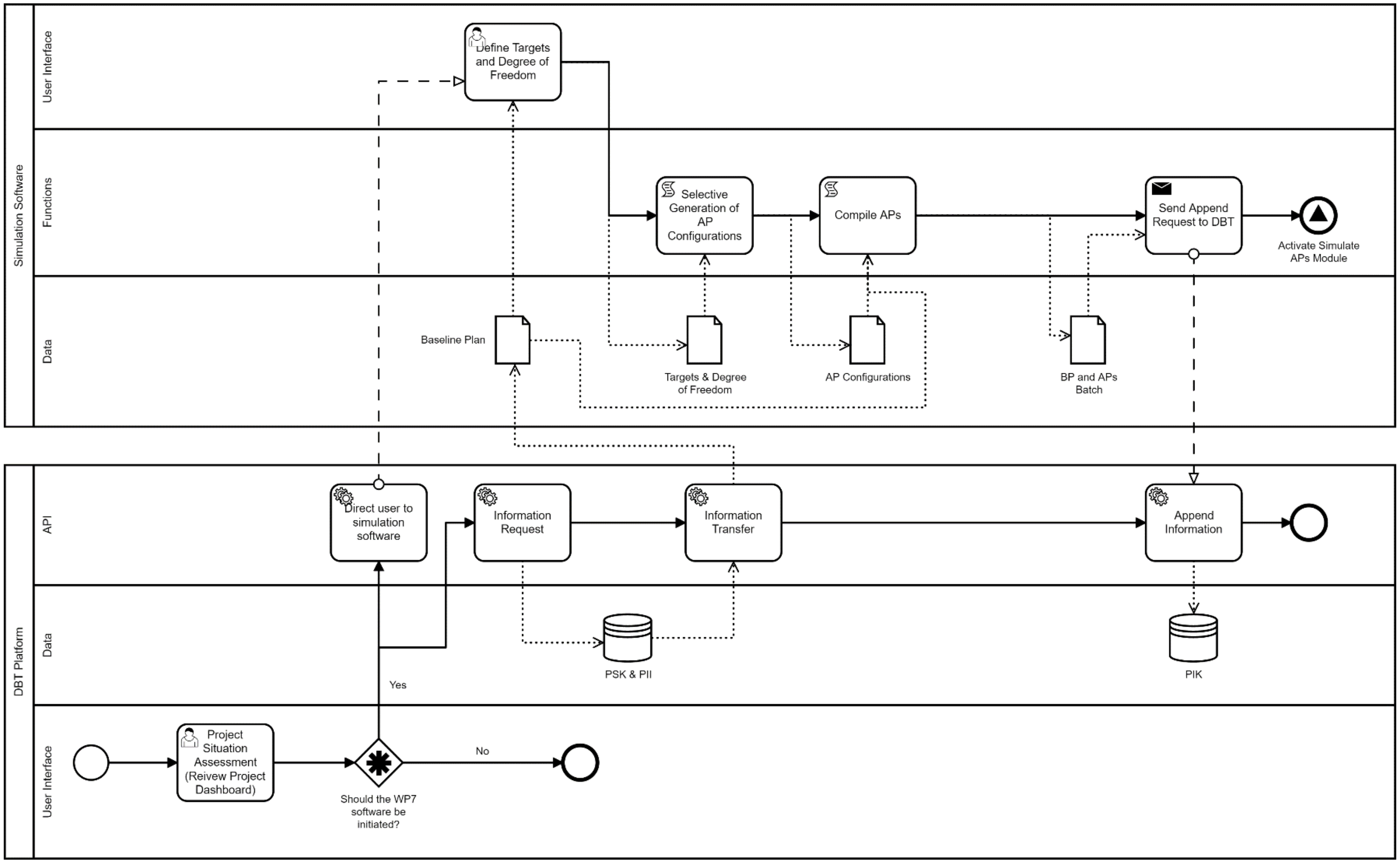

Figure 5. BP automatically modified

7.4 Simulate APs

The **Simulate APs** component of the simulation software executes automatically without the need for user interaction. When an AP is queued to be simulated, the software requests information from the **PSK** and the **PIK** (see Figure 6). The project status knowledge, including KPIs and productivity data, is used to compute the simulation parameters, which adjust the simulation environment to capture the physical world realistically. Meanwhile, the AP obtained from the PIK is interpreted and translated into **Simulation Components**, which are the agents and behaviors needed for the simulation. The simulation parameters and components are fed into the **Simulate AP** module, which contains the agent-based simulation engine. Finally, the simulation output data **of the AP** is appended back to the **PIK**.

a

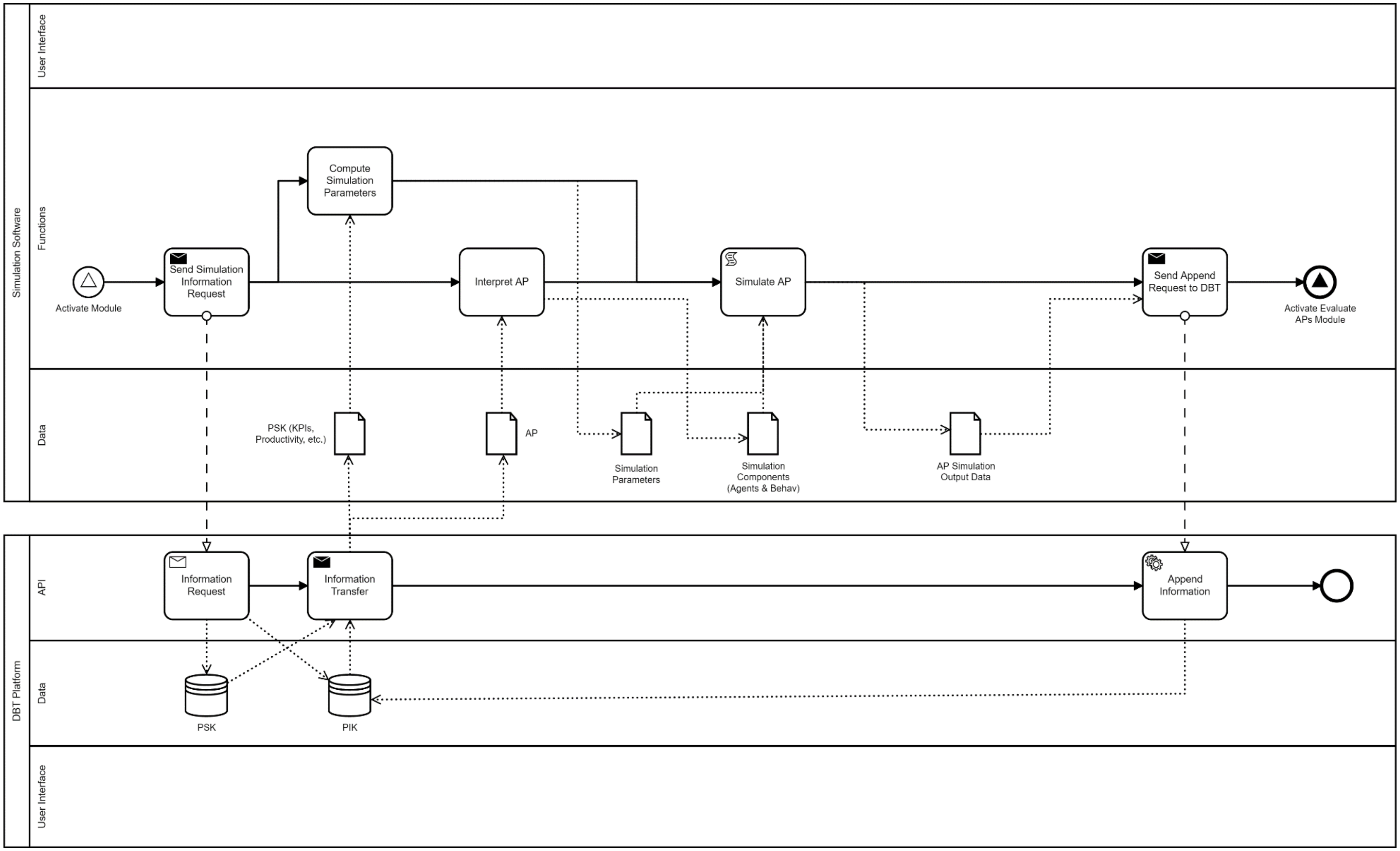

Figure 6. APs simulation

7.5 Evaluate APs

Just like the Simulate APs component, the **Evaluate APs** component is an automatic process acting on a single AP unit. The software takes **AP Simulation Output Data** from the **PIK** to **Generate Decision Aids** and calculate **KPIs and Utility Functions**. Decision aids are elements to be displayed in the **Recommendation Dashboard** to facilitate the decision-making process, such as schedule, resource utilization diagram, and cash flow. Utility functions are constructed according to the targets given by the user during the **User Input and Generate APs** process.

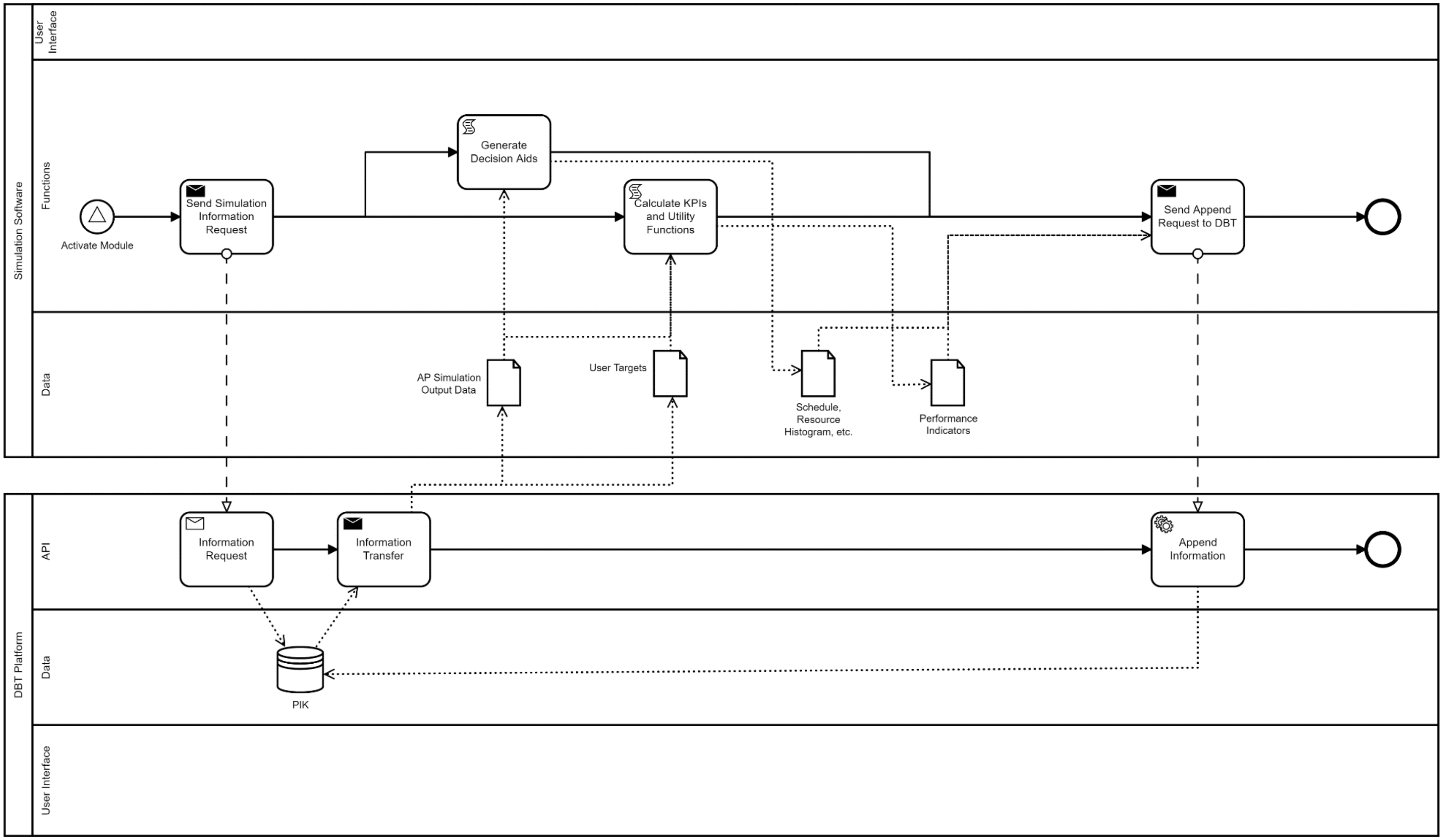

Figure 7. APs evaluation

8 USER INPUT AND OUTPUT REQUIREMENTS

8.1 Objectives

This section aims to provide an overview of inputs and outputs requirements for the simulation and prediction software. Input requirements refer to the information retrieved from the DBTP, user targets and constraints, and simulation parameters. On the other hand, the output requirements refer to the information that will be displayed in the recommendation dashboard, including KPIs and decision-making aids. Input requirements

8.1.1 Targets

As defined in section 4, users can define targets and constraints prior to beginning the simulation and prediction process. Targets are user objectives to evaluate the AP performances. For the simulation and prediction purposes, targets include (1) milestone completion dates, (2) environmental regulations, (3) safety thresholds, and (4) desired project cost and duration. *Milestones:* milestones refer to all the activities and interim steps needed to implement the project. Milestones are usually defined during the planning stage and then documented in the project schedule. Milestones are essential for evaluating construction progress performance and generating project implementation reports [12]. To support the simulation and prediction process, users will define projected milestones to assess the possible outcomes derived from any changes in the construction plan. For instance, users will be able to change milestones-related information, including completion dates, and simulate its impact on the project duration and cost.

- *Environmental regulations: c*onstruction activities are capable of producing a high impact on the environment. Every construction project results in gas emissions of carbon dioxide, methane, and other waste products that pollute the air and contribute to global warming [13]. As a consequence, several environmental regulations have emerged to reduce the impact caused by construction activities. To manage these regulations and simulate their effects, users will define how these regulations could affect or delay the construction project status in terms of duration or cost. More specifically, users will establish which activities can be performed or delayed depending on applicable environmental regulations
- *Site safety threshold:* Construction site safety is an aspect of construction-related activities that protect workers and others from death, injury, illness, or other health-related risks. To reduce the safety risk impact in the construction project performance, users will define the minimum and maximum site safety threshold levels, which reduces the probability of risk.
- *Target cost and duration*: project cost and duration are the most critical targets for production planners. Indeed, construction activities’ performance is commonly assessed following these two factors. To control the project cost and duration, users will be able to introduce aspects such as cost and duration (e.g., per phase, activity, and task) as targets for the simulation and prediction process. For instance, Users will introduce the cost of completing the project by phase, activity, or task and then obtain simulated plans according to these targets.

8.1.2 Constraints/Degree of Freedom

Constraints refer to the scope of changes or actions that users have with respect to as-planned information. In other words, constraints represent the production planners' degree of freedom when faced with changing the production system. For this particular case, constraints can be cataloged into four types: (1) location, (2) resources, (3) schedule, and (4) design constraints.

- *Location breakdown:* Construction management practices aim to control cost and time based on a hierarchical work breakdown structure (WBS). The work to be done on a project is defined in work packages. However, for construction projects, the current use of WBS creates a significant amount of data redundancy because all of the work is location-specific [14]. To mitigate this redundancy, location is a more appropriate unit of analysis and a feasible conceptual framework for construction projects. As part of the multiple constraints that users can define to initialize the simulations, the construction location breakdown must be well-defined. This means that users must be able to introduce information related to the work area and how it is divided and structured to assign specific tasks to the crews.

Resources in construction are defined as people, equipment, facilities, funding, or anything else (usually other than labor) required to complete a project activity. For the simulation and prediction process, construction resources were classified into three different types: (1) construction equipment, (2) workers crews, and (3) construction materials.

- *Construction Equipment:* construction equipment refers to heavy-duty vehicles, material handling equipment, and other equipment specially designed for executing construction tasks. Indeed, the proper management of this resource might increase project efficiency and reduce waste [15]. However, the high cost of renting or acquiring this resource and its underutilization make it challenging to optimize its operation. Therefore, as part of the inputs for simulation and prediction, users will modify or define the number of hours and days of equipment operation and the maintenance schedule to reach the minimum cost and cycle time.
- *Crews:* Construction workers are an essential resource in the construction industry. Nevertheless, this resource is characterized by its variability and uncertainty during the construction stage. To minimize the variability and uncertainty in the simulation and prediction process, users will limit the number of workers for each crew, restrict their possible locations, productivity rates, the maximum number of crews per floor, and crews' schedules. Besides, users may define some crews' behavior that makes different decisions based on their interests and motivations.
- *Materials:* Construction materials represent another essential resource that directly influences the cost and duration of the project. More specifically, a delay in delivering materials or the wrong quantity can significantly affect the construction flow. To simulate and predict the impact of those scenarios on the project schedule and cost, users will limit the range of arrival dates and the batch sizes of construction materials for each crew, activity, or task.
- *Schedule:* A construction schedule lists all the project's terminal elements with their expected start and end dates. To guarantee proper construction project control, the schedule outlines each step that should be completed by a specific date before the next step can be performed. Nevertheless, changes in activities sequences and duration highly impact the project performance. To reduce the uncertainty of those changes, users will constrain activities' sequences, duration, and constraints that might influence the project outcomes.

8.1.3 Simulation elements

Simulation parameters are performance indicators that users can customize to better conform the simulation to the reality on the construction site. However, using the simulation parameters, especially performance factors, will depend on the user's capability to access the required data.

8.1.3.1 Performance Factors

- *Labor productivity:* labor productivity has been defined as the ratio between the units of work accomplished (i.e., outputs quantity) and the hours of work (i.e., inputs for labors) [16]. This index aims to measure the effectiveness with which labor is used in the construction process. Furthermore, as part of the performance factors for the simulation and prediction, Labor productivity will allow determining the project cost and duration, considering aspects such as variability and flow.
- *Percent Plan Complete (PPC)***:** PPC is a primary measure of construction planning reliability. It measures the percentage of assignments that are 100% completed when compared to what was planned [7]. It is calculated as the number of promises/activities completed on the day stated divided by the number of promises/activities made/planned for the week. As part of simulation and prediction factors, PPC will be computed for alternative plans to calculate the reliability of the construction planning.
- *Rework/Defect probability:* Rework/defect probability is the possibility that unnecessary effort will be required to redo a process or activity that was implemented the first time incorrectly. It often occurs due to incorrect construction methods, poor quality materials, and incorrect work practices. As part of the simulation elements, these rates will be given for each activity and task to determine their probability of completion.
- *Equipment maintenance rate:* The equipment maintenance rate is a factor that determines how often construction equipment requires maintenance. This specific rate is associated with the time operated or distance covered by the construction equipment. This specific rate will be given before beginning the simulation and the generation of the alternative plan.
- *Weather influence rate:* Weather conditions can highly affect the performance of the construction project. Indeed, adverse weather conditions such as heavy rain or dry weather can impact construction equipment's performance. To consider this factor, the simulation and prediction software will be able to capture information regarding forecast weather conditions and their effects on the project schedule.

8.1.3.2 Information

- *Schedule:* The simulation and prediction software will require information pertaining to the project schedule. More specifically, the software will retrieve data related to construction activities, their start dates and end dates, milestones, costs, resources, and dependencies associated with each activity.

- *Building information model (BIM):* BIM represents one of the main information sources for the simulation and prediction software. BIM contains data related to the project schedule, constructive methods, elements properties, objects geometry, cost, and material-based information.
- *Cost data:* This refers to the cost of all construction phases, activities and tasks that will be performed during the construction stage. This information would be captured either from the BIM or the project schedule

8.2 Output requirements

Once all APs have been simulated and evaluated, an alternative plan must be chosen for the next production cycle. Ultimately, this is the responsibility of the project managers and their production control staff. However, in the Digital Twin Construction (DTC) paradigm, they are supported by the DTBP, and their selection is informed by the outputs of the simulation, evaluation and optimization modules contemplated here in WP 7.

This sub-section lists the requirements for user outputs and outlines two methods for decision-making – one using a weighted utility function, which is also used for automated optimization, and a second using the 'Choosing by Advantages' (CBA) method.

8.2.1 KPIs

KPIs are quantifiable measures of performance over time for a specific construction project objective. KPIs provide goals for construction stakeholders and insights to assist them in the decision-making process. By using simulation and prediction software, users will receive a set of KPIs aimed at improving the situational awareness of construction planning, leading to better decisions. These KPIs are described below:

- *Throughput (TH):* TH in construction refers to the number of products created within a specified period. In other words, TH represents the average production rate (the number of finished products per given time interval) [17]. To improve the production process and increase the situational awareness of production planners, the simulation and prediction software will display the TH for each construction activity and task.
- *Cycle time (CT):* CT is the average time for a single product to go through the entire production system, including processing, setup, and waiting times [18]. CT will be generated for each project phase, activity, and task as an outcome of the simulation and prediction process. Also, each CT computed by the simulation process would be compared to ones previously defined in the PII.
- *Work in progress (WIP):* WIP embodies the number of unfinished units in a specific moment in time [19]. To enhance the flow in construction and reduce waste, it is vital to diminish the WIP levels for each trade. For this purpose, the WIP of each alternative plan will be calculated by activity and task and then compared to its optimal value.
- *CT and TH variability rates*: CT and TH variations are metrics for continuous improvement to drive down the deviations in the time and production rate needed to produce successive units in the construction project. To address this factor, CT and TH variations will be calculated for each crew, as well as for activities and tasks.

- *Workforce capacity & utilization rate:* Workforce capacity is an index intended to measure workforce time used per production unit. The main objective is to establish the threshold values of workforce capacity to determine if the actual capacity level is reasonable. To have a clear overview of these values, the recommendation dashboard will display both workforce capacity and utilization rate.
- *Equipment utilization rate:* Equipment utilization rate refers to the index used to measure the equipment utilization time per production unit. To have a clear situational awareness of this factor, users will have the possibility to determine the utilization rate of equipment based on the simulation results. Moreover, users will compare the planned equipment utilization rate against the simulated utilization rate for each alternative plan generated.
- *Construction flow index (CFI):* CFI is a combined measure that reflects the quality of production flow in repetitive construction projects. It incorporates measures of work continuity for crews, processing continuity for locations, production rate variation, amounts of work in progress, interference, and operation sequence logic. As an approach for assessing production planning, The resulting CFI will be displayed for each alternative plan to decrease waste and increase productivity in the construction project [17].
- *Expected project/milestones completion date:* Milestones completion date refers to the date on which a particular milestone is targeted for achievement or completion. For each alternative plan generated by the simulation process, users will be capable of determining the completion date of each milestone previously defined by the user.
- *Safety design index (SDI):* SDI is a measure used to calculate the probability of risk associated with each AP. More specifically, once users define new objectives and constraints, a new AP-derived SDI is calculated, according to the resource modification, construction methods, and project schedule.

8.2.2 Decision-making aids

Decision-making aids are tools commonly applied in construction management, intended to control the project cost and duration. The recommendation dashboard will display tools including the project schedule, cash flow forecast, resource utilization chart, and simulation results. The Decision-making aids proposed are described below:

a) Project schedule:

- *Master plan:* defines the construction tasks that "should" be done. The master plan incorporates the planning of each project activity by establishing relationships in time and space between different activities scheduled, setting milestones required for compliance with the established deadlines, and defining the scope and terms of partial deliveries if there were [20]
- *Phase plan:* represents the second planning level and becomes necessary when projects are long and complex. The master plan can be divided into phases, with activities that are explored as task sets that cover the entire duration of the activity. Each set of tasks work group should be carried out in spatial and temporal proximity [7].
- *Look ahead plan:* Intermediate plan, commonly referred to as "lookahead" in the literature, delves into planning activities in an intermediate period. This intermediate plan could be defined according to the needs of each particular case and can vary from 4-5 weeks to 15-16 weeks [20]. In this way, the intermediate plan defines what "can" be done in the

stipulated period. To accomplish this goal, this plan needs to identify and incorporate the supplies necessary to develop the activities and those responsible for them.

- *Weekly plan:* defines what "will be done" during the coming week based on the objectives achieved in the completed weekly plan, those foreseen in the intermediate planning, and current restrictions [21]. Construction activities proposed to be carried out have been part of the executable work inventory defined in the previous stage.

b) **Cash Flow**: In general terms, 'cash flow' is the movement of income into and expenditure out of a construction project over time. More specifically, cash flow refers to an analysis of when costs will be incurred and how much they will amount to during the project life.

c) **Resource Utilization Chart**: this chart gives production planners an overview of how balanced the resources' working hours and free hours are. Resources include equipment and trade crews. The level of detail for human resources is an individual crew, not an individual worker. The level of detail for equipment includes equipment used by crews, though it does not extend to hand tools. Ultimately, resource utilization charts enable production planners to measure efficiency and determine the amount of waste each resource has with respect to its full available hours.

d) **Simulation Results**: Simulation results indicate a list of outcomes that will be obtained from a set of simulation runs. These results can be categorized as variability/risk and probabilities factors. Variability/risk is the extent to which APs in a statistical distribution or data set diverges from the average value. On the other hand, probability factors explicitly represent APs' uncertainty by stipulating inputs as probability distributions and specifying any random events affecting the system. If the inputs describing a system are uncertain, the prediction of the APs is necessarily uncertain

8.2.3 Utility Function

A weighted utility function will be formulated to enable comparative evaluation of the different alternative plans (APs). The primary purpose of this function is to present the relative value of each AP so that production planners can select the one that most closely matches their interests. Utility function will consider net income, income for work performed, cost per unit, cost of materials consumed, cost of excess material, resource costs, and fixed overheads. Users will be able to set the different weights for each component parameter, and for each alternative plan generated, users will be able to visualize their utility function results.

Another essential purpose of the utility function will be to serve as the core evaluation tool for the optimization module.

8.2.4 Multicriteria Decision Making

The decision-making process in the construction industry is characterized as group decision-making in which many project stakeholders are involved (owner, architect, structural, mechanical, project manager, electrical, supervisor, etc.) and regulatory agencies [22]. Authors such as Rodriguez-Nikl and Brown [23] stated that decision-making methods could influence decision outcomes. Moreover, decision-making methods influence people's decisions, decisions trigger actions, and actions cause results [24].

Intending to offer production planners a tool that enhances their decision-making process and minimizes uncertainty, we propose implementing a tool that applies the Choosing by Advantages (CBA) approach. CBA is a multicriteria method that guides users to collect, prioritize and compare facts before choosing. The CBA recognizes that all multi-criteria decisions are subjective and are designed to guide participants in basing subjectivity on factually discovered and documented facts. According to Arroyo [25], the steps to implement CBA for construction projects decision-making are the followings:

1. Identify alternatives
2. Define factors that aid to differentiate the alternatives
3. Define the evaluation criteria
4. Compute or extract the attributes of each criterion
5. Decide the importance of each advantage
6. Evaluate with cost data

WP7 through task 7.1 will create an interface that will interactively guide the user in applying the CBA method for a multi-objective comparison between several alternative plans. A **CBA Interface** will be designed as a complementary solution to the **Recommendation Dashboard** for evaluating and selecting APs. The CBA interface comprises a set of windows in which the end-user follows the steps mentioned above, ranging from the definition of factors, assignment of the importance, calculation of attribute values, the definition of advantages, and cost calculation. Most of the factors used to compare alternatives will be retrieved from the DBTP (e.g., Lead time, waste percentage, breaks in continuity, among others), and end-users will introduce others based on their criteria.

9 SYSTEM INPUT AND OUTPUT REQUIREMENTS

The input and output requirements for the envisioned simulation and prediction software are derived from the BPMN diagrams presented in Sections 4 to 7. This section details the format and content of the data received and delivered to and by each software component.

9.1 User Input Interface

As described in Section 5, there are three possibilities of how the user interacts with, or inputs to, the User Input Interface. Each possibility accompanies a different set of inputs and outputs.

The first possibility is when the user desires to evaluate custom APs significantly different from the BP stored in the DBT. In this case, the User Input Interface component receives these user-defined APs from the DBT core platform's side and a confirmation message from the user's side. This message then triggers the interface to push the APs to the Generate APs component for further processing. Therefore, the output of this scenario is the set of individual APs.

The second and third possibilities are when the user desires to evaluate APs incrementally adapted from the current BP stored in the DBTP. These adaptations may be derived manually or automatically. In the manual case, the user inputs the sets of AP configurations in numerical or boolean (toggle) form through interactive guidance on the interface. Alternatively, in the automatic case, the user instead defines the degree of freedom for modification. In other words, they define a feasible range of values for each parameter of interest. For example, a user might define the minimum and maximum size of a work crew for a given trade, or the maximum and minimum number of such crews that can be employed on site at any one time. In either case, once the user commits their input, the interface translates the input into tabular lists of AP configurations and delivers the list to the Generate APs component.

It is essential to recognize that that the BP stored in the DBTP must be updated before it can be used as the basis for any new APs (as contemplated above and in Sections 7.2 and 7.3). In general, a new BP is stored and operationalized at the end of each planning cycle. Simulation and selection of an AP, which will replace the current BP for the next planning cycle, takes place at a point in time close to the start of the consecutive planning cycle. Thus work has been performed between the time at which the BP was adopted and the current time, and this is almost a full planning cycle. The BP must therefore be updated to reflect any work packages, activities and/or tasks that have been performed, partially or fully, in that time. We assume that the project status model is updated at greater resolution, e.g. daily, so that all product objects (as-built model objects from the PSI) and process model objects (as-performed objects from the PSI) are up to date, and can be used to inform the updating of the BP in the prediction system.

Figure *8* illustrates the timeline, showing the gap between finalizing the previous cycle's BP and the time at which the prediction module is used for the following planning cycle.

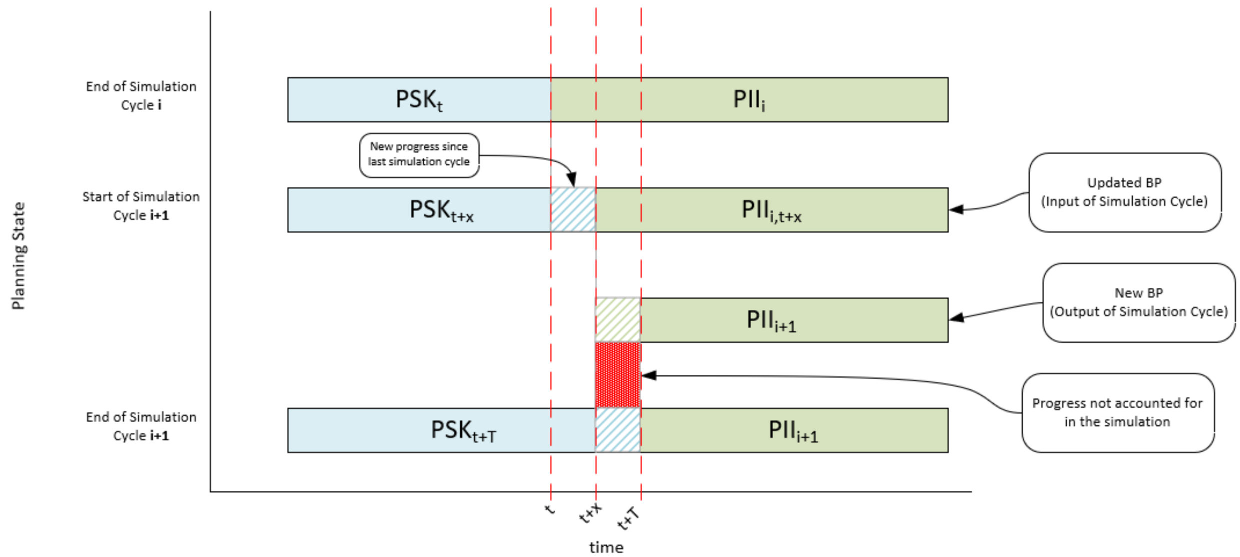

Figure 8. Update of the BP for use by the Prediction modules to be built in WP7.

9.2 Generate APs

The Generate APs component receives either a batch of APs or a list of AP configurations depending on the output of the User Input Interface. It also calls in the baseline plan (BP) from the DBTP After processing, the component delivers a batch of simulation-ready BP and APs. These BP and APs are indistinguishable in terms of data structure as they all conform to the schema requirement of the DBTP. The software also labels each plan in the batch with a unique identifier representing the simulation cycle and iteration before delivering them to the PIK database within the DBTP.

9.3 Simulate APs

Once the Simulate APs component receives an activation signal, it requests two items from the DBTP: a simulation-ready plan (BP or AP) from the PIK and the project status from the PSK. The project status comprises of 1) the performance factors (Section 8.1.3.1), which are transformed into simulation parameters and used to adjust the simulation environment according to the reality captured by the DBTP, and 2) the work progress for updating the BP as discussed in Section 7.1 The simulation engine performs multiple simulations for the input plan, and for each simulation run, it returns output data in tabular time-series form. The software batches and delivers these outputs to the PIK database within the DBT, where the output batch is linked back to the relevant plan.

9.4 Evaluate APs

Once activated, the Evaluate APs component requests a simulated construction plan, its simulation output data, and the user targets (Section 8.2.1) collected from the User Input Interface component. The software synthesizes these items to produce decision aids (Section 8.3.3) and to quantify KPIs (Section 8.3.1) and objective scores (Section 8.3.2). The produced items are delivered to the DBTP with links to the relevant plan.

9.5 Recommendation Dashboard

The Recommendation Dashboard receives all plans in a simulation cycle accompanied by their decision aids and evaluation. With this information, the user can make an informed decision on the production plan to be applied in the next production cycle. The user can make three possible decisions, and the Recommendation Dashboard outputs a different directive for each decision.

1. The first possible decision is to update the BP with one of the APs. Since all the APs are stored centrally in the DBT database, the dashboard component only needs to deliver a message to the DBT core platform to replace the BP with the selected AP while specifying the AP using its unique identifier. In this case, the previous BP is archived and the AP selected is now labeled as the current BP,
2. The second decision is to go back to the User Input Interface and restart the simulation cycle by feeding the software new inputs. In this case, the Recommendation Dashboard sends a message to the software to direct the user back to the User Input Interface.
3. Lastly, the user can choose to exit the software without further action. The dashboard then sends two messages. One is sent to the software to direct the user back to the user interface in the DBT core platform, and the other is sent to the DBT core platform to end the simulation cycle.

10 DBT FUNCTIONALITY AND DATA SCHEMA REQUIREMENTS

10.1 Information requirements

The quality of simulation-based prediction is strongly dependent on the availability of up-to-date, accurate, and precise information on the project status and intent. This section specifies the information required from the PSK, the PII, and the PIK for accurate simulation of the future project status.

10.1.1 From PSK

Firstly, performances factors are expected to be readily available in the PSK, either stored or computed in real-time. These factors are namely production rates, utilization rates, and reliability. For each work crew and each piece of operational equipment, these factors should be computed according to their historical performance record. Historical data should also be used to determine the reliability of material delivery for each supplier and the mechanical reliability of each piece of operational equipment. Finally, the uncertainty, or variability, associated with these factors can be encapsulated in an additional uncertainty indicator.

Second, the PSK should provide the complete status of as-performed work with associations to the as-planned activities in the BP from the PII. The completed activities should be indicated in the updated BP, while in-progress activities should be associated with the as-built element parts and the remaining as-planned tasks. Overall, the progress or status of work should be available in various degrees of resolution: by elements, by activities, and by work packages.

Lastly, current site information should be available either in the PSK or a separate digital twin site. Current site information refers to both the site organization plan and the logistics of resources. Site organization plan involves the designations of material storage areas (quantity and capacity), travel routes, and hazardous areas for crew and equipment. Ideally, such designations should be dynamic, meaning that they should be constantly updated in response to the actual processes performed on-site. For example, a travel route can become temporarily blocked due to an ongoing hoisting activity above the route by the tower crane. Meanwhile, the logistics of resources (labor, material, and equipment) include their locations, travel routes, operation paths or destinations, availability, and utilization records.

10.1.2 From PII

The as-planned BIM model stored in the PII should present the as-designed building with sufficient resolution and accuracy. Specifically, the BIM model should, at the minimum, adhere to the Level of Development 400 (LOD 400) requirements as set out in the LOD Specification by the BIM Forum [26], which states,

"The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information."

In other words, the BIM model should contain the complete and final geometry of all building elements, prefabricated or crafted, and complete component details for prefabricated elements or components specifically.

In addition, the PII should contain the BP, which is the current as-designed construction plan consisting of the work breakdown schedule, the location breakdown structure, a planned construction and material delivery time schedule, availability constraints for labor and equipment, labor assignments, equipment utilization, product information requirements, cost data, and site safety information. Elements in the BP should be linked to the BIM model and may also be associated with predefined milestones and objectives defined by the DBT user.

10.1.3 From PIK

All simulation-related information generated by the simulation software should be contained in the PIK, where the knowledge of predicted performance is stored. This information consists of simulation-ready APs, computed simulation parameters, simulation raw output data, evaluation results, and decision aids described in Sections 5 through 7.

10.2 Data Schema Requirements

The data schema requirements for the DBTP concerning production planning through simulation and prediction are presented in the following UML class diagrams (***Figure 9***, ***Figure 10***, ***Figure 11***, ***Figure 12***, ***Figure 13***, ***Figure 14***). In collaboration with TUM for WP2, the data schema is developed by first adopting a preliminary version of the as-planned and as-performed process model as the backbone and then deriving additional classes, properties, and associations according to the information requirements outlined in Section 8.1. These diagrams presented are strictly for expressing the essential information and associations needed for data-driven production planning in the digital twin construction environment and should not be viewed as the final data schema represented in the DBTP – this is the domain of responsibility of WP2.

The as-planned process model (**Figure 9**) contains the construction plan's work breakdown structure (WBS) and its associated information. These data represent the as-planned processes in a construction project and belong to the PII. Going down the level of granularity, the WBS comprises Work Package, Activity, and Task, with each composed of instances of the latter. A Work Package is an executable construction deliverable that describes in detail a specific scope of work, and is usually restricted to the work of a single skilled crew in a single project location. Activities detail the construction method of the Work Package they compose – they are the operations, while the Tasks outline the specific deliverable objectives in an Activity. A Task applies the work of an operation to a specific building element, or to part of a building element.

For example, the Work Package of “exterior structural walls in zone B of floor 2” is composed of construction activities “first-side formwork,” “rebar fixing,” “close formwork”, “pour concrete” and “strip formwork.” Each activity applies to the full set of building elements included in the Work Package. Within the activity of “first-side formwork” are the construction tasks associated with the individual building elements: “first-side formwork for Column 1,” “formwork for Column 2,” etc.

A Work Package is typically associated with user-defined milestones such as handover dates. Work Packages should be associated with As-planned Zones, including As-planned Work Location, As-planned Hazardous Zone, and As-planned Travel Route. An As-planned Work Location defines where the associated work should be performed and is an essential component for Location-based Scheduling [27]. An As-planned Hazardous Zone is an area determined as unsafe, liable to safety hazards. Such a zone changes dynamically through time according to the construction activities in and around it. An As-planned Travel

Route can refer to the operation route of equipment, such as the crane radius, or the travel route of work crews and materials.

Constraints, or preconditions, play an essential role in construction projects' performance since they highly affect their cost and duration. To have efficient constraint management, implementation of constraint-based planning is critical to enhance planning reliability, reduce uncertainties in construction processes, and increase the transparency of project management. More specifically, construction tasks require all constraints to be fulfilled and eliminated before they are begun. According to lean construction principles, insufficient planning at the task level is often the single most important factor that affects project workflow breakdowns.

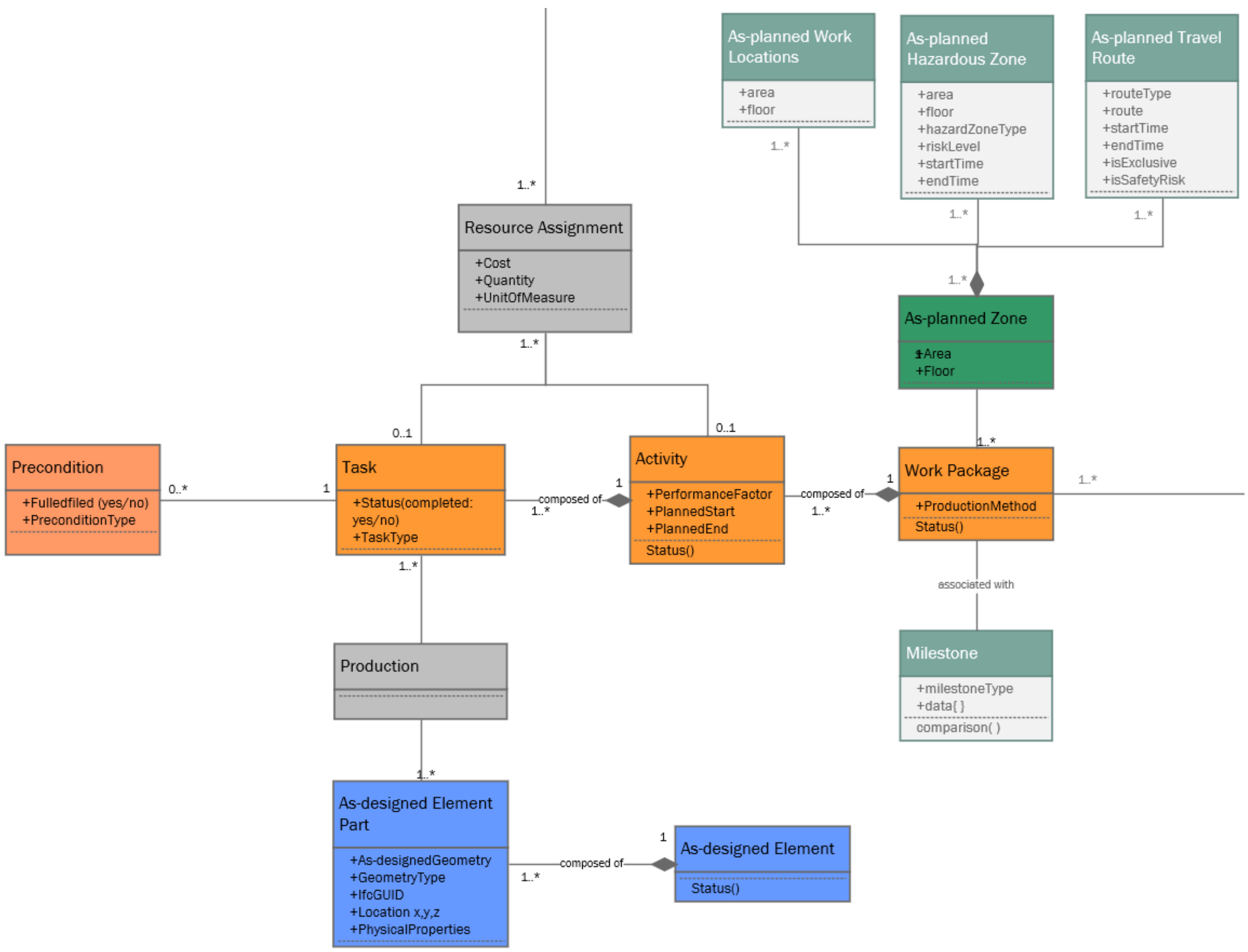

Figure 9. UML class diagram for as-planned process model

Figure *10* presents the data schema for as-planned resource assignment, which captures the intended resource allocation through time in a construction project. As-planned Resources are contextualized within the construction schedule through associations with Tasks and Activities (**Figure *9***) via the relational class Resource Assignment. These associations are inherited by the sub-classes of As-planned Work Crew, As-planned Equipment, and As-planned Material Batch, which represents the resource types of labor, equipment, and material, respectively. Additionally, As-planned Equipment is associated with an As-planned Equipment Maintenance Schedule, while a material batch is associated with a delivery schedule.

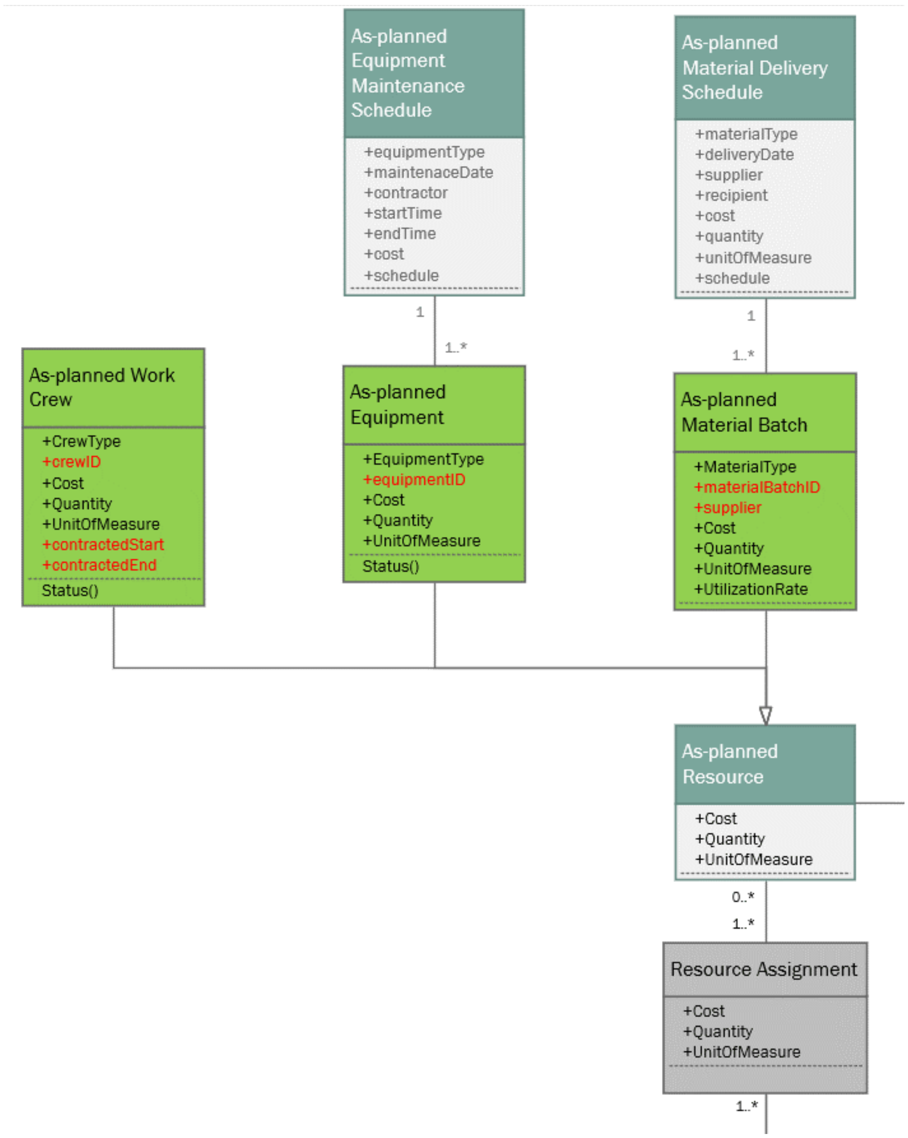

Figure 10. UML class diagram for as-planned resource assignment

As provided by the WP7 software, simulation input and output (**Figure *11***) contribute to the knowledge in the execution performance and thus constitute part of the PIK within the DBTP. A simulation-based planning cycle is represented through the Simulation Cycle class, composed of Simulation Parameters, Simulation Raw Output, Evaluation Result, and Decision Aids. Since these components are only of interest to the WP7 planning software, we envision that their data can be stored in the form of linked files.

Meanwhile, a Simulation Cycle is also associated with As-planned Construction Plans (BP or APs) composed of Work Packages and their subsequent associations. "Construction plan" is a term intentionally chosen to highlight the structural similarity between BP and AP. Apart from the domain they belong to – BP in PII and AP in PIK – BP and AP are indistinguishable in their data structure, and it is this characteristic that enables the seamless updating of the current BP with the selected AP in a planning cycle, as discussed in Section 4.3.2 and 7.5.

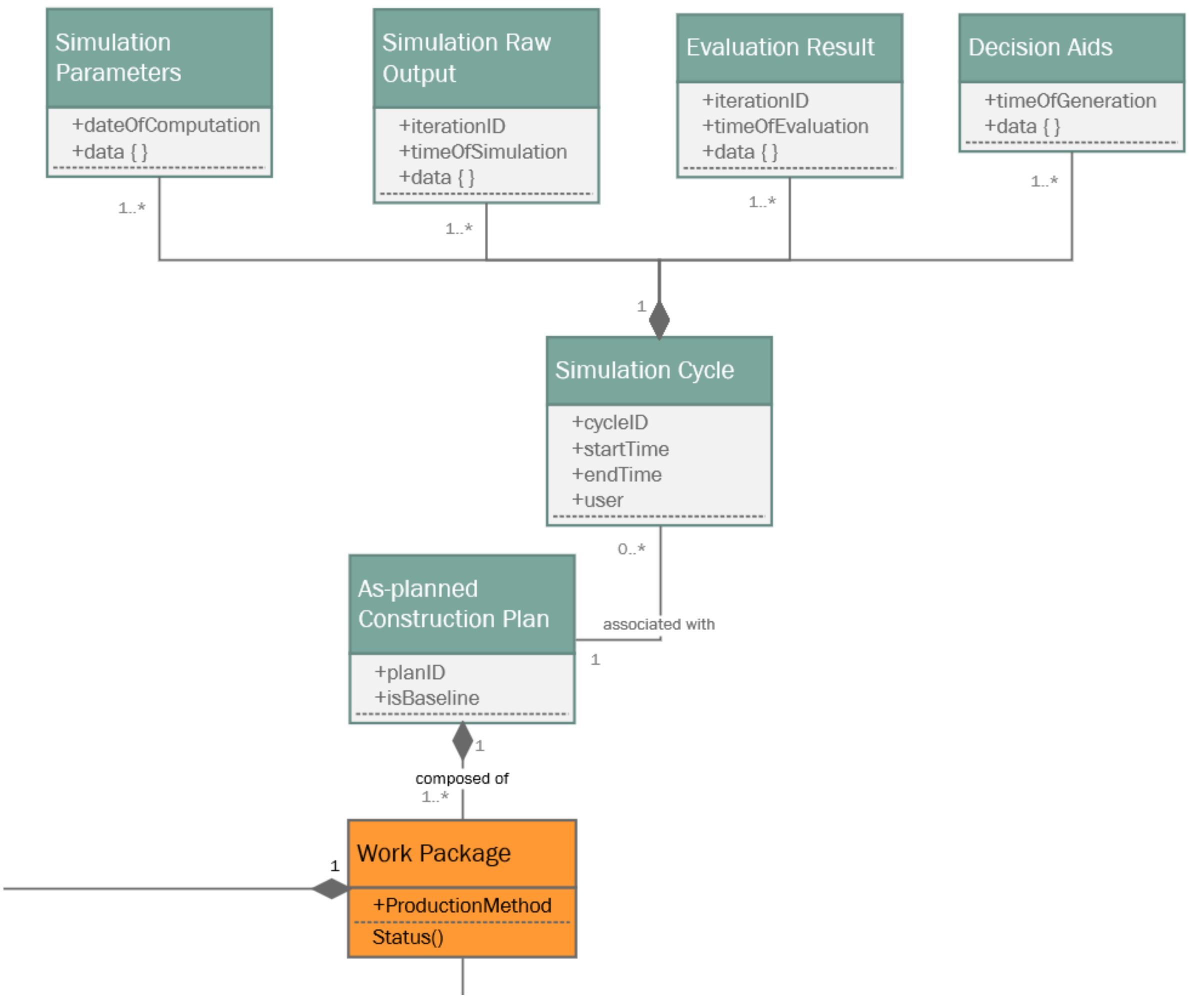

Figure 11. UML class diagram for simulation input and output

The as-performed process model (**Figure *12***) represents the as-performed processes captured from the construction site. This information belongs to the Project Status Information (PSI) and is encapsulated in the PSK. The proposed model parallels the as-planned process model (**Figure *9***) in its data structure, highlighting the intricate physical-virtual and status-intent relationships in DTC.

The core process components of the as-performed model are Construction, Operation, and Actions, with each of the former being a composition of the latter. Construction and Operation are essentially the same in nature as the Work Package and Activity respectively on the as-planned side. Where execution follows plan perfectly, their instances will be directly equivalent and have the same property values and relationships. However, in most cases, execution does not follow plan precisely, so that deviations from plan will arise. Small deviations may require m-n relationships between instances of Activities (as-planned) and instances of Operations (as-performed). More significant deviations will lead to m-n relationships between Work Package instances (as-planned) and Construction instances (as-performed). The Action class instances, however, are expected to correspond in form and association with the Task instances, although they may belong to non-corresponding Activity/Operation instances.

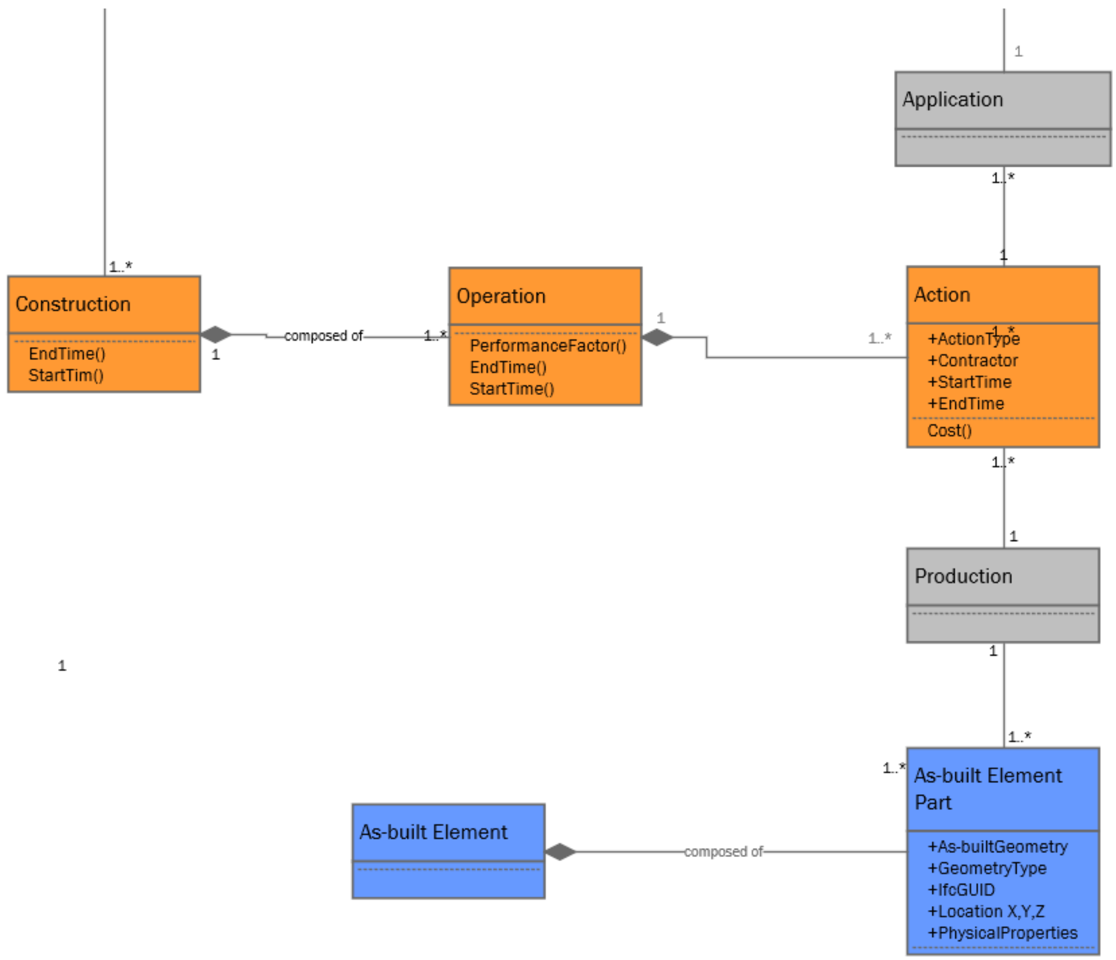

Figure 12. UML class diagram for as-performed process model

The As-performed Zones reflect the on-site spatial organization and its characteristics as they were actually performed. The data structure is identical to that in the as-planned model. The key difference that differentiates them from their as-planned counterpart is that they are expected to change dynamically daily or hourly to reflect the actual situation on site.

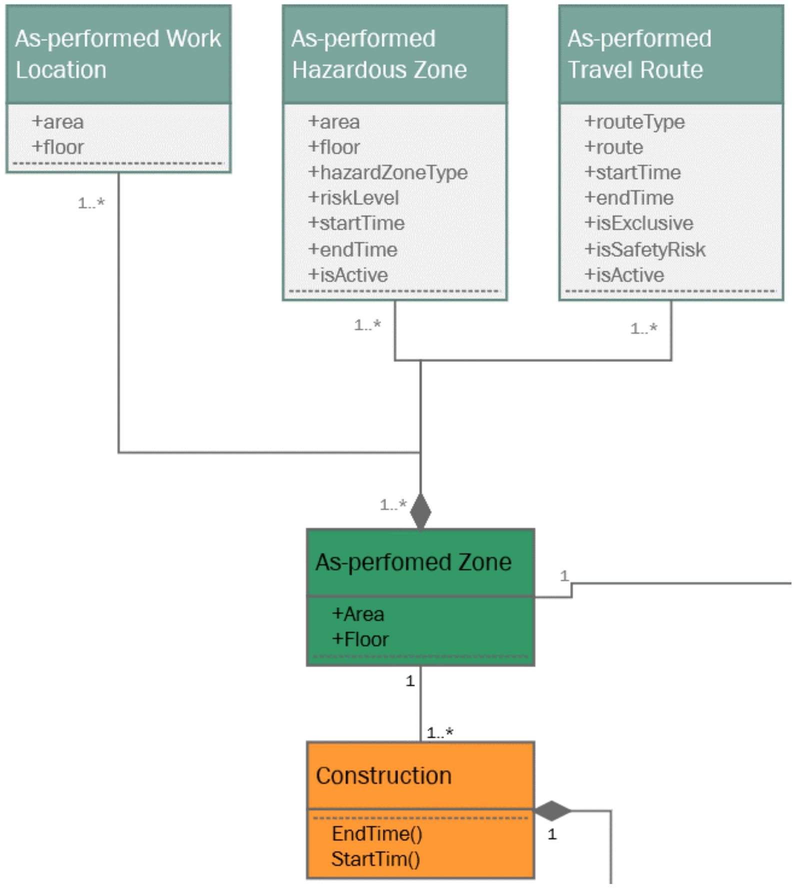

Figure 13. UML class diagram for as-performed zone

The data schema presented in **Figure *14*** details how the as-performed resource application can be represented in the DBTP. The As-performed Resources maintain the same class structure as their as-planned counterparts, with the main difference being that the equipment maintenance and material delivery classes represent specific instances of such events rather than the entire planned schedule. The As-Performed Resources in the PSI are also associated with Performance Indicators residing in the PSK.

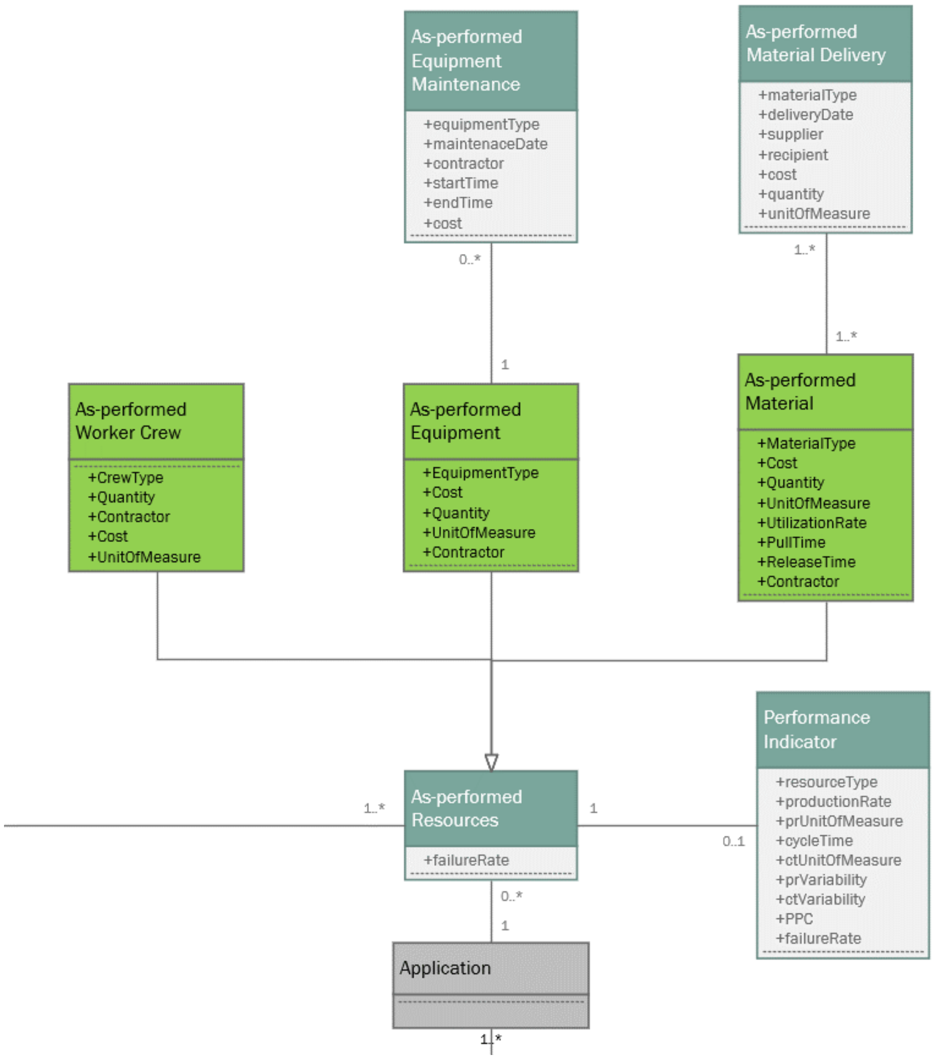

Figure 14. UML class diagram for as-performed resource application

10.3 Function requirements (APIs)

10.3.1 Database (Backend) Requirements

The DBT must possess the ability to create, store, query, modify, and replace information in the DBT database. A DBT agent (or DBT engine) should be capable of computing the performance factors discussed in Section 8.1. An application performance interface (API) should be provided for information requests and software module activations. Furthermore, this API should also enable data and file transfer between the DBT and the simulation software over the internet or a local network.

In the final version of this report, a table will be provided below detailing the data manipulations (create, remove, query, update, replace) expected to be performed on each data related to this work package.

10.3.2 Platform (Frontend) Requirements

The core dashboard in the DBT platform should allow the user to initiate the simulation software and navigate between the core dashboard and the user interface of the simulation software. It should provide the production planners with sufficient situational awareness information to judge whether countermeasures are necessary against the current project status, and APs should be investigated in the WP7 software.

11 Summary and Discussion

The objective of this technical report is to present the system design and the definition of the requirements and specifications for simulation and prediction. In addition, the technical report is intended to serve as the basis for developing a collection of software applications that will allow users to generate, evaluate, optimize APs and receive recommendations to improve the decision-making process.

In support of this goal, eighteen (18) semi-structured interviews were conducted to collect information directly from production planners working in the AEC domain. The objective was to understand operational decisions that production planners make during the course of construction projects and delineate the use cases intended for the simulation and prediction software. The case studies and the literature review revealed that production planners mostly conduct nine types of changes in the production system to achieve the project goals, including (1) add, reduce, or allocate resources (labor, material, and machinery), (2) change the original design, (3) incorporate new subcontractors, (4) reschedule some construction activities, (5) modify construction methods (6) standardize the construction activities to reduce waste and enhance the production flow, (7) divide the jobsite into locations for measuring its performance (location-based method), (8) reduce the batch size in order to decrease the work-in-progress (WIP) and, (9) balance the capacity of the resources (labor and machinery) to minimize the no-value added time. These changes are anchored to the production planners' degree of freedom and their impact on the project's total cost and duration. Finally, use cases for the simulation and prediction software were derived from this set of possible changes in the production system.

The overall system architecture is lays out the principles for determining the requirement specifications for the DBTP and defining the workflow and dependencies between the user, DBTP, and the simulation and prediction software that WP7 will develop. Then, the user inputs and outputs for the simulation and prediction are determined according to the system architecture. Finally, the DBTP functionality and data schema requirements are established to specify the information required from the PSK, the PII, and the PIK for accurate simulation of the future project status.

The overall system architecture was designed based on three main components depicted in a BPMN diagram. The first BPMN swim lane presents the user inputs and recommendation dashboard interface. This set of interfaces will allow users to define targets, constraints, and simulation parameters and utilize different decision-making aids. The second BPMN swim lane embodies actions performed by the simulation and prediction software to generate, simulate, evaluate, and optimize APs. More specifically, once all the information is collected, APs will be developed according to the user's targets and constraints and then simulated using the current project status information. Later, each AP will be evaluated by KPIs and utility functions and then optimized using genetic algorithms. Finally, the third BPMN swim lane depicts the information exchanged with the PII, PSK, and the historical DBT. The process in this swim lane defines the procedures for storing the entire simulation cycle as PIK.

Derived from the system architecture, there are three possible scenarios for interacting with the user interface. The first is when users want to evaluate custom APs significantly different from the BP stored in the DBT. The second and third possibilities are when the user desires to evaluate APs incrementally adapted from the current BP. The generation of these scenarios will be originated manually or automatically, allowing the user to interact directly with the different software modules. These scenarios will be complemented with the recommendation dashboard, in which users can make informed decisions on the production plan to be applied in the next production cycle. Finally, and driven by the necessity of having up-to-date, accurate, and precise information on the project status and intent, the system will require readily available information from the PSK, historical data, PII, and PIK. The information requirements are presented in a set of UML class diagrams which were developed in collaboration with members of WP2. The UML diagram depicts the essential information and associations needed for data-driven production planning in a DBT environment.

In general terms, the system design is centered around agent-based simulation parameters and lean construction principles. More specifically, the software structure compiles procedures for predicting outcomes of changes to production plans/product designs based on simulations and predicting operational outcomes subject to current conditions and plans. The system design is modular, separating the software into components (generate, simulate, evaluate and optimize APs) according to functionality and purpose. The main objective is to improve the software design and implementation process by allowing reusability, workload handling, and straightforward validation. Additionally, Agent-based simulation (ABS) will be the approach to generate and simulate APs, together with a "bottom-up" method to model the interactions between individual agents. The ABS will be implemented based on the assumption that construction projects have distributed managing control rather than central control.

Finally, the system design and implementation may present various challenges to consider and address. First, the many agents involved in construction projects make the systems complex to simulate and predict emergent outcomes. Second, capturing and validating the proper agents' behavior are non-trivial tasks. Third, the time of the simulation cycle (run time) must be constrained to provide answers for construction planners in a reasonably short time, ideally less than an hour at most, even for complex projects. Finally, the simulation architecture must provide a system flexible enough to allow rapid and automated compilation of simulations for a wide variety of construction environments and scenarios.

11.1 Implications and future deliverables

This report was intended to serve as a scheme for developing a suite of software applications that will enable operators to generate APs, evaluate APs by simulating their likely outcomes and receive recommendations concerning possible courses of action. As a next step and together with FIRA and SPADA, WP7 will design and specify a software that simulates and predict the operational outcomes of a given production plan during interior and structural work. First, key indicators (cost, time-to-delivery, quality, safety) will be defined and described to achieve this goal. Then, the crews, equipment, and material delivery behaviors that underlie the workflows for agent-based simulation will be documented. Finally, the set of decision parameters (e.g., number of workers, material quantity, production rates, work sequence) necessary for the model to generate alternative plans will be established. The deliverables of this task are a complete list and description of the key performance indicators for production plans, behavior trees, and descriptions of the parameters of the simulation (agent-based behaviors); and the workflow of the simulation and predictive loop.

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13 Annex I

This annex provides the detailed results and analyses for the 18 case studies collected.

CASE STUDY REPORT # 1

Type of project	Residential building
Role of the interviewee	Site Manager
Location of the work	Interior
Country	Finland
Nature of the problem	Product issue
Category	Error in the execution of the task

Case study description
The site manager noticed that the prefabricated bathrooms subcontractor had used wall tiles instead of floor tiles. This non-conformity to design results in an unacceptable product. To amend the error, three possible solutions were considered: (1) install the correct tiles on top of the current ones, (2) replace the tiles with the correct ones, and (3) apply a non-slip coating on the current tiles.
Decisions considered to mitigate the problem
The action selected was to remove the current (wrong) tiles and install new correct ones.
Changes in the production system
• Add a new subcontractor work crew for the task. • Adjust the project budget and schedule by incorporating this new task. • Prepare new work instructions/work breakdown structure of the new task.

Did the decisions require authorization?	Yes
From whom?	Construction Manager and Owner
Degree of freedom	Low

Limitations and constraints
Lack of information regarding the status of tiles installed in bathrooms throughout the project

Document used and updated
Project schedule, Plans and Budget

KPIs implemented
Activity total cost, activity duration and total number of defects that occurred during interior work

Desired information
Daily Information on the progress and quality of indoor work and resources productivity rates and real-time Information concerning the location of subcontractors and workers on the jobsite

CASE STUDY REPORT # 2

Type of project	Residential building
Role of the interviewee	Site manager
Location of the work	Exterior
Country	Finland
Nature of the problem	Product issue
Category	Incorrect preliminary studies

Case study description	
Due to possible structural damage that could be generated in a building (art gallery) located next to the construction site, the excavation process had to be redesigned to minimize the impact on the structure.	
Decisions considered to mitigate the problem	
Use blasting charges smaller than planned to reduce the structural impact on the neighboring building. Additionally, it was required to drill into the bedrock from the side of the building.	
Changes in the production system	
Hire an external consultant to design the tremor threshold control procedure, assign new resources for this activity and reschedule some construction tasks	
Did the decisions require authorization?	Yes
From whom?	Owner and project manager
Degree of freedom	Low

Limitations and constraints
The decision did not produce any limitations or constraints during its implementation

Document used and updated
Project schedule, customer requirements (Contract), project plans and resources’ productivity rates

KPIs implemented
Activity total cost and Activity duration

Desired information
Information related to the legal permits required to conduct excavations (Historical information)

CASE STUDY REPORT # 3

Type of project	Residential building
Role of the interviewee	Foreman
Location of the work	Interior
Country	Finland
Nature of the problem	Process issue
Category	Incorrect sequence of activities

Case study description	
During the construction of one of the residential buildings, the Foreman discovered that the project planning was not in harmony with the logical sequence of activities that have been carried out before the installation of the apartment floors. More specifically, the electrical installation activity was scheduled after the installation of the apartment floor. This issue was discovered based on historical information from other similar projects	
Decisions considered to mitigate the problem	
It was necessary to reschedule some construction activities such as electrical and flooring work.	
Changes in the production system	
The activities performed by the carpentry and flooring installing subcontractor were postponed. In contrast, the electrical work was performed prior to the flooring work. This decision required various modifications and changes, more specifically in the project schedule and resource assignment	
Did the decisions require authorization?	Yes
From whom?	Site manager
Degree of freedom	High

Limitations and constraints
The decision did not produce any limitation or constraint during its implementation

Document used and updated
Project budget and schedule.

KPIs implemented
Activity total cost and activity duration

Desired information
Number of workers by subcontractor, resources productivity rate and days that subcontractors are available for work

CASE STUDY REPORT # 4

Type of project	Residential building
Role of the interviewee	Site manager
Location of the work	Exterior
Country	Portugal
Nature of the problem	Process issue
Category	Incorrect design

Case study description	
During the construction of the retaining wall for a residential construction project, the project manager noticed that it was neither technically nor financially feasible to build the wall based on the original design.	
Decisions considered to mitigate the problem	
The project manager proposed several more feasible and lower-cost solutions to build the retaining wall, however, the owner refused to choose between the solutions given. As a consequence, the project manager had to adapt the production system to meet the initial requirements.	
Changes in the production system	
To carry out this activity and meet the initial requirements, it was necessary to rent additional excavators as well as commission a new soil study. Therefore, resources in labor and machinery increased the direct and indirect costs of the construction project.	
Did the decisions require authorization?	Yes
From whom?	geotechnical engineer, project manager and owner
Degree of freedom	Low

Limitations and constraints
Technical limitation related to soil density and resistance

Document used and updated
Preliminary studies, plans, soil study, contract, and budget

KPIs implemented
Activity total cost and activity duration

Desired information
Resources rates in real-time, number of workers for each subcontractor

CASE STUDY REPORT # 5

Type of project	Residential building
Role of the interviewee	Site manager
Location of the work	Exterior
Country	Finland
Nature of the problem	Process issue
Category	Incorrect sequence of activities

Case study description	
To reduce the project schedule duration, the Site manager proposed changing the concrete mix to minimize the concrete curing time.	
Decisions considered to mitigate the problem	
The concrete mix of the cast floor structures was changed to one with higher resistance and lower water-to-cement ratio. As a result, the concrete curing was faster when compared with the initial concrete mix.	
Changes in the production system	
Change the technical specification of the concrete mix, modify the construction schedule, and re-assign construction activities	
Did the decisions require authorization?	Yes
From whom?	Structural engineer and construction manager
Degree of freedom	Medium

Limitations and constraints
The decision did not produce any limitation or constraint during its implementation

Document used and updated
Structural designs, cost and properties of different concrete mixes, project budget and schedule.

KPIs implemented
Activity total cost, and activity duration

Desired information
Curing times for different concrete mixes, different concrete material types, and under different weather conditions (winter: dry and cold, fall and spring moist and cold, summer moist and hot)

CASE STUDY REPORT # 6

Type of project	Infrastructure
Role of the interviewee	Construction manager
Location of the work	Exterior
Country	Spain
Nature of the problem	Product issue
Category	Incorrect technical studies

Case study description	
An archaeological site was found during the excavation process. Consequently, the construction project was suspended until a decision was made to move the construction site to another location or to excavate at lower depth.	
Decisions considered to mitigate the problem	
The proposed solution consisted of digging at a lower depth (1 meter) instead of 1.5 meters to avoid damage to the archaeological site	
Changes in the production system	
The solution required carrying out new soil studies, topographic surveys, resizing the terrain, and recalculating the resources necessary for its execution. Implementation of this solution is expected to reduce cycle times by approximately two months	
Did the decisions require authorization?	Yes
From whom?	Owner
Degree of freedom	Low

Limitations and constraints
Legal authorizations and resources availability (technical studies and construction materials)

Document used and updated
Soil study, topographic survey, plans, budget, schedule, technical studies based on international standards.

KPIs implemented
Activity total cost, activity duration and resources productivity rate

Desired information
Resource productivity rates (in real-time), workers and crews location, assignments and schedule

CASE STUDY REPORT # 7

Type of project	Residential building
Role of the interviewee	Supervisor
Location of the work	Interior
Country	Colombia
Nature of the problem	Product and process issue
Category	Design

Case study description	
The sales office did not deliver the technical information for two apartments to the finishing area on time. Therefore, the supervisor in charge of the interior works built the kitchens and bathrooms according to the specifications of the initial design.	
Decisions considered to mitigate the problem	
Since many of the bathroom and kitchen components were not available, the supervisor together with the construction manager made the decision to take these parts from other finished apartments for their installation in the two recently sold apartments.	
Changes in the production system	
Incorporate a new subcontractor to install the kitchen parts, hire two new workers for finishing work, a carpenter, a plumber, and four workers for the cleaning	
Did the decisions require authorization?	Yes
From whom?	Construction manager
Degree of freedom	Medium

Limitations and constraints
Lack of parts available for bathroom and kitchen modification

Document used and updated
Plans, budget, customer requirements

KPIs implemented
Activity total cost, Activity total duration, Number of nonconformities during the finishing work

Desired information
Information regarding design changes (construction elements changed in the design according to customer requirements), and parts inventory provided in real-time

CASE STUDY REPORT # 8

Type of project	Residential building
Role of the interviewee	Superintendent
Location of the work	Interior
Country	Colombia
Nature of the problem	Product issue
Category	Design

Case study description
Due to extreme weather conditions, it was required to add an additional cover on the rooftop of the building which was not contemplated in the initial design. This decision was made due to the heavy rains that occurred in the city those days and that affected the building interiors due to leaks.
Decisions considered to mitigate the problem
Install a new cover roof to prevent leaks from damaging interior work.
Changes in the production system
Hire a new crew of workers to carry out this task and request additional construction materials

Did the decisions require authorization?	Yes
From whom?	Construction manager
Degree of freedom	High

Limitations and constraints
The decision did not have any limitation or constraint during its implementation

Document used and updated
Plans, budget and schedule

KPIs implemented
Activity total cost and activity total duration

Desired information
The Superintendent expressed the need to have more information on the status of the project and worker productivity rates in real time.

CASE STUDY REPORT # 9

Type of project	Infrastructure
Role of the interviewee	Superintendent
Location of the work	Exterior
Country	Colombia
Nature of the problem	Product issue
Category	Error in the topographic survey

Case study description	
Due to an incorrect topographic survey, the terrain dimensions were erroneously calculated. As a result, the distances between the building columns were different when compared to as-planned. Initially, 6 meters distance between columns was planned, however, the actual distance was 5.85 meters	
Decisions considered to mitigate the problem	
Replace the concrete beams with steel beams which can be adapted to the new measurements between columns.	
Changes in the production system	
Changes in the construction system and placement of the beams	
Did the decisions require authorization?	Yes
From whom?	Construction manager
Degree of freedom	High

Limitations and constraints
The decision did not have any limitation or constraint during its implementation

Document used and updated
Plans, topographic survey and budget

KPIs implemented
Activity total cost and activity total duration

Desired information
Resources productivity rate, historical information related to previous survey topographic studies.

CASE STUDY REPORT # 10

Type of project	Infrastructure
Role of the interviewee	Project manager
Location of the work	Exterior
Country	Colombia
Nature of the problem	Product issue
Category	Change in the original design

Case study description	
Due to the owner’s request with respect to the project duration, the construction company together with the auditing firm made the decision to remove one asphalt layer from the pavement and thus reduce the time required for the construction of road surfaces	
Decisions considered to mitigate the problem	
Remove one asphalt layer from the pavement. The decision was implemented following the project schedule and the technical requirements in order to shorten the construction project time from 45 days to 5 days. The implementation of this decision took place during the construction stage (50 percent of project progress approximately).	
Changes in the production system	
Conduct new technical studies to determine the feasibility of the proposed solution, reassign resources to other project activities (assign new tasks to the work crew in charge of this activity), adjust the project schedule by eliminating the construction task and change the original design of the project	
Did the decisions require authorization?	Yes
From whom?	Owner and Highway engineer
Degree of freedom	Low

Limitations and constraints
The main limitation was the time required for accepting the proposed decision. For the reasons explained above, changes in construction projects financed with public resources require prior authorization of various parties involved. More specifically, the auditing company first required technical studies to authorize the change, then it was necessary to update the contract and the project budget.

Document used and updated
Plans, technical studies of the pavement, productivity rates of the workers, schedule and project budget.

KPIs implemented
Activity total cost and activity total duration

Desired information
Technical studies pertaining to other similar construction projects, precise information about the current worker productivity rate, accurate information on the assignment of tasks to workers and machinery to define their workload.

CASE STUDY REPORT # 11

Type of project	Building construction
Role of the interviewee	Procurement manager
Location of the work	Interior
Country	Panama
Nature of the problem	Process issue
Category	Delay in delivery of materials

Case study description
The kitchens, doors and cabinet supplier did not provide the building materials on time. Therefore, the procurement manager had to make the decision to change the current supplier to smaller local suppliers. Since there was a contract between the parties, the process of cancelling the contract took more than six months. This problem increased the project duration by 18 months.
Decisions considered to mitigate the problem
Order kitchens, doors, and closets from local suppliers located in Italy and Costa Rica Duplicate work shifts to almost 24 hours to speed up apartments finishing work Prioritize the movement of personnel and material on the jobsite for this specific task.
Changes in the production system
Hire new crews for finishing work in order to reduce the expected duration of the project. Change the priority of access to the jobsite elevators, specifically to workers and materials associated with the installation of kitchens, doors and cabinets.

Did the decisions require authorization?	Yes
From whom?	Owner representative and project manager
Degree of freedom	Low

Limitations and constraints
Lack of local suppliers located in the country, Limited number of elevators for resources transportation on the jobsite

Document used and updated
Plans and schedule

KPIs implemented
Plans and schedule

Desired information
Real-time information on the progress and quality of indoor work, Productivity of resources and location of subcontractors and workers”

CASE STUDY REPORT # 12

Type of project	Building construction
Role of the interviewee	Foreman
Location of the work	Interior
Country	Panama
Nature of the problem	Product issue
Category	Error in the original plans

Case study description	
When starting the layout of the gas line inside the building, the foreman in charge noticed an error in the project’s initial plans. For example, various construction components such as beams, and walls were blocking gas piping installation.	
Decisions considered to mitigate the problem	
Redesign the gas piping installation method by changing the original route and incorporating new construction materials	
Changes in the production system	
Redesign the plans Draw a new route for the gas line installation to avoid the aforementioned obstacles Change the gas piping material in certain sections of the route	
Did the decisions require authorization?	Yes
From whom?	Electrical/mechanical engineer (Subcontractor representative)
Degree of freedom	Medium

Limitations and constraints
The main limitation was delays in the approval of the proposed decision by the electrical/mechanical engineer

Document used and updated
Plans, schedule and budget

KPIs implemented
Activity total cost and activity total duration

Desired information
Real-time information on the progress and quality of indoor work, and productivity rates in real time

CASE STUDY REPORT # 13

Type of project	Institutional and Commercial
Role of the interviewee	Site manager
Location of the work	Exterior
Country	Spain
Nature of the problem	Product issue
Category	Construction methods

Case study description	
During the retaining wall construction, the Site manager noticed that the machinery was spending more time than initially planned. This was due to the fact that the chosen construction method required first digging, reinforcing, and pouring in parts.	
Decisions considered to mitigate the problem	
Change the construction method. Instead of digging in parts, it was decided to excavate a complete section, build reinforcements and pour the entire section into concrete. The number of workers remained constant, however, reinforcements initially used were replaced by more rigid ones. The decision increased the cost of the reinforcement by 5 percent	
Changes in the production system	
Change the construction method. Instead of digging in parts, it was decided to excavate a complete section, build reinforcements and pour the entire section into concrete.	
Did the decisions require authorization?	Yes
From whom?	Project manager
Degree of freedom	High

Limitations and constraints
Technical limitations related to the stiffness of the reinforcement due to these require special handling

Document used and updated
Plans and resource productivity rate

KPIs implemented
Activity total cost and activity total duration

Desired information
N/A

CASE STUDY REPORT # 14

Type of project	Building construction
Role of the interviewee	Site manager
Location of the work	Exterior
Country	Panama
Nature of the problem	Product issue
Category	Construction methods

Case study description	
During the structural work, the concrete resistance (6000 psi) was lower than expected (10000 psi). The concrete test was taken by the concrete supplier and then analyzed by a private lab. The results were then sent to the structural engineer, who checked it with respect to safety factors. The results showed that the concrete resistance was under the safety factors.	
Decisions considered to mitigate the problem	
Reinforce vertical elements such as columns and structural walls and at the same time, continue working until floor 30th	
Changes in the production system	
Reinforce vertical elements such as columns and walls, assign one specific crew for this task and build until level 30, which was the maximum number of floors authorized by the structural engineer	
Did the decisions require authorization?	Yes
From whom?	Concrete supplier, subcontractor and structural engineer
Degree of freedom	Medium

Limitations and constraints
Structural engineer approval

Document used and updated
Concrete technical specification, plans, and schedule

KPIs implemented
Activity total cost and duration

Desired information
Real-time information regarding to outdoor progress and resources productivity rate

CASE STUDY REPORT # 15

Type of project	Building construction
Role of the interviewee	Site manager
Location of the work	Exterior
Country	Panama
Nature of the problem	Product issue
Category	Errors in the original design

Case study description	
The topographic survey had an error of 5 cm on the Z-axis. This error affected the elevator installation as the level reached by this was higher than the first-floor slab.	
Decisions considered to mitigate the problem	
The first-floor columns were increased in 5cm height with respect to the original design	
Changes in the production system	
Modify the structural plan Increase the height of the first-floor columns by 5 cm Change the power plant location from the basement to the first floor Order additional construction materials for the concrete pouring of the columns	
Did the decisions require authorization?	Yes
From whom?	Project manager and structural engineer
Degree of freedom	Medium

Limitations and constraints
Delay during authorization for the acquisition of construction materials

Document used and updated
Concrete technical specification, plans, and schedule

KPIs implemented
Activity total cost and duration

Desired information
N/A

CASE STUDY REPORT # 16

Type of project	Building construction
Role of the interviewee	Supervisor (Electromechanical engineer)
Location of the work	Interior
Country	Panama
Nature of the problem	Product issue
Category	Errors in the original design (conflict between and architectural and electrical design)

Case study description
The proposed electrical connection system was initially based on busbars. However, during the measurement process, the Electromechanical Engineer noticed that there was not enough space for the installation of these busbars. This was because the water pipes had occupied the space for the installation of the busbars. The Electromechanical Engineer claimed that one of the causes was an incompatibility between architectural and electrical design.
Decisions considered to mitigate the problem
Change the electrical system design and implementation. The change took 2.5 months approximately
Changes in the production system
Modify the electrical plan Replace busbars with pipes to introduce the electrical wiring Move the power plant from floor 0 to floor 5 in order to reduce wiring costs

Did the decisions require authorization?	Yes
From whom?	Electromechanical and structural engineer
Degree of freedom	Medium

Limitations and constraints
Delay during the power plant installation and decision approval. However, the proposed change reduced the project cost and time. It was because pipes and electrical wires were easier to find in Panama when compare with busbars

Document used and updated
Concrete technical specification, plans, and schedule

KPIs implemented
Activity total cost and duration

Desired information
Real time information regarding the construction site progress, worker’s productivity rate and quality check in real time

CASE STUDY REPORT # 17

Type of project	Infrastructure construction
Role of the interviewee	Technical office (Architect)
Location of the work	Exterior
Country	Spain
Nature of the problem	Product issue
Category	Errors in the original design

Case study description	
During the construction stage, the technical office noticed a discrepancy between the architectural and structural plans. More Specifically, the retaining wall height in the structural plans was lower than it was in the architectural plans	
Decisions considered to mitigate the problem	
Change structural design	
Changes in the production system	
The production system was not modified. No crews were added or removed	
Did the decisions require authorization?	Yes
From whom?	Site manager
Degree of freedom	High

Limitations and constraints
No limitations were found

Document used and updated
Architectural and structural plans

KPIs implemented
Activity total cost and duration

Desired information
Quality check and progress monitoring in real-time for the exterior work

CASE STUDY REPORT # 18

Type of project	Infrastructure construction
Role of the interviewee	Site manager
Location of the work	Exterior
Country	Spain
Nature of the problem	Product issue
Category	Construction method

Case study description
During the foundation process, the site manager noticed a delay in the project compared to as-planned. To meet the project schedule, the site manager proposed a change in the construction method which consisted of replacing vertical concrete elements with metal elements.
Decisions considered to mitigate the problem
Change the construction method to meet the project deadline. More specifically, vertical elements such as columns were replaced with metallic elements.
Changes in the production system
Change the vertical concrete elements for metal elements Modify the structural plans Adjust the schedule and budget Contact new material suppliers Assign new crews for this task

Did the decisions require authorization?	Yes
From whom?	Structural engineer, project manager and owner
Degree of freedom	Low

Limitations and constraints
Time required to change and approve architectural and structural plans and apply them

Document used and updated
Architectural and structural plans, budget, and schedule

KPIs implemented
Activity total cost and duration

Desired information
N/A