COGITO

CONSTRUCTION PHASE
DIGITAL TWIN MODEL

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D2.3 – COGITO Evaluation Methodology

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Disclaimer

Executive Summary

The assessment and evaluation of the impact of a project is a critical process. This document presents the work conducted in task T2.3 'Development of an Evaluation Methodology for the impact of COGITO Tools'. The objective of this task is to develop an evaluation methodology that defines the way COGITO outputs will be evaluated in the pre-validation and validation activities (WP8 'Integration, Validation & Evaluation Activities').

The evaluation strategy focuses on the COGITO tools performance and their impact on: i) the immediate benefits on construction in terms of time, productivity, cost, safety and sustainability (including meeting the EC Green Deal objectives); and ii) the more indirect benefit of accelerating the digitalization rate of the construction sector. To achieve this goal, the methodology identifies and selects suitable Key Performance Indicators (KPIs) and the methods – quantitative or qualitative – that are to be employed to measure them.

Regarding the impact of the COGITO solution in the five main areas of time, cost, quality, safety, and energy efficiency, the proposed methodology reviewed KPIs and corresponding measurement methods currently employed in industry and/or described in the literature (including methodologies adopted in relevant EU-funded projects). For the KPIs employed in industry, input has been sought from the consortium's internal experts (in particular among COGITO's industrial partners) as well as external experts. This was done through the Questionnaire and Workshops used as part of T2.1 'Elicitation of Stakeholder Requirements' (see D2.1 [1] for details), as well as additional dedicated meetings focusing on the different COGITO Business Scenarios (BSs) and Use Cases (UCs). The technical partners then selected a preliminary list of KPIs that would be best suited to assess the impact of the COGITO tools. This list was finally reviewed by the pilot site industry partners to assess measurability, collectability, and comparability.

The result of that process is a list of 55 Project Performance KPIs, divided into 11 time/scheduling KPIs, 10 cost KPIs, 4 quality KPIs, 20 safety KPIs, and 10 energy efficiency KPIs. In the case of time, cost, quality, and safety, the KPIs aim to measure not only the performance of the project in that area (e.g. project is completed within budget and schedule), but also the performance of the processes required to plan and monitor time, cost, quality, and safety. The energy-efficiency KPIs only measure the performance of the project in that area. This is because benefits in energy efficiency are only indirectly realised through the impact of the COGITO tools on time performance (e.g. productivity improvement and reduced waiting time). The necessary input parameters for all calculations are identified and ways to capture all this information during the piloting activities (e.g. sensor measurements, tools user feedback, manual measurements, visual inspection results) are defined.

Regarding the impact of COGITO on accelerating the digitalization rate of the construction sector, its benefits should be realised by demonstrating, with the pilot sites, the added value of the COGITO tools in the above five areas. However, a broader methodology, based on the Technology Acceptance Model (TAM) theory, is also proposed that actively assesses technology User Acceptance (UA). In total, 10 UA KPIs will be measured. These are qualitative and measured on the Likert scale. Their evaluation will be facilitated via bespoke forms for the various stakeholders to ensure balanced views are captured.

Overall, the COGITO methodology creates a robust framework that enables the definition of adequate COGITO Key Performance Indicators (KPIs) and measurement methods. These form the basis for the design and development of the activities related to the COGITO pre-validation, validation, and overall impact assessment activities of WP8 (which will be reported in deliverable D82, D8.4 and D8.5 respectively). The results reported here will also influence some of the technical work, to ensure that the developed tools capture and record required input data for the evaluation of the selected KPIs.

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List of Acronyms

Term	Description
ACWP	Actual Cost of Work Performed
AEC	Architecture, Engineering & Construction
AIFR	All Injury Frequency Rate
API	Application Programming Interface
AR	Augmented Reality
BCWP	Budgeted Cost of Work Performed
BIM	Building Information Model
BoQ	Bill of Quantity
BS	Business Scenario
CA	Cost Account
CAVAR	Cost Account Variance
COGITO	Construction Phase diGItal Twin mOdel
DART	Days away, restricted or transferred
DBT	Digital Building Twin
DOA	Declaration of Action
DT	Digital Twin
EU	European Union
EVA	Earned Value Analysis
GJ	Gigajoule
ICT	Information and Communications Technologies
IoT	Internet of Things
IT	Information Technologies
KPI	Key Performance Indicator
LTI	Lost Time Injury
LTIFR	Lost Time Injury Frequency Rate
MS	Milestone
MTI	Medical Treatment Injury
O&M	Observations and Measurements
PaaS	Platform as a Service
PD	Planned Duration
PM	Person Month
PPE	Personal Protective Equipment
PSM	Project Status Model
QA	Quality Assurance
QC	Quality Control
QM	Quality Manager
RIFR	Reportable Injury Frequency Rate
SLAM BIM	Success Level Assessment Model for BIM projects
SPI	Schedule Performance Index
SR	Stakeholder Requirement

SV	Schedule Variance
T	Task
TAM	Technology Acceptance Model
TCIR	Total Case Incident Rate
TPB	Theory of Planned Behaviour
TRIR	Total Recordable Incident Rate
TRIFR	Total Recordable Injury Frequency Rate
UA	User Acceptance
UC	Use Case
UTAUT	Unified Theory of Acceptance and Use of Technology
WBS	Work Breakdown Structure
WP	Work Package

1 Introduction

1.1 Scope and Objectives of the Deliverable

The objective of T2.3 is to develop a methodology that describes how the COGITO solution will be evaluated. Specifically, T2.3 aims to define the Key Performance Indicators (KPIs) that are necessary to characterise the performance and impact of the COGITO solution and tools, and the methods that can and will be employed to measure those KPIs in the pilot sites and beyond the life of the COGITO project. The deliverable D2.3 is the output of the work carried in Task 2.3.

The evaluation focuses on the COGITO tools performance and their impact on: i) the immediate benefits on construction in terms of time, productivity, cost, safety and sustainability (such as meeting the EC Green Deal objectives); and ii) the more indirect benefits accelerating the digitalization rate of the construction sector.

A review of the activities conducted in T2.1 (Elicitation of Stakeholder Requirements) to define the Business Scenarios (BSs) and Use Cases (UCs) (see deliverable D2.1 [1]) established that the COGITO solution should enhance construction project performance in the following categories:

- Schedule/workflow,
- Cost,
- Quality,
- Safety,
- Energy efficiency (and therefore reduction in carbon footprint) of the construction process.

These benefits are expected to be the result of integrated more efficient communication and data exchange, more systematic and detailed planning, as well as timely monitoring of construction activities, which will be enabled by the ecosystem of the COGITO Services and Tools integrated around the COGITO Digital Twin Platform.

Beyond the direct impact on project performance, User Acceptance (UA) of the COGITO tools should be assessed. UA is a necessary pre-condition for the exploitation of the tools and their proliferation in the construction industry, thereby delivering the benefits in terms of accelerating the digitalization rate of the construction sector.

This report presents the outcome of the methodology followed to identify and select the KPIs and the methods to be employed to measure them in the context of the pilot sites. It must be highlighted that, in the case of schedule/workflow, cost, quality, safety and energy, measuring the impact of the COGITO tools requires measuring the selected KPIs when applying the COGITO solution as well as baselining those KPIs for current practice. In contrast, UA only needs to be assessed for the COGITO solution.

Section 2 summarises the methodology followed in T2.3. Then, accordingly, Section 3 presents the review of existing assessment methodologies (KPIs and measurement methods) for time, cost, quality, safety and energy efficiency performance. This is complemented in Section 4 with a presentation of relevant EU projects. Section 5 reports the outcome of the analysis of the review and presents the KPIs selected for the above categories and their calculation methods, along with the approaches to be followed for baselining them. Section 6 focuses on UA. It first presents a review of existing UA assessment methodologies and then establishes the methodology, including KPIs, proposed specifically for assessing UA in the context of the COGITO project. Section 7 concludes the document.

1.2 Relation to Other Tasks and Deliverables

D2.3 sits in a continuum of tasks and their respective deliverables informing and conducting the evaluation of the COGITO solution:

- D2.1 (output of T2.1 - Elicitation of Stakeholder Requirements) that defines the Business Scenarios (BSs), Use Cases (UCs) and Stakeholder Requirements (SRs) that are focused on COGITO and are to be validated through the pilot site activities.
- D2.3 (this deliverable, output of T2.3 - Development of an Evaluation Methodology for the Impact of COGITO Tools) that develops the methodology for the evaluation of the COGITO solution and tools, from both functional and usability viewpoints.
- D8.2 (output of T8.2 - COGITO ICT System Pre-Validation) that reports the outcomes of the COGITO solution pre-validation that will be able to measure at least some of the KPIs while testing and pre-validating the solution under realistic, but controlled conditions.
- D8.4 (output of T8.4 - Demonstration of COGITO Tools on Construction Projects) that reports on the outcomes of the COGITO demonstration activities.
- D8.5 (output of T8.5 - COGITO Impact Assessment) that conducts the overall analysis and evaluation of the collected information and stakeholder opinions after the pre-validation and validation phases of the project across the pilot sites.

The results reported here will also impact some technical work, mainly to ensure that the developed tools capture and record any data that is required as input for the evaluation of the selected KPIs.

2 Methodology

The section summarises the approach followed in T2.3. Two distinct methodologies are considered to assess: i) the immediate benefits on construction in terms of time, productivity, cost, safety and sustainability (such as meeting the EC Green Deal objectives); and ii) the more indirect benefits accelerating the digitalization rate of the construction sector.

To evaluate the time, cost, quality, safety and energy improvement in construction project delivery, a methodology was developed with inspiration from the Success Level Assessment Model for BIM projects (SLAM BIM), which is a goal-driven method that was proposed in [2] to measure the success of BIM projects. The methodology proposed here has five steps:

1. Identify areas in which COGITO shall enhance construction project performance, through an analysis of COGITO goals of enhancing construction performance in terms of time, cost, safety and sustainability, and the activities conducted in T2.1 'Elicitation of Stakeholder Requirements' to define the Business Scenarios (BSs) and Use Cases (UCs).
2. Review of the KPIs currently employed in industry in those five areas with broad relevance to the COGITO UCs. This review considered input from the consortium's internal expertise (in particular existing methodology employed in practice and contributed by the industrial partners) and input from external expertise (captured through the Questionnaire and Workshops used as part of T2.1).
3. Review of the KPIs considered in recent EU-funded projects with broad relevance to COGITO.
4. Production of an initial list of KPIs to be employed in COGITO by the technical partners.
5. Review of the preliminary list of KPIs by the industry partners to assess *measurability*, *collectability* (in general or specifically to the selected pilot sites) and *comparability* (in relation to baselining). The outcome of this final step is a list of KPIs and methods to be followed to measure them that could be employed in the context of the COGITO pilot sites. However, it must be highlighted that several uncertainties surrounding the pilot sites means that this list of KPIs remains provisional and will need to be revisited in the context of the work conducted in WP8 (Integration, Validation & Evaluation Activities) once more detailed information about the pilot sites is available.

In Section 1, the areas where the COGITO solution will enhance construction project performance (Step 1 above) identified the following categories:

- Schedule/workflow;
- Cost;
- Quality;
- Safety;
- Energy-efficiency (or reduction in carbon emissions) of the construction process.

The remaining Sections discuss Steps 2-5. Results of step 2 are reported in Section 3; results of step 3 are reported in Section 4; and results of step 4 and 5 are reported in Section 5.

Demonstrating the impact of the COGITO solution on construction in terms of time, cost, safety and sustainability (such as meeting the EC Green Deal objectives), should directly contribute to COGITO's aim of accelerating the digitalization rate of the construction sector (because industry would more likely want to use those tools). But, to achieve a more holistic assessment of the likelihood of end-users adopting the COGITO solution (or similar ICT solutions), and therefore of COGITO's contribution to accelerating the digitalization rate of the construction sector, it is proposed to measure 'Technology User Acceptance (UA)'. Here, a simple two-step process is followed, with results reported in Section 6:

1. Review existing technology UA assessment methodologies. This is mainly based on literature review and the consortium's internal expertise.

2. Establishment of the specific technology UA assessment methodology to be applied in the COGITO project.

3 Existing Assessment Methodologies for Schedule, Cost, Quality, Safety and Energy Efficiency

In this section, we review existing construction performance assessment methodologies, with focus on:

- Schedule/workflow (Section 3.1);
- Cost (Section 3.2);
- Quality (Section 3.3);
- Safety (Section 3.4) and
- Energy efficiency and Carbon footprint of the construction process (Section 3.5).

In the case of the first four areas, the analysis covers the performance of construction projects in these areas, but also very importantly the performance of the processes, i.e. the effort, required to plan and monitor those areas. This is because COGITO aims to impact both aspects. In contrast, for energy efficiency the review only focuses on the performance of construction projects in that area, as the impact of COGITO in this area is only indirect, principally through schedule/workflow performance enhancement.

3.1 Assessment of Construction Project Scheduling Performance

Project scheduling performance has two parts: (1) the performance of the output schedule at planning stage; (2) the performance of the schedule-related processes, including scheduling at planning stage, and schedule monitoring at delivery stage. The following subsections investigate both separately.

3.1.1 Performance of Output Schedule

The performance of the output schedule at planning stage is essentially measured by the project ***Planned Duration (PD)***. PD should have two characteristics:

- be **short**: short PD is sought by clients as this enables them to receive their asset faster and therefore generate income faster and ultimately improve their competitiveness.

- be **achievable** (be **predictable**): the construction suffers heavily from delayed completion times. While delay can be the result of unforeseeable events (e.g. some weather events or patterns), the industry is arguably poor at setting schedules that are actually achievable. The resulting poor predictability of final project completion time negatively impacts the financial stability of construction companies (which is an important reason for the sector's very high rates of insolvency and bankruptcy). Construction companies with good track record in delivering projects on time are most likely to remain solvent, strive and secure more projects.

As discussed in Deliverable D2.1 [1] and detailed in [3] and [4], the project schedule results from the scheduling of each of the individual activities making up the project as defined in the Work Breakdown Structure (WBS) [5], and their sequencing. Therefore, a short and predictable project depends on the length and predictability of the individual activities, as well as the correctness and effectiveness of the sequencing. Focusing on the scheduling of individual activities, the duration is a function of: the quantity of work, the selected method and productivity of the resources allocated to deliver the work. With BIM technology, the quantity of work, formally referred as the Bill of Quantity (BoQ) can now be often calculated quite accurately from the BIM model. What remains challenging for planners is setting an adequate productivity value so that the duration estimation is reliable. Setting such a value is made difficult because it is not always easy to predict the conditions within which the work will be conducted (especially for works done in unpredictable environments, such as outdoors) [6]. These conditions as well as the performance of the supply chain (of all resources required to conduct an activity) impact productivity by either slowing or even by preventing some work. In fact, it is well established (especially by the Lean Construction community) that poor labour productivity in the industry is particularly the result of idle time, which is often the result of supply chain underperformance (within and to the construction site). Therefore, resource (labour or equipment) idle time can be measured in addition to activity time, as this can provide additional insight on the reasons for any observed performance.

Summarising the discussion above, the first two parts of Table 3-1 list Key Performance Indicators (KPIs) that can be used to measure the absolute schedule performance and schedule predictability performance [7] [8]. It should be highlighted here that time performance typically impacts cost performance, and therefore the KPIs that will be discussed later on cost performance will have some connection to the scheduling KPIs presented here. In fact, the Earned-Value Analysis (EVA) is a project monitoring method that integrates (and disentangles) the monitoring of both time and cost performance [9]. The EVA, presented in more detail in Deliverable D2.1 and discussed further in Section 3.2, does provide some schedule KPIs, but it will be shown that a number of these are not particularly useful.

3.1.2 Performance of Schedule-related Processes

The time performance of the process of planning a schedule is simply the time required for creating the schedule. This could be measured as an absolute value or as a value relative to the size of the project, e.g. the duration or budget of the project.

The time performance of the process of monitoring the delivery of the schedule is the time spent monitoring costs. This could also be measured as an absolute value or as a value relative to the size of the project. Here again, the resources involved are mainly labour, such as the cost of the corresponding work done by quantity surveyors and foremen. An indirect measure could also be considered, such as the frequency of progress reporting (a higher frequency suggesting a more effective process).

The third part of Table 3-1 lists those KPIs related to the performance of those schedule planning and monitoring processes.

The reader is reminded that the KPIs listed in Table 3-1 (and in similar tables in the following sub-sections of Section 2) include KPIs that are commonly used in practice in the construction industry as well as KPIs that may not be commonly measured. In Section 5, the KPIs that the consortium hopes to be able to employ in the context of the COGITO pilot sites are selected from this list based on criteria of measurability, collectability and comparability (see Section 5 for details).

Table 3-1: Potential KPIs for Scheduling

Duration	Description
Planned Project Duration	The duration of the entire project estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders). This can also be broken down per milestones. This may be measured relative to some main quantity (e.g. building square footage).
Actual Project Duration	The duration of the entire project measured once the project is completed. This can also be broken down per milestones. This may be measured relative to some main quantity (e.g. building square footage).
Planned Activity Production Rate / Productivity	The duration of an activity estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders), and measured relative to some quantity (e.g. m^3 of concrete).
Actual Activity Production Rate / Productivity	The duration of an activity measured once the activity is completed, measured relative to some quantity (e.g. m^3 of concrete).

Resource Non-Productive Time	The percentage of working time of a worker or piece of equipment that is non-productive (e.g. waiting).
Rework Duration	The duration of all reworks conducted over the project. This may be measured relative to the Project Duration.
Duration Predictability	**Description**
Project (Unit) Duration Predictability	The difference between the Planned Project Duration and Actual Project Duration. This may be measured relative to some main quantity (e.g. building square footage).
Project Duration Predictability Performance	The percentage of projects completed within X% of their Planned Duration [e.g. X = 0% or maybe 2%]
Activity Productivity Predictability	The difference between the Planned Activity Production Rate and the Actual Activity Production Rate.
Activity Duration Predictability Performance	The percentage of activities within a project that are completed within X% of their Planned Duration [e.g. X = 0% or maybe 2%]
Scheduling Processes (planning and monitoring)	**Description**
Duration of Project Scheduling	The time effort of scheduling activities. This may be measured relative to the project size (duration or cost)
Cost of Project Scheduling	The overall cost of resources (labour, tools, etc.) involved in scheduling. This may be measured relative to the project budget.
Labour Cost of Project Scheduling	The cost of labour involved in scheduling, possibly relative to the project budget. This may be measured relative to the project budget.
Duration of Progress Monitoring	The time effort of progress monitoring and reporting activities. This may be measured relative to the project size (duration or cost).
Cost of Project Progress Monitoring	The overall cost of resources (labour, tools, etc.) involved in progress monitoring and reporting. This may be measured relative to the project budget.
Labour Cost of Project Schedule Monitoring	The cost of labour involved in progress monitoring and reporting. This may be measured relative to the project budget.
Frequency of Progress Reporting	The frequency at which progress is reported for the whole project, and broken down per activity.

3.2 Assessment of Construction Project Costing Performance

Project cost performance has two parts: (1) the performance of the output budget at planning stage; (2) the performance of the cost-related processes, including budgeting at planning stage, and cost monitoring at delivery stage. The following subsections investigate both separately.

3.2.1 Performance of Output Budget/Cost

The performance of the output costing at planning stage is essentially measured by the project ***Budget***. The budget should have two characteristics:

- be **low**: the lower the cost, the more likely the contractor will secure the work and the client can utilise the saved funds to other purposes, which should ultimately improve their competitiveness.

- be **achievable** (be **predictable**): the construction suffers heavily from projects going over budget. While budget increase can be the result of unforeseeable events (e.g. unforeseen schedule delay - see Section 3.1.1; or sudden increase in material costs), the industry is arguably poor at setting budgets that are achievable. The resulting poor predictability of final project completion costs negatively impacts the financial stability of construction companies (which is an important reason for the sector's very high rates of insolvency and bankruptcy) as well as their clients. Construction companies with good track record in delivering projects on budget are most likely to remain solvent, strive and secure more projects.

As discussed in Deliverable D2.1 [1] and detailed in [3] and [4], the project budget results from the budgeting of each of the individual activities – aka Work Packages (WPs) – making up the project, as defined in the WBS [5]. Therefore, a low and predictable project budget depends on the level and predictability of the individual WP budgets. Focusing on the budgeting of individual activities, the budget (like the duration) is a function of: the quantity of work, the selected method and productivity of the resources allocated to deliver the work. With BIM technology, the quantity of work can now be often calculated quite accurately. The selected method defines the type of labour and equipment to be engaged in the activity, and the productivity of the resources defines how long they will be involved in the activity. Setting an adequate productivity value, so that the duration and cost estimations are reliable, is challenging. This is because it is not always easy to predict the conditions within which the work will be conducted (especially for works done in unpredictable environments, such as outdoor).

Overall, the costs incurred by the individual WPs mainly include:

- Labour;
- Equipment/Plant and Tools;
- Materials (including haulage).

In addition, the overall project costs will include:

- Overheads;
- Reserves and Contingencies.

The project management team will create Cost Accounts (CAs) to monitor those items. In order to be able to measure cost performance per WP – e.g. using the Earned Value Analysis (EVA) method [9] – such CAs should be created for each WP. Cost Account Variance (CAVAR) reports can then be generated during construction to compare planned and actual performance [1].

The Earned Value Analysis (EVA) is a project monitoring method that integrates (and disentangles) the monitoring of both time and cost performance [9]. Focusing on cost, the EVA method measures the Budgeted Cost of Work Performed (BCWP), or Earned Value, as well as the Actual Cost of Work Performed (ACWP) and the comparison of two enables an "apple-to-apple" comparison of planned and actual costs, in a way that is (somewhat) independent of schedule performance. The corresponding two performance metrics are:

- Cost Variance (CV):

$$CV = BCWP - ACWP$$

- Cost Performance Index (SPI):

$$CPI = \frac{BCWP}{ACWP}$$

If CV < 0 or CPI < 1, then the activity/project is under budget. If SV > 0 or SPI > 1, then the activity/project is over budget.

The SV and SPI values measure the activity/project's performance to date. They can also be used to estimate the duration and cost at completion. Various formulas can be used to get those estimations, depending on the assumptions made for the performance of the project from now until the end (will the cost performance remain the same or can it be anticipated to change?).

Summarising the discussion above, Table 3-2 lists Key Performance Indicators (KPIs) that can be used to measure the absolute budget performance and budget predictability performance [7] [8]. It is important to note that cost performance is impacted by schedule performance. Thus, some of the KPIs listed here will have some connection to the scheduling KPIs presented earlier. But, as discussed above, from a project monitoring viewpoint, the EVA method has the goal of dissociating schedule from cost performance, which is useful for root cause analysis and decision making.

3.2.2 Performance of Cost-related Processes

The cost performance of the process of budgeting is simply the cost of the resources involved in creating the budget. This could be measured as an absolute value or as a value relative to the size of the project. The resources involved mainly include the planners.

The cost performance of the process of monitoring the costs during construction is the cost of the resources involved in monitoring costs. This could also be measured as an absolute value or as a value relative to the size of the project. Here again, the resources involved are mainly labour, such as the cost of the corresponding work done by quantity surveyors and foremen. An indirect measure could also be considered, such as the frequency of cost reporting (a higher frequency suggesting a more effective process).

The last part of Table 3-2 lists those KPIs related to the performance of those cost planning and monitoring processes.

Table 3-2: Potential KPIs for budgeting

Budget	Description
Project budget (or Planned Project Cost)	The budget of the entire project estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders). It should distinguish direct costs and site and company overhead. This may be measured relative to some main quantity (e.g. building square footage).
Actual Project Cost	The cost of the entire project measured once the project is completed. This may be measured relative to some main quantity (e.g. building square footage)
Planned Activity Unit Cost	The budget of an activity estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders), measured relative to some quantity (e.g. m^3 of concrete). The budget may also be broken per cost category (labour, equipment and materials). Note that activities are also classified using job codes that categorise the type of activity.
Actual Activity Unit Cost	The cost of an activity measured once the activity is completed, measured relative to some quantity (e.g. m^3 of concrete). The unit cost may also be broken per cost category (labour, equipment and materials, subcontractors). Note that activities are also classified using job codes that categorise the type of activity.
Rework costs	The cost of all reworks conducted over the construction of the project. This may be measured relative to the Project Budget.
Budget predictability	**Description**
Project (Unit) Cost predictability	The difference between the Planned Project Cost (i.e. Project Budget) and the Actual Project Cost. This may be measured relative to some main quantity (e.g. building square footage).

	When using the EVA method, this is measured by CV or CPI.
Project Cost Predictability Performance	The percentage of projects completed within X% of their (planned) budget [e.g. X = 0% or maybe 2%]
Activity Unit Cost Predictability	The difference between the Activity Budget and the actual activity cost (obtained once construction is completed), measured relative to some main quantity (e.g. m^3 of concrete). When using the EVA method, this is measured by CV or CPI.
Activity Cost Predictability Performance	The percentage of activities actually completed within X% of their (planned) budget [e.g. X = 0% or maybe 2%].
Cost processes (planning and monitoring)	**Description**
Cost of Budgeting	The overall cost of resources (labour, tools, etc.) involved in budgeting, possibly relative to the project budget.
Labour Cost of Budgeting	The labour cost involved in budgeting, possibly relative to the project budget.
Cost of Cost Monitoring	The overall cost of resources (labour, tools, etc.) involved in monitoring and reporting cost performance, possibly relative to the project budget.
Labour Cost of Cost Monitoring	The labour cost involved in monitoring and reporting cost performance, possibly relative to the project budget.

3.3 Assessment of Quality Performance

Construction projects require rigorous Quality Assurance (QA) processes. In most cases, Project Managers and Quality Managers (QMs) have to follow regulatory standards and specifications set by the client.

As discussed in Deliverable D2.1 [1], constructed elements have to pass a quality control check and the outcome must be recorded and be reported to the QM and Project Manager, the client, and in some cases the local authorities too. Usually, these Quality Control (QC) activities require a surveyor to conduct visual inspections and/or employ various survey tools (total stations, levels, laser scanners, etc.) to verify all the necessary geometric measurements. In addition, material quality needs to be checked too, usually involving lab tests (either internal or outsourcing it).

Project quality performance has two parts: (1) the output quality of the construction works; and (2) the performance of the QA/QC processes. The COGITO solution does not intend to improve construction quality directly, but instead QA/QC processes, and more specifically QC processes.

3.3.1 Performance of Project

QC process performance impacts project performance by: (1) reducing the risk of bottlenecks that can delay projects; and importantly (2) reducing the occurrence of late-detected deficiencies (e.g. defects or out-of-tolerance situations) which would otherwise lead to disruptive late rework, with both time and cost implications. Therefore, avoiding deficiencies or detecting them early, through systematic and rapid QC, can help ensure projects are delivered on time and budget, i.e. improve schedule and budget predictability. The first part of Table 3-2 lists KPIs that could be considered for assessing the impact of QC on Project Duration Predictability and Project Cost Predictability.

3.3.2 Performance of QC Processes

As suggested above and also detailed in Deliverable D2.1 [1], QC processes, like any business process, require dedicated efforts. These have time and cost implications of their own. The second part of Table 3-2 lists KPIs that could be considered for assessing the performance of QC processes. Note, while they could be considered, no time-related KPI is suggested here. The reason is that QC activities are not always clearly scheduled and so the time allocated to QC activities may be hard to monitor. Cost is easier to monitor and can in fact be considered as a proxy to time performance.

Table 3-3: Potential KPIs for QC

QC impact on Schedule and Cost Predictability	Description
Number of Late-Detected Deficiencies	Number of late-detected deficiencies (i.e. deficiencies that are detected during activities subsequent to the one during which the components were constructed). The metric may be measured relative to the project size (e.g. budget).
Cost of Rework of Late-Detected Deficiencies	Cost of rework of late-detected deficiencies (i.e. deficiencies that are detected during activities subsequent to the one during which the components were constructed). The metric may be measured relative to the project budget.
Delay due to Rework of Late-Detected Deficiencies	Schedule delay, in days, due to the rework of late-detected deficiencies (i.e. deficiencies that are detected during activities subsequent to the one during which the components were constructed). The metric may be measured relative to the project duration.
QC process	**Description**
Cost of QC Activities	The cost of conducting all QC process activities (i.e. planning and monitoring of quality). It includes labour, tools, etc. The metric may be measured relative to the project budget.
Labour Cost of QC Activities	The labour cost of conducting all QC process activities (i.e. planning and monitoring of quality). The metric may be measured relative to the project budget.

3.4 Assessment of Construction Safety Performance

In construction safety, two major groups of indicators are traditionally used to assess safety performance, namely the lagging and leading indicators. **Lagging indicators** are based on past safety results and therefore, often provide no value in detecting or preventing safety hazards [10], whereas **leading indicators** are measures, conditions or events, that occur just before incidents, accidents or unsafe conditions happen and have predictive value [11]. For example, recording of the number of injuries is a lagging indicator, while the number of training hours or the number of safety inspections are leading indicators. The selection of relevant KPIs is essential since measuring as many indicators as possible does not lead to optimal safety performance. On the contrary, it is useful only to measure indicators that can be used for decision-making, such as the development of safety plan within a project [12].

3.4.1 Lagging indicators

Lagging indicators come with advantages and drawbacks. Lagging indicators are widely used measures in industry and given that they are based on the analysis of past events, are very accurate. However, looking in the past often provides no value in detecting or preventing safety hazards [10]. Furthermore, lagging indicators do not provide information about the causes of hazards and therefore, deciding on mitigation measures and corrective actions upon lagging indicators is not possible.

In practice, the safety lagging KPIs can be further classified in frequency rates and incident rates. Frequency rates illustrate the number of undesired events (e.g., injuries, fatalities) that happened in a given period of time by a standardised number of hours worked. Incident rates, not to be confused with incidence (meaning frequency), show the number of undesired events that happened in a given period of time by a standardised number of employees. The purpose of using standardised numbers in the calculation of safety KPIs, such as the 200,000 and 1,000,000 hours worked, is to produce numbers that are easy to comprehend and relate in practice. In the example of lost-time injuries (LTIs), meaning the events that result in fatality, permanent disability or time lost from work, a number of 0.0001 lost time injuries (LTIs) per hour over a period of 12 months with a total of 2 million hours worked is not as effective in interpretation as when it is calculated over the standardised period of 1,000,000 worked hours. This results in '5 lost time injuries for every million hours worked over a year', which is easier to comprehend. It is worth mentioning that the number of 200,000 work hours for example, refers to 100 full-time employees working 40 hours per week during 50 weeks in a year as defined by the U.S. Occupational Safety and Health Administration [13]. The first section of Table 3-4 lists commonly used lagging safety KPIs, adapted from [14].

3.4.2 Leading indicators

Leading indicators focus on mitigation measures to prevent hazards, which is reflected on how they are defined in the literature, such as in [15] where leading indicators are *"the quantity of safety management activities performed to prevent injuries*". Leading indicators come with significant advantages compared to lagging indicators. They allow for proactive changes before the occurrence of hazardous events, focusing on processes rather than results. Additionally, the approach of establishing proactive safety measures transforms the uncontrolled hazards to controlled risks that safety managers and key stakeholders can identify, evaluate and mitigate. When evaluation is done in real time, safety results can be further improved. However, in [10], the author argues that (real-time) leading indicators with modern sensing and actuating technologies can only improve safety performance given that safety measures are taken quickly enough. In addition to that, leading indicators measuring the quantity of safety management activities, even though important, do not necessarily reflect the actual safety record, and therefore, measuring the outcome of those activities against established goals is critical [16].

Leading indicators in construction can be classified as active and passive [17]. The difference between active and passive leading indicators is that the former typically refer to the quality of implementation of safety measures that change throughout the lifetime of the construction project (e.g., the frequency of pre-task safety meetings, degree of upper-management involvement), whereas the latter refer to actions often implemented before initiating the construction works and remain relatively unchanged throughout the project lifetime, such as the use of Personal Protective Equipment (PPE) or a comprehensive written safety plan [17].

In addition to the indicators that are traditionally measured in construction, indicators can be considered that attempt to track root causes. As highlighted by [18] and illustrated in Figure 3-1, one minor injury occurs after numerous at-risk behaviours and close calls, while serious injuries are even more rare. As serious injuries are considered by the scholars, cases that result to being unable to perform all normally assigned work (Restricted Work Case, RWC) or restrict one to return to work the day following the injury (Loss Workday Case, LWC), and cases that require treatment by professional medical personnel (Medical Treatment Case, MTC). The Close Call frequency rate measures the frequency of occurrence of close calls during the reporting period, whereas the At-Risk Behaviour frequency rate indicates how frequently unsafe behaviours occur that might lead to hazardous situations.

The second section in Table 3-4 summarises typical leading indicators identified by [17].

3.4.3 Performance of Safety Processes

Like in the previous section, safety processes, like any business process, require dedicated efforts. These have time and cost implications of their own. The third part of Table 3-4 lists KPIs that could be considered for assessing the performance of safety processes. Similarly to QC, no time-related KPI is suggested here because safety activities are not always clearly scheduled and so the time allocated to such activities may be hard to monitor. Costs are easier to monitor, in particular labour costs because it is better known which staff members are involved in safety processes. It must be noted that the process KPI 'Labour Cost of Safety Activities' relates to the leading safety KPI 'Staffing for safety'.

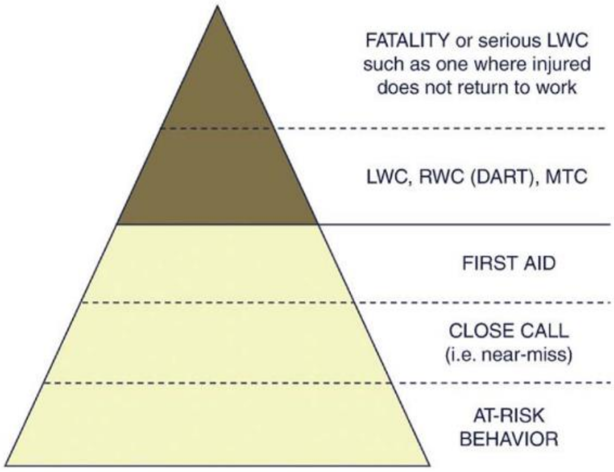


Figure 3-1: Safety pyramid and estimated ratios [18]

Table 3-4: Potential KPIs for Safety.

Lagging KPI	Description
Total case incident rate (TCIR)	The number of work-related injuries per 100 full-time workers during a one-year period.
Total Recordable Incident Rate (TRIR)	The number of work-related injuries per 100 full-time workers during a one-year period. (It is used interchangeably with TCIR)
Total Recordable Injury Frequency Rate (TRIFR)	The number of fatalities, lost time injuries, cases or substitute work and other injuries requiring medical treatment by a medical professional per million hours worked.
Total Recordable Case Frequency (TRCF)	A 12-month rolling average total recordable case frequency per 1 million man-hours. Man hours are based on a 12-hour working day or actual hours worked if recorded.
All Injury Frequency Rate (AIFR)	This is a measure of all reportable injuries - lost time injuries, restricted work injuries and medical treatment cases - per 200000 hours worked.
Medical Treatment Injury (MTI)	An injury or disease that resulted in a certain level of treatment (not first aid treatment) given by a physician or other medical personnel under standing orders of a physician.
Lost Time Injury (LTI)	A lost-time injury is a hazardous event that results in a fatality, permanent disability or time lost from work. It could be as little as one day or shift.
Lost Time Injury Frequency Rate (LTIFR)	The number of lost time injuries that occurred during the reporting period. Most companies choose to calculate LTIFR per 1 million man-hours worked.
Reportable Injury Frequency Rate (RIFR)	Records the number of incidents requiring medical treatment, divided by the number of hours worked within an accounting period, multiplied by 100,000.

Days Away, Restricted or Transferred (DART)	Measures workplace injuries and illnesses that result in time away from work, restricted job roles, or permanent transfers to new positions.
Severity Rate	Average of the number of lost days per recordable incident.
Close Call Frequency Rate	The frequency of occurrence of close calls per 1 million hours worked
At-risk Behaviour Frequency Rate	The frequency of occurrence of at-risk behaviours per 1 million hours worked
Leading KPI	**Description**
Upper-management involvement	The degree of upper-management commitment to safety aspects of worker safety and health
Training/orientation	The degree of providing training and orientation of jobsite hazards for skilled and unskilled workers.
Training performance	The range of scores (or marks) obtained by workers on training formative assessments.
Pre-task safety meeting	The frequency of pre-task safety planning conducted by both supervisors and workers as daily tasks to ensure that day-to-day activities are performed safely.
Safety inspections/observation	The frequency of safety inspection/observation to identify hazards or safety violation to ensure worker safety and health
Hazard and accident analysis	The frequency of safety hazard and accidents analysis reported and reviewed for construction process
Owner involvement	The degree of owner involvement in safety aspects
Safety record	The degree of reporting and maintaining accident records and safety performance records
Worker involvement	The degree of worker involvement in safety aspects, such as safety decisions and feedback to top management
Safety resource	The effort of the safety committee (e.g., supervisory, owner safety representative, and project leaders) in providing required safety resources
Staffing for safety	The number of certified safety representatives in the worksite
Written safety plan	A complete and comprehensive safety plan that guides project safety
Personal protective equipment (PPE)	The provision of the required PPE for all workers
Substance abuse	The frequency of random drug and alcohol tests to prevent substance abuse among workers
Incentives	The safety promotions and praise for workers with positive and safe work behaviour
Safety process	**Description**
Cost of Safety Activities	The cost of conducting all safety process activities (i.e. planning and monitoring of quality). It includes labour, tools, etc. The metric may be measured relative to the project budget.
Labour Cost of Safety Activities	The labour cost of conducting all safety process activities (i.e. planning and monitoring of safety). The metric may be measured relative to the project budget.

3.5 Assessment of Construction Energy and Carbon Footprint

Assessing the energy efficiency and the carbon footprint of the construction process is of increasing interest to construction companies due to the broader societal drive to reach “net zero carbon” and the corresponding commitment they make.

The consumed energy and respective carbon footprint over the life cycle of a building or infrastructure asset can be divided into: operational, embodied, and decommissioning parts. Within COGITO, only the embodied part will be taken into account in the energy and carbon footprint related KPI calculations [19].

Embodied energy is non-renewable energy required to build the asset as well as maintain it during its lifecycle. It includes energy used to acquire, process and manufacture the building materials and products, including any transportation related to these activities (indirect energy); energy used to transport building products to the site and construct the building (direct energy); and energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building (recurring energy).

Embodied Carbon footprint is the amount of carbon dioxide released to the atmosphere as a result of activities consuming the embodied energy, defined previously.

The reason for calculating the energy and carbon footprint separately, lies on the fact that an energy consuming activity does not necessarily means that it has a large carbon footprint and vice versa. Therefore, minimizing the overall energy consumption during construction (referred to as “construction process energy” below which is also captured as embodied energy) does not guarantee the reduction of its equivalent carbon emissions. Minimising construction process energy can be achieved by using the least energy intensive means and methods of construction. This is possible if the contractor, during pre-construction planning, has access to information regarding energy consumption during construction to identify activities that consume more energy and have larger carbon footprint respectively. The obtained information would help contactors focus on energy and carbon emissions intensive activities and develop energy efficient means and methods to minimize energy consumption and reduce their carbon footprint during construction.

As discussed in Sections 3.1 and 3.2, planning works for scheduling and budgeting requires the identification of all Work Packages (WPs) and for each WP, the materials, labour and equipment required for completing the WP (aka Activity). This information can be leveraged, not only to plan time and cost, but also estimate the direct embodied energy, including the energy contributed by the construction process. Table 3-5 gives an example of table that could be produced with the embodied energy estimated for each activity.

However, some sources of energy cannot be easily allocated to individual activities. These include the energy consumed for managerial activities, provision of welfare, etc. – which can be considered as “energy overhead” just like managerial costs are considered as cost overheads (see Section 3.2), but also energy consumed that serves numerous activities, such as generators that may provide energy across the construction site. It must however be noted that the latter should be avoided if possible and the energy consumed allocated adequately to the WPs that consume it. Table 3-6 gives an example of project-level energy consumption itemisation.

Table 3-5: Example of energy consumption estimations in tones per construction task.

Activity ID	Description	Labour Energy (GJ)	Equipment Energy (GJ)	Total Energy (GJ)	% of total
1.2.3.4	Bearing Wall	8,000	-	17,000	16%
1.3.2.4	Backfill mechanical	1,000	5,000	6,000	5%
4.2.3.1	Clear/Grub	2,000	7,000	9,000	8%

Table 3-6: Example of indirect energy consumption estimations in gigajoule (GJ).

Item	Energy Consumption (GJ)	% of total
Diesel generator	17,000	16%
Management team	10,000	14%
Security lights	9,000	8%

To assess the energy efficiency and equivalent carbon emissions of the construction project, the above two groups of energy consumptions and carbon footprints should be estimated along with the total energy budget and carbon footprint. These estimations will help identify the most energy demanding activities that could then be replaced with less energy demanding ones. For example, a task involving cast-in-place concrete might be more energy demanding than assembling on site precast concrete walls (considering the whole embodied energy).

Besides energy, carbon estimations should also be performed because the same amount of energy may be produced by less carbon intensive processes, in which case benefits could still be achieved without reducing energy consumption. As it is estimated for the energy consumptions, similar estimations can be performed for the carbon footprint of task-level activities and general indirect activities. Examples of carbon footprint estimations are presented in the following tables (Table 3-7 and Table 3-8).

Table 3-7: Example of carbon footprint estimations in tones per construction task.

Activity ID	Description	Labour carbon footprint (tones)	Equipment carbon footprint (tones)	Total carbon footprint (tones)	% of total
1.2.3.4	Bearing Wall	0.01	-	0.01	1%
1.3.2.4	Backfill mechanical	0.02	0.2	0.22	22%
4.2.3.1	Clear/Grub	0.02	0.1	0.12	12%

Table 3-8: Example of carbon footprint estimations for indirect activities in tones.

Item	Carbon footprint (tones)	% of total
Diesel generator	0.1	80%
Management team	0.02	16%
Security lights	0.01	8%

From the above discussion, Table 3-9 lists KPIs that could be employed to assess Energy Efficiency performance and Carbon footprint of the construction process.

Table 3-9: Potential KPIs for Energy Efficiency and Carbon Footprint.

Energy	Description
Activity Direct Energy	The sum of equipment and labour energy for accomplishing the given activity.
Direct Energy	Sum of all Activity Direct Energy
Activity Indirect Energy	Energy consumed for an activity supporting direct construction works (e.g. management office).
Indirect Energy	Sum of All Activity Indirect Energy
Total Energy	Sum of Direct Energy and Indirect Energy.
Project-level energy	**Description**
Activity Direct Carbon Footprint	CO2-equivalent emissions resulting for the operation of equipment and labour for accomplishing the given activity
Direct Carbon Footprint	Sum of all Activity Direct Carbon Footprint values
Activity Indirect Carbon Footprint	CO2-equivalent emissions resulting from an activity supporting direct construction works (e.g. management office).
Indirect Carbon Footprint	Sum of all Activity Indirect Carbon Footprint values
Total Carbon Footprint	Sum of Direct Carbon Footprint and Indirect Carbon Footprint.

4 Relevant EU projects

A review of prior EU-funded projects is carried out in this section in order to identify performance assessment methodologies and possible benchmarks that could be leveraged by COGITO. Table 4-1 lists projects that were identified with relevance to Digital Twinning and the COGITO project's focus. Multiple current H2020 research projects use IT models to represent building related data. Out of these projects, five are focused on BIM concepts: BIMERR, SPHERE, STEPUP, BIM2TWIN and ARTWIN. Four out of these five, introduce also the concept of Digital Twin into their investigations.

These projects are focused on different domains. Two of them (BIM2TWIN and SPHERE) are concentrated on construction management, while BIMERR and STEPUP focus on building renovation and ARTWIN is designed aiming at the inclusion of augmented reality devices to the digital twin (BIM, construction site, factory facility, etc.) generation and maintenance.

4.1 BIMERR[1]

The main focus of the BIMERR project is the development of an ICT-enabled Renovation 4.0 framework to support the renovation stakeholders during the renovation process of existing buildings, from concept to delivery. To achieve this, BIMERR integrates a number of components, including:

- A BIM Management Platform to manage enhanced digital models of existing buildings that go beyond geometrical information.
- An ontological framework which supports interoperability and data links to other data sources.
- An innovative Renovation Decision Support System (RenoDSS) which should enable AEC stakeholders in charge of design & planning to quantitatively evaluate the available options across several key target metrics.

In BIMERR, KPIs are classified into three categories: Cost/Time, Energy and User Acceptance and include:

- Energy related measures that reflect to the energy footprint before and after renovation (energy demand, energy consumption).
- Cost and time related measures that refer to the installation as well as the maintenance and operation facility before and after the renovation measures.
- Environmental measures to assess the environmental and sustainability impact of the renovation plans (Greenhouse gas emissions, water and air pollution).
- Well-being metrics referring to user comfort which act as feedback to renovation decisions.

4.2 SPHERE[2]

SPHERE aims to bring together under the same platform two research trends:

- the Digital Twin Concept (involving not only the Design and Construction of a Building but also its Manufacturing and the Operational phases); and
- the ICT Systems of Systems infrastructure based on the Platform as a Service (PaaS) concept to allow large scale integration and synchronization of data, information and knowledge.

The SPHERE platform will facilitate improvements in the energy performance of buildings from the start of the construction process. In addition, it will also reduce ***time, costs, and the environmental impact of construction processes and improve the indoor environment due to a seamless integration of each meaning dimension and respective stakeholders within the platform***.

[1] https://bimerr.eu/
[2] https://sphere-project.eu/

In summary, twinning this virtual information model with the reality helps decision-making during each phase of the whole building's lifespan, ***increases collaboration and reduces inefficiencies, while improving the energy efficiency and reducing time and costs***. In numbers (KPIs), it should help achieve 15% reduction in residential buildings' energy demand during the operational phase, 25% reduction in construction time and 25% reduction in CO_2 and other GHG emissions in buildings' construction and operational phases.

4.3 STEPUP[3]

StepUP aims to develop a new process for deep renovation for decarbonisation, to minimise performance gap, reduce investment risk and maximise value. StepUP uses BIM & Digital Twins to Optimise Renovation and Drive Zero-Carbon. The Key Performance Indicators (KPIs) developed for the StepUP project represent the financial, energetic and qualitative values of the project, and are intended to help evaluate the overall renovation improvement. In StepUp KPIs are classified into three categories: social, environmental and financial.

Social KPIs include metrics related to the user wellbeing such as thermal, acoustic and visual comfort. Environmental KPIs are related to global warming potential measures and energy quantities from renewable resources. Finally, the financial KPIs are referring to the installation and maintenance costs of the renovation works, the change in the property value from the renovation and the savings in the energy bills. A complete list of the project's KPIs can be found at StepUP KPI list .

4.4 BIM2TWIN[4]

BIM2TWIN, which is close in concept to COGITO, aims to build a Digital Building Twin (DBT) platform for construction management that implements lean principles to **reduce operational waste of all kinds, shortening schedules, reducing costs, enhancing quality and safety and reducing carbon footprint**. Applications include monitoring of schedule, quantities & budget, quality, safety, and environmental impact. It supports a closed loop Plan-Do-Check-Act mode of construction and an extensive set of construction management applications.

The key research features of BIM2TWIN are:

- Digital collaboration among project stakeholders to advance industry standards, methods and best practices.
- Grounded conceptual analysis of data, information and knowledge in the context of DBTs, which underpins a robust system architecture.
- A common platform for reality data acquisition and complex event processing to interpret multiple monitored data streams from construction site and supply chain to establish real-time project status and condition in a Project Status Model (PSM).
- Exposure of the PSM to a suite of construction management workflow applications through an easily accessible application programming interface (API) and directly to users through a visual information dashboard.
- Applications include monitoring of **schedule, quantities & budget, quality, safety, and environmental impact.**

4.5 ARTWIN[5]

The ARtwin project aims to provide Construction 4.0 with an ARCloud platform that meets the industry's needs, offering three key services: (i) an accurate and robust 3D registration for any AR device in large-scale and dynamic environments, enabling to present relevant information to workers at the right time and place; (ii) reduction of the difference between the physical and digital world by continuously maintaining the Digital Twin/BIM model

[3] https://www.stepup-project.eu/
[4] https://bim2twin.eu/
[5] https://artwin-project.eu/

based on vision sensors located in the factory or on construction sites; and (iii) display of complex 3D augmentations on any AR device by remotely rendering them in the cloud with ultra-low-latency.

The ARtwin platform will account for the available technological capabilities and infrastructure of the user, enabling optimal and **cost-effective service delivery** and seamless high-resolution AR experiences across different devices. The project aims at **increasing the productivity and flexibility in the construction design, as well at improving the product quality and reducing costs**.

The ARtwin platform will offer the following services:

- Unified global map
- Localisation for AR devices
- 3D Digital Twin/BIM update
- AR remote rendering

4.6 BIMprove[6]

The BIMprove project aims to improve the European construction industry by providing a dynamic digital system that uses Digital Twin Technology for construction sites. The main objectives of BIMprove are: (i) a significant reduction in costs, (ii) a better use of resources and (iii) a reduction in the number of accidents on construction sites. The core of the BIMprove platform is a cloud-based, data integration service, where the information is exchanged, and data processing is possible through modular interfaces (APIs) that allow to add, remove, and update information in the supported layers (Digital Twin, Analytics, Safety, Cost, Scheduling and BIM layers).

The BIMprove platform will support several aspects in construction sites, including planning, construction, operation, renovation, and demolition. The expected results of the BIMprove project (KPIs) include:

- To increase scheduling forecast capacity (20%);
- To reduce costs in construction projects (20%);
- To make industry less exposed to labour accidents.

4.7 ASHVIN[7]

The ASHVIN project aims at enabling the European construction industry to improve its productivity, to reduce cost and to ensure safe work conditions The project provides a proposal for a European digital twin standard, including an open-source digital twin platform integrating IoT and image technologies, and a set of tools to apply such platform, with the goal of **improving capabilities and accuracy, reducing construction costs, reducing the number of on-site accidents, and increasing resource efficiency.**

The ASHVIN platform aims to be interoperable with a wide range of design and engineering applications, which will allow to represent as-designed models, as well as a to continuously synchronize between the as-designed and the as-built models.

The ASHVIN project aims at offering the following services:

- Means to fuse video data and sensor data;
- Integration of geo-monitoring data;
- Multi-physics simulation methods for digital representing the behaviour of a product;
- Evidence-based engineering methods to design for productivity and safety;
- 4D simulation and visualization methods of construction processes;
- Lean planning process supported by real-time data.

[6] https://www.bimprove-h2020.eu/
[7] https://www.ashvin.eu/

4.8 TWIN-CONTROL[8]

Twin-control project aims to develop a simulation system for machine tools and machining processes. It integrates the different aspects that affect machine tool and machining performance, including lifecycle concepts, providing better estimation of machining performance than single featured simulation packages and improving the productivity of manufacturing processes. This simulation system will provide a more realistic performance of the models, which leads to a more accurate estimation.

Additionally, the simulation systems will allow direct control of the process through monitoring to improve the performance of the manufacturing process by controlling component degradation and optimize maintenance actions.

The project aims at achieving the following results (KPIs):

- A reduction of time to get machine working as designed (10% time and cost reduction);
- A reduction of time to get process working as designed (20% time and cost reduction);
- Getting a first time-right part manufacturing (75%) of all new processes;
- An improvement of process performance trough model-based control (increase of 1-2% in machine up-time);
- The reduction of energy consumption (25-50%);
- An improvement of machine reliability and increase machine up-time due to a proactive maintenance (2-4.5%);
- Reduction of machine tool life cycle costs (15%) with a reduction of O&M costs in the range of 25% for manufacturing system and process.

4.9 Analysis

These projects use different metrics to assess performance. In some projects, like STEPUP, these KPI metrics have been published, while in others the KPIs can only be inferred by the project description. In a broad sense, six KPI categories (Cost, Delivery Time, Health and Safety, Energy, Environment and Well-being) can be identified and their adoption in the eight aforementioned projects is presented in Table 4-1.

In COGITO, performance metrics from five of those six categories will be adopted (all but well-being), to assess the performance of a construction project in a multifaceted manner, to cover all of its aspects and to highlight the benefits of digitization in real-world case studies. This will accelerate the digitization of future construction projects and facilitate the adoption of advanced ICT-based solutions, which will enable multi-objective optimization techniques applied on these processes in a fast and efficient manner.

The setup of the final KPI list in WP8 will trigger another review of the presented related EU projects at their current future state, to do comparisons of COGITO's performance with respect to these projects and draw final conclusions.

Table 4-1: EU-funded projects related to Digital Twinning and the COGITO project, and the areas where they aim to deliver improvements (by measuring KPIs).

Project / KPIs	Cost	Delivery Time	H&S	Energy	Environment	Well-being
BIMERR	√	√		√	√	√
SPHERE	√	√		√	√	√
STEPUP	√			√	√	√

[8] https://twincontrol.eu/

Project / KPIs	Cost	Delivery Time	H&S	Energy	Environment	Well-being
BIM2TWIN	√	√	√		√	
ARTWIN	√	√				
BIMprove	√		√	√	√	
ASHVIN	√		√	√		
TWIN-CONTROL	√	√		√		

5 COGITO Assessment Methodology for Schedule, Cost, Quality, Safety and Energy Efficiency

In this section, we report the KPIs and measurement methods that have been selected by the COGITO consortium for assessing the impact of the COGITO solution. Keeping user acceptance (UA) aside, the selection of the time, cost, quality, safety and energy KPIs is a compromise between (1) the assessment requirements; and (2) a preliminary assessment by the industrial partners of their capacity to measure them. It must be noted that the relevance and usability of the selected KPIs in the context of the COGITO pilot sites will be revisited later in the project, as more information about the selected sites will become available.

A three-step process was used to select the COGITO KPIs:

1. Production of an initial list of KPIs by the technical partners based on: (1) the knowledge of the main impacts of their tools that should be measured and their knowledge of construction; (2) initial discussions and input obtained through the workshops and questionnaires established as part of the COGITO task T2.1 - Elicitation of Stakeholder Requirements (see deliverable D2.1 [1]).

2. Review of the preliminary list of KPIs by the industry partners to assess *measurability*, *collectability* (in general or specifically to the selected pilot sites) and *comparability* (in relation to baselining). This review was conducted through a dedicated workshop that included both pilot site and technical partners, as well as through offline analysis by additional experts within the pilot site partner organisations.

3. The reviews were then collated and analysed to issue a first list of COGITO KPIs alongside suggestions regarding their calculation/measurement methods.

It must be noted that a significant number of the selected KPIs are already established in the construction industry and tracked by construction companies. Others may either require the use of new bespoke measurements or can be readily inferred from already measured KPIs. This is particularly the case for all KPIs related to the work of the management team (e.g., scheduling and cost planning and monitoring). Besides, some of the selected KPIs may not be measurable within the lifetime of COGITO but should be measurable within a short period (i.e., within maximum a year) after the completion of COGITO.

Baselining methodology is necessary to support the before-vs-after comparison. A corresponding discussion is provided for the major KPIs related to the five areas of project time, cost, quality, and safety, and energy. It is worth noting here that the COGITO project is allocating 9 months for ‘COGITO Tools Roll-Out & Deployment for Demonstration & Validation Activities’ (T8.3) and ‘Demonstration of COGITO Tools on Construction Projects’ (T8.4), with an additional 5 months prior to those for ‘COGITO ICT System Pre-Validation’ (T8.2). Considering the fact that deployment should occur at three pilot sites (one for pre-validation and two for validation) and challenges may arise (e.g. additional resource commitments from the industry partners required to employ the COGITO solution), it is reasonable that data collected for measuring a number of the selected KPIs can be collected for no more than a few months at each site, and most likely much less (e.g. 1 month) when dedicated sensing systems need to be deployed at one and subsequently the other site (e.g. IoT technology for resource location tracking). For some parts of the assessment, this will also require measuring KPIs when employing current practice on site (i.e., without employing any COGITO tool) prior to measuring them when employing the COGITO solution. However, more details about the validation activities cannot be provided at this time because implementation will depend on the pilot sites which remain to be confirmed and for which further information will need to be obtained (including the likely construction progress by M25 when T8.2 starts). Those details will thus be reported in WP8 deliverables, such as D8.4 ‘Report on the COGITO demonstration activities’.

The COGITO project seeks to develop solutions to TRL 6 (‘Technology demonstrated in industrially relevant environments in the case of key enabling technologies’). The pre-validation and validation activities will provide the opportunity to test the tools using real data and in relevant environments, and the KPIs selected here will allow to perform a comprehensive evaluation of the tools to inform further development for testing to higher TRL levels.

The proposed list of KPIs are presented in the five sub-sections 5.1 to 5.5 (and corresponding Table 5-2 to Table 5-6). For each KPI, the following information is provided:

- ***ID***, the unique ID of the KPI for unambiguous referencing;
- ***Name***;
- ***Description***, to help clarify why this specific KPI is important in the evaluation framework of COGITO;
- ***Units*** of the KPI measure***;***
- A short explanation of the ***Calculation Method*** that shall be used to measure it.
- An estimation of the ***Ease of Calculation*** of that KPI in practice. This estimation was made by the consortium based on the current practice of the industry partners and any relevant information pertaining to the pilot sites (which is limited at the time of writing this document). Here, a 5-point scale is used with descriptions in Table 5-1. Note that the level '1' is not used in the following KPI tables because this level was used to reject potential KPIs.

Table 5-1: The scale employed to estimate the Easer of Calculation of the proposed list of COGITO KPIs.

Value	Description
1	Not measured by the industry partners and not measurable; (in a few cases, this value was also used for KPIs that were considered redundant or unnecessary).
2	Not measured by the industry partners and some indirect measurement method can be considered.
3	Not measured by the industry partners, but some direct measurement method can be introduced (e.g. using a tool being developed in COGITO).
4	Some part of the calculation may be easily obtained, but others may be harder to obtain (and this may vary from project to project).
5	Routinely measured by the industry partners.

Each submission also includes a short discussion of the methodology that will be followed to collect the data necessary to apply the proposed KPI calculation methods when employing the COGITO solution and when employing current practice (i.e. baselining).

5.1 Scheduling Assessment

Table 5-2 summarises the KPIs for schedule, schedule predictability and scheduling processes (planning and monitoring) to be considered in COGITO, following the initial analysis by the technical and pilot site partners.

Assessment Methodology and Baselining:

Most of the KPIs are considered easy to assess using current project practice and so can easily be measured for current practice and when employing the COGITO solution on the pilot sites. It is nonetheless noteworthy that the performance of scheduling processes (and as will be seen later other indirect works) is not explicitly tracked. However, initial discussions with the pilot site partners suggest that KPI-SC-11 may be calculated as an estimated percentage of the project overhead costs. The comparison with the baseline would then require estimating the percentages for current practice and when employing the COGITO solution.

5.2 Cost Assessment

Table 5-3 summarises the budgeting, budget predictability and costing processes (planning and monitoring) KPIs to be considered in COGITO, following the initial analysis by the technical and pilot site partners.

Assessment Methodology and Baselining:

The KPIs mainly match corresponding scheduling KPIs in Table 5-2, and therefore the same analysis can be made about them: Most of the KPIs are considered easy to assess using current project practice and so can easily be measured for current practice and when employing the COGITO solution on the pilot sites. It is nonetheless noteworthy that, similarly to scheduling processes, the performance of costing processes is not explicitly tracked. However, initial discussions with the pilot site partners suggest that KPI-CO-10 may be calculated as an estimated percentage of the project overhead costs. The comparison with the baseline would then require estimating the percentages for current practice and when employing the COGITO solution.

5.3 Quality Control Assessment

As discussed in Section 3.3, the COGITO solution focuses on improving the QC process and its capacity to prevent missing quality deficiencies (that can result in highly negatively impactful late reworks).

Table 5-4 summarises the Quality Control KPIs to be considered in COGITO, following the initial analysis by the technical and pilot site partners.

Assessment Methodology and Baselining:

The methodology and baselining method for Quality Control assessment is challenging. Aside for KPI-QC-1, the other KPIs are not easily measured in construction, because not already explicitly tracked by construction companies.

KPI-QC-2 and KPI-QC-3 may be measurable by manually looking at work orders, or bespoke monitoring may be required for specifically monitoring this. In addition, for KPI-QC-3, there is the need to know whether the rework falls on the schedule's Critical Path, which may need discussions with site managers to figure out.

Regarding KPI-QC-4, similarly to the corresponding Schedule and Cost KPIs, this is not measured explicitly in most projects. However, it may be calculated as an estimated percentage of the project overhead costs. The comparison with the baseline would then require estimating the percentage for current practice and when employing the COGITO solution.

5.4 Safety Assessment

Table 5-5 summarises the Safety KPIs to be considered in COGITO, following the initial analysis by the technical and pilot site partners. The list currently contains 20 KPIs, which is somewhat larger than the other areas of time, cost, energy efficiency and quality. However, a number of lagging KPIs, in particular, are related to each other and are unlikely to be considered altogether during validation. The selection of the most suitable ones will be made once more knowledge is available about However the select pilot sites and the safety-related data that will be recorded on them.

Assessment Methodology and Baselining:

As mentioned above, the selected KPIs include several established lagging and leading indicators that must be reported by law, and so are already measured by construction companies across Europe. These will thus be captured easily for current practice and when employing the COGITO solution.

However, it is also proposed to measure safety indicators (considered as lagging indicators) that focus on the root causes of *close calls* and *at-risk behaviour*. These are not normally measured (mainly due to lack of suitable technology), but tools developed as part of COGITO should support their measurement. Therefore, bespoke measurement of those KPIs using the COGITO solution will have to be planned for both current work practice (baseline) and when employing the COGITO solution.

Furthermore, to assess safety awareness through continuous safety training and advanced construction site monitoring, it is possible evaluate the *safety awareness and behaviour scores* [20]. While the impact of this may be hard to measure, the principle of linking training performance to safety performance could at least be demonstrated.

5.5 Energy and Carbon Footprint Assessment

As discussed in Section 3.5 the energy efficiency and carbon footprint assessments within COGITO will be performed taking into account only the consumed energy and equivalent CO_2 emissions related to the on-site construction phase of a project without considering its operation and decommission phases.

Table 5-6 summarises the Energy Efficiency KPIs (energy and carbon footprint) to be considered in COGITO, following the initial analysis by the technical and pilot site partners.

Assessment Methodology and Baselining:

As summarised in the column 'Calculation Method' of Table 5-6, calculating energy consumed by and carbon emissions resulting from activities is challenging. Generally, calculation of the energy (and carbon footprint) will be estimated per unit of activity time, and the final values calculated by multiplying those values by the duration of the activity. Productivity gain measurements (calculated by comparing the KPI-SC-4 values for the baseline context and when using the COGITO solution) would then be converted into energy (and carbon footprint) reductions.

Table 5-2 – Proposed COGITO KPIs for Scheduling.

KPI	Name	Definition/Description	Units	Calculation Method	Ease of Calculation
Schedule					
KPI-SC-1	**Planned Project Duration**	The duration of the project estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders). This can be broken down per milestone. This may be measured relative to some main quantity (e.g. building square footage).	Days (or days/unit)	Easily extracted from the construction schedule produced at planning stage. Adjustment for change orders should be obtainable during construction because these are a matter of livelihood. Nonetheless, some difficulties may arise to capture and allocate those exactly.	4
KPI-SC-2	**Actual Project Duration**	The duration of the project measured once the project is completed. This can also be broken down per milestone. This may be measured relative to some main quantity (e.g. building square footage).	Days (or days/unit)	Easily obtained from the recorded start and completion dates.	5
KPI-SC-3	**Planned Activity Production Rate / Productivity**	The duration of an activity estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders), and measured relative to some unit quantity of work (e.g. m^3 of concrete).	Days/unit	Activity durations at the end of the planning stage are easily obtained from the schedule produced then. Adjustment for change orders should be obtainable during construction because these are important, especially if they can be parts of claims for project extensions.	3-4

				Nonetheless, some difficulties may arise to capture and allocate those exactly.	
KPI-SC-4	**Actual Activity Production Rate / Productivity**	The duration of an activity measured once the activity is completed, measured relative to some unit quantity (e.g. m^3 of concrete).	Days/unit	This is recorded through the issue of work orders and reporting of activity completions.	5
KPI-SC-5	**Resource Non-Productive Time**	The percentage of working time of a worker or piece of equipment that is non-productive (e.g. waiting).	%	This is currently not tracked at all, because it is hard. However, COGITO is proposing to introduce some location/motion tracking sensors to measure productive time (and thus non-productive time). This technology would have to be deployed on operations conducted using normal practice (i.e. without COGITO), maybe during pre-validation.	3
KPI-SC-6	**Rework Duration**	The duration of all reworks conducted over the project. This may be measured as a percentage of the Project Duration.	Days (or %)	Unless rework arises from a client-led change order, it is typically not systematically tracked. So, this would require bespoke measurement, e.g. through manual review of work orders or use of dedicated job codes.	2
Schedule Predictability					
KPI-SC-7	**Project Duration Predictability**	The difference between the Planned Project Duration and Actual Project Duration. This may be measured relative to some main quantity (e.g. building square footage).	Days (or days/unit)	= KPI-SC-1 - KPI-SC-2 (possibly divided by main quantity, e.g. building square footage)	5
KPI-SC-8	**Project Duration Predictability Performance**	The percentage of projects completed within X% of their Planned Duration [e.g. X = 10%]	%	= KPI-SC-7 / KPI-SC-1 is the measurement of the delay in completion of the project relative to the planned project duration.	5

				Given this measure, this new KPI can be easily calculated over many projects.	
KPI-SC-9	**Activity Productivity Predictability**	The difference between the Planned Activity Production Rate and the Actual Activity Production Rate.	Days/unit	= KPI-SC-3 - KPI-SC-4	5
KPI-SC-10	**Activity Duration Predictability Performance**	The percentage of activities within a project that are actually completed within X% of their Planned Duration [e.g. X = 10%]	%	= KPI-SC-9 / KPI-SC-3 is the ratio of the difference between actual and planned productivity by planned productivity. Given this measure, this new KPI can be easily calculated over many activities.	5
Scheduling Process					
KPI-SC-11	**Labour Cost of Project Scheduling activities (planning and monitoring)**	The cost of labour involved in scheduling (planning and monitoring).	€ (or %)	This is not measured explicitly in projects. But, it corresponds to a portion of the time of the project management team. So, this may be calculated as a percentage of the project overhead.	2

Table 5-3 – Proposed COGITO KPIs for Cost.

KPI	Name	Definition/Description	Units	Calculation Method	Ease of Calculation
Budget					
KPI-CO-1	**Project budget (or Planned Project Cost)**	The budget of the project estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders). It should distinguish direct costs and site and company overhead. This may be measured relative to some main quantity (e.g. building square footage).	€ (or €/unit)	Easily extracted from the construction budget produced at planning stage. Adjustment for change orders should be obtainable during construction because these are a matter of livelihood. Nonetheless, some difficulties may arise to capture and allocate those exactly.	4
KPI-CO-2	**Actual Project Cost**	The cost of the project measured once the project is completed. This may be measured relative to some main quantity (e.g. building square footage).	€ (or €/unit)	Easily obtained from the costs until completion	5
KPI-CO-3	**Planned Activity Unit Cost**	The budget of an activity estimated at the end of the planning stage, prior to construction starts, but adjusted for viable change orders (e.g. client change orders), measured relative to some quantity (e.g. m^3 of concrete). The budget may also be broken per cost category (labour, equipment and materials, subcontractors).	€/unit	Activity budgets (broken down by cost category) at the end of the planning stage are easily obtained from the budget produced then. Adjustment for change orders should be obtainable during construction because these are a matter of livelihood. Nonetheless, some difficulties may arise to capture and allocate those exactly. Note that activities are also classified using job codes that categorise the type of activity.	4

KPI-CO-4	**Actual Activity Unit Cost**	The cost of an activity measured once the activity is completed, measured relative to some quantity (e.g. m^3 of concrete). The unit cost may also be broken per cost category (labour, equipment and materials, subcontractors).	€/unit	This is recorded through the issue of work orders and reporting of activity completions and equipment usage tracking forms. Note that activities are also classified using job codes that categorise the type of activity.	5
KPI-CO-5	**Rework costs**	The cost of all reworks conducted over the construction of the project. This may be measured relative to the Project Budget.	€ (or %)	Unless rework arises from a client-led change order, it is typically not systematically tracked. So, this would require bespoke measurement, e.g. through manual review of work orders or use of dedicated job codes.	2
Budget Predictability					
KPI-CO-6	**Project Cost predictability**	The difference between the Planned Project Cost (i.e. Project Budget) and the Actual Project Cost. This may be measured relative to some main quantity (e.g. building square footage).	€ (or €/ unit) CV (€) CPI (unitless)	= KPI-CO-1 - KPI-CO-2 When using the EVA method: = CV, or = CPI (possibly divided by main quantity, e.g. building square footage).	5
KPI-CO-7	**Project Cost Predictability Performance**	The percentage of projects completed within X% of their (planned) budget [e.g. X = 10%]	%	= KPI-SC-6 / KPI-SC-1 is the measurement of the overspending (or underspending) of the project relative to the budget. Given this measure, this new KPI can be easily calculated over many projects.	5
KPI-CO-8	**Activity Unit Cost Predictability**	The difference between the Planned Activity Unit Cost and the Actual Activity Unit Cost (obtained once construction is completed).	€/unit	= KPI-SC-3 - KPI-SC-4 When using the EVA method = CV divided by quantity (e.g. m^3 of concrete) = CPI	5

KPI-CO-9	**Activity Unit Cost Predictability Performance**	The percentage of activities completed within X% of their (planned) budget [e.g. X = 0% or maybe 2%].	%	= KPI-SC-8 / KPI-SC-3 is the ratio of the difference between actual and planned activity unit costs by planned unit cost. Given this measure, this new KPI can be easily calculated over many activities.	5
Cost Processes					
KPI-CO-10	**Labour Cost of Project Cost Activities (planning and monitoring)**	The cost of labour involved in budgeting and cost monitoring. So, this may be calculated as a percentage of the project overhead.	€ (or %)	This is not measured explicitly in projects. But, it corresponds to a portion of the project overheads. So, this may be calculated by estimating the percentage of the project overhead that should represent the effort put on these activities.	2

Table 5-4 – Proposed COGITO KPIs for Quality Control.

KPI	Name	Definition/Description	Units	Calculation Method	Ease of Calculation
Impact of QC on Project Performance					
KPI-QC-1	Number of Late-Detected Deficiencies[9]	Number of late-detected deficiencies[9]. The metric may be measured relative to the project size (e.g. budget).	Deficiencies	Late-detected deficiencies, and their potential corresponding rework, are typically not tracked explicitly. This would require setting job codes specifically for this type of work so that work orders (which are used to track corresponding costs and durations) can be retrieved and analysed. For the third KPI (i.e. delay), there is however the additional challenge of not knowing if the work described in a work order is on the critical path.	4
KPI-QC-2	Cost of Rework of Late-Detected Deficiencies[9]	Cost of rework of late-detected deficiencies[9]. The metric may be measured relative to the project budget.	€ (or %)		3
KPI-QC-3	Delay due to Rework of Late-Detected Deficiencies[9]	Schedule delay due to the rework of late-detected deficiencies[9]. The metric may be measured relative to the project duration.	Days (or days/days)		2
QC Processes					
KPI-QC-4	Labour Cost of QC Activities	The labour cost of conducting all QC process activities (i.e. planning and monitoring of quality) The metric may be measured relative to the project budget.	€ (or %)	This is not measured explicitly in projects. But, it corresponds to a portion of the project overheads, alongside some portion of the direct costs. So, this may be calculated by estimating those percentages.	2

[9] *Late-detected deficiencies* are deficiencies that are detected during activities subsequent to the one during which the components were constructed)

Table 5-5 – Proposed COGITO KPIs for Safety.

KPI	Name	Definition/Description	Units	Calculation Method	Ease of Calculation
Safety Lagging KPIs					
KPI-SA-1	**Lost Time Injury Frequency Rate (LTIFR)**	The number of lost time injuries that occurred during the reporting period. Most companies choose to calculate LTIFR per 1 million man-hours worked.	Lost time injuries / 1,000,000 man-hours	Already tracked by one or both pilot site partners (or data is available and could be tracked)	5
KPI-SA-2	**Total case incident rate (TCIR)**	The number of work-related injuries per 100 full-time workers during a one-year period.	Injuries / 100 worker-years	Not explicitly monitored, tracked and report. However, the data may be available for calculation.	4
KPI-SA-3	**Total Recordable Injury Frequency Rate (TRIFR)**	The number of fatalities, lost time injuries, cases or substitute work and other injuries requiring medical treatment by a medical professional per million hours worked.	Recordable injuries / 1,000,000 man-hours	Not explicitly monitored, tracked and report. However, the data may be available for calculation.	4
KPI-SA-4	**Total Recordable Case Frequency (TRCF)**	A 12-month rolling average total recordable case frequency per 1-million-man hours. Man hours are based on a 12-hour working day or actual hours worked if recorded.	Cases / 1,000,000 man-hours	Not explicitly monitored, tracked and report. However, the data may be available for calculation.	4
KPI-SA-5	**All Injury Frequency Rate (AIFR)**	This is a measure of all reportable injuries - lost time injuries, restricted work injuries and medical treatment cases - per 200,000 hours worked.	Injuries / 200,000 man-hours	Not explicitly monitored, tracked and report. However, the data may be available for calculation.	4

KPI-SA-6	**Medical Treatment Injury (MTI)**	An injury or disease that resulted in a certain level of treatment (not first aid treatment) given by a physician or other medical personnel under standing orders of a physician.	Medical treatment injuries	Not explicitly monitored, tracked and report. However, the data may be available for calculation.	4
KPI-SA-7	**Reportable Injury Frequency Rate (RIFR)**	Records the number of incidents requiring medical treatment, divided by the number of hours worked within an accounting period, multiplied by 100,000.	Reportable injuries / 1,000,000 man-hours	Not explicitly monitored, tracked and report. However, the data may be available for calculation.	4
KPI-SA-8	**Severity Rate**	Average of the number of lost days per recordable incident.	Days / incident	Not explicitly monitored, tracked and report. However, the data may be available for calculation.	4
KPI-SA-9	**Close Call Frequency Rate**	The frequency of occurrence of close calls per 1 million hours worked	Close calls / 1,000,000 man-hours	Using the IoT+DT solution of COGITO, occurrences can be measured. Baselining will require using the IoT+DT solution with normal practice (i.e. without the COGITO safety planning and training tools). Comparison will then be made with similar activities conducted when the COGITO safety planning and training tools have been employed.	3
KPI-SA-10	**At-risk Behaviour Frequency Rate**	The frequency of occurrence of at-risk behaviours per 1 million hours worked	At risk behaviour instances / 1,000,000 man-hours	Using the IoT+DT solution of COGITO, occurrences can be measured. Baselining will require using the IoT+DT solution with normal practice (i.e. without the COGITO safety planning and training tools). Comparison will then be made with similar activities conducted when the COGITO safety planning and training tools have been employed.	3

Safety Leading KPIs					
KPI-SA-11	**Safety inspections/observation**	The frequency of safety inspection/observation to identify hazards or safety violation to ensure worker safety and health	Safety inspections / month	Not explicitly monitored, tracked and report. However, the information may be retrievable.	4
KPI-SA-12	**Safety record**	The degree of reporting and maintaining accident records and safety performance records	Unitless	The degree of reporting and record maintenance may be measured qualitatively, e.g. on a Likert scale. This assessment could draw on quantitative information obtainable from construction projects (e.g. checking at completeness of records).	4
KPI-SA-13	**Worker involvement**	The degree of worker involvement in safety aspects, such as safety decisions and feedback to top management	Unitless	The level of involvement may be measured qualitatively, e.g. on a Likert scale, using information obtainable from construction projects (e.g. knowledge of aspect of the involvement).	4
KPI-SA-14	**Staffing for safety**	The number of certified safety representatives in the worksite	Persons.	Already tracked by one or both pilot site partners (or data is available and could be tracked)	5
KPI-SA-15	**Written safety plan**	A complete and comprehensive safety plan that guides project safety	Unitless (binary)	Already tracked by one or both pilot site partners (or data is available and could be tracked)	5
KPI-SA-16	**Personal protective equipment (PPE)**	The provision of the required PPE for all workers	Unitless (binary)	Already tracked by one or both pilot site partners (or data is available and could be tracked)	5
KPI-SA-17	**Substance abuse**	The frequency of random drug and alcohol tests to prevent substance abuse among workers	Substance tests / month	Already tracked by one or both pilot site partners (or data is available and could be tracked)	5
KPI-SA-18	**Incentives**	The safety promotions and praise for workers with positive and safe work behaviour	Unitless	The level of incentives may be measured qualitatively, e.g. on a Likert scale, using information obtainable from construction projects	4

				(e.g. existence of various kinds of awards for best performing crews).	
KPI-SA-19	**Training Performance**	Safety performance on training assessment	Unitless	This is typically not measured/tracked in projects/companies. However, the COGITO solution is developing a VR training solution that shall return safety awareness and behaviour scores.	3
Safety Process					
KPI-SA-20	**Labour Cost of Safety Activities**	The labour cost of conducting all safety process activities (i.e. planning and monitoring of safety). The metric may be measured relative to the project budget.	€ (or %)	This is not measured explicitly in projects. But, it corresponds to a portion of the project overheads, alongside some portion of the direct costs. So, this may be calculated by estimating those percentages.	2

Table 5-6 – Proposed COGITO KPIs for Energy Efficiency.

KPI	Name	Definition/Description	Units	Calculation Method	Ease of Calculation
			Energy		
KPI-EE-1	**Activity Direct Energy**	The sum of the equipment and labour energy consumptions.	KWh	Equipment: It can be computed by estimating the typical energy use of the piece of equipment if in constant use, and multiply it by a productivity factor calculated based KPI-SC-5. Labour: It can be computed by multiplying the daily energy intake of a typical work by the number of works and the number of days for the activity to be completed.	2
KPI-EE-2	**Total Direct Energy**	It is the sum of the energy consumption of all activities.	KWh	= Σ(KPI-EE-1)	5
KPI-EE-3	**Indirect Energy**	The sum of the equipment and labour energy consumptions to perform a general (or indirect) activity (e.g. office management).	KWh	Equipment: It can be computed by multiplying the power of the required construction tools per construction task by their time in operation. Labour: It can be computed by multiplying the daily energy intake of a typical work by the number of works and the number of days for the activity to be completed.	2
KPI-EE-4	**Total Indirect Energy**	The sum of the indirect energy consumptions of all general (or indirect) activities.	KWh	= Σ(KPI-EE-3)	5
KPI-EE-5	**Total Construction Energy**	The sum of the Direct and Indirect Energy consumption of the overall construction project.	KWh	= KPI-EE-2 + KPI-EE-4	5

Carbon Footprint					
KPI-EE-6	**Activity Direct Carbon Footprint**	CO2-equivalent emissions resulting for the operation of equipment and labour for accomplishing the given activity	g CO_2	Equipment: it can be calculated by multiplying the equipment energy (calculated as part of KPI-EE-1 by an emission factor that reflects the source of energy utilised to operate the equipment. Labour: it can be calculated by multiplying the equipment energy (calculated as part of KPI-EE-by an emission factor for humans. Alternatively, it can be measured based on the work duration and using an annual emission factor for human of ~2 tonnes CO_2 / year)	2
KPI-EE-7	**Total Direct Carbon Footprint**	Sum of all Activity Direct Footprint values	g CO_2	= Σ(KPI-EE-6)	5
KPI-EE-8	**Indirect Carbon Footprint**	CO2-equivalent emissions resulting from an activity supporting direct construction works (e.g. management office).	g CO_2	Equipment: it can be calculated by multiplying the equipment energy (calculated as part of KPI-EE- by an emission factor that reflects the source of energy utilised to operate the equipment. Labour: it can be calculated by multiplying the equipment energy (calculated as part of KPI-EE-by an emission factor for humans. Alternatively, it can be measured based on the work duration and using an annual emission factor for human of ~2 tonnes CO_2 / year)	2
KPI-EE-9	**Total Indirect Carbon Footprint**	Sum of all Indirect Carbon Footprint values.	g CO_2	= Σ(KPI-EE-8)	5
KPI-EE-10	**Total Construction Carbon Footprint**	Sum of Direct Carbon Footprint and Indirect Carbon Footprint values.	g CO_2	= KPI-EE-7 + KPI-EE-9	5

6 User Acceptance

This section focused on the assessment of the User Acceptance (UA) of the COGITO tools and solution. In contrast to the previous KPI categories, User Acceptance (UA) performance is not assessed using baselining but using a direct absolute measurement method applied to the COGITO solution only.

As discussed in Section 2, the approach to establish the UA assessment methodology is simple. In a first step, we reviewed the literature on existing standards and methods for UA assessment. The results of that review are reported in Section 6.1. Then, we drew on the literature to establish the UA assessment methodology to be employed in COGITO that is presented in Section 6.2, with the KPIs listed in Section 6.3.

6.1 Existing Assessment Methodologies

User Acceptance (UA) defines the system's compatibility with the requirements of the users and the characteristics of the task to be executed. It is an indicator for successful user support by an information system and should be assessed for every product/service developed. In engineering and its various sub-disciplines, a dedicated testing process – often called *user acceptance testing* - is commonly conducted to determine if the requirements of a specification or contract are met. Specific acceptance criteria are defined and a system/component is tested against them to ensure that it fulfils all the requirements to be accepted by a user. UA should be especially assessed when novel information systems and technologies are introduced in workspaces. In this case, the factors that can facilitate the acceptance of these new technologies should be considered and analysed towards promoting and supporting an organisational transformation in a smooth way. UA of innovative technologies is analysed in [21] whilst the factors that could influence the acceptance of new technologies in the workspace are examined in [22].

Digital Twinning will bring about unprecedented automation in the management of any physical asset. One of the first concerns that can be a stumbling block for the adaptation of digital twins just like any other automation technologies will be its acceptability by the workforce [23]. Although CAD and BIM solutions have increased awareness on digitalisation across the AEC sector, the level of acceptance of automation, including automating processes through digital twinning, remains low among relevant actors, who cannot articulate these technology components or envision added value in their everyday workload from such technologies [24].

To this end, an important objective of the COGITO evaluation methodology is to assess UA of the COGITO tools by the end-users (i.e. construction managers, on-site workers, etc.). UA is a necessary pre-condition for the further exploitation of the COGITO tools and their proliferation in the construction industry. It will be used to validate the benefits and value created for the construction stakeholders in specific use cases. Thus, it can be further used to develop a sustainable marketing strategy as well.

It should be mentioned that – even from the proposal phase of the project – UA was considered and guided decisions made in terms of the project development lifecycle. To this end, COGITO has adopted a *user-centric design* through direct involvement of stakeholders and living lab activities in the implementation process (see also Deliverable D2.1). Thus, the COGITO system has been designed from the onset to cover actual stakeholders' requirements and needs. Therefore, COGITO aims at delivering a prototype system that can reach high levels of UA. Considering that UA is a key priority of COGITO, we now briefly present the most commonly used standards and methodologies for assessing technology acceptance by users.

Standards

Technology acceptability is closely linked to system usability. The ISO 9241-11 standard [25] defines usability as "*the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*". The ISO/IEC 25022 [26] recommends that usability metrics are part of systems and software quality assessments and should include:

- ***Effectiveness:*** The accuracy and completeness with which users achieve specified goals [5] that can be quantified measuring the completion rate and the number of errors made from a user when trying to complete a task [27].
- ***Efficiency:*** The resources expended in relation to the accuracy and completeness with which users achieve goals [25]. Efficiency can be quantified using time related metrics. For example, time-based efficiency (total time required by a user to complete a task) and relative efficiency (the ratio of the time taken by the users who successfully completed the task in relation to the total time taken by all users) can be used [27].
- ***Satisfaction:*** The comfort and acceptability of use [25]. Satisfaction can be measured using task or test level satisfaction metrics that are quantified based on users' feedback on questionnaires after the completion of a task or a sequence of tasks (test) respectively [27].

Methodologies

Technology Acceptance Model (TAM) [28] has been one of the most frequently used models of technology acceptance. It considers two primary cognitive factors influencing an individual's intention to use new technology [29]:

- ***perceived ease of use*** that refers to the assessment of whether the use of the information system can be learned without difficulty and effort.; and
- ***perceived usefulness*** that is used to assess how the use of a specific IT application improves the execution of work tasks within a specific organizational acceptance context.

It is evident that the higher the ease of use, the more likely it is for users to be willing to use the system. In the TAM, the interaction of the two factors—perceived usefulness and perceived ease of use—results in an intention of the user to use the specific technology (behavioural intention to use). This, in turn, is correlated with the actual use of the system. Both factors are further impacted by other independent variables such as culture, job position and function, data quality, and system security. However, all these external factors are supposed to influence intention and attitude indirectly through perceived usefulness and ease of use, as illustrated in Figure 6-1.

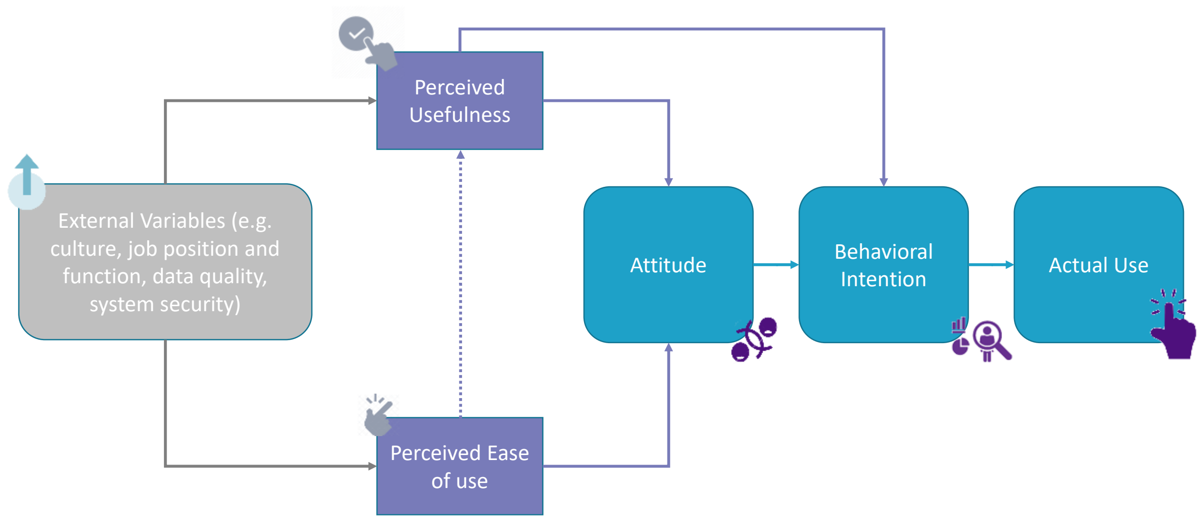


Figure 6-1: Technology Acceptance Model (TAM) by Davis (1989) – reproduced from [30]

While TAM has been criticised on a number of grounds [31], it serves as a useful general framework and several multi-disciplinary studies have used the TAM as a grounding framework. It is the most influential, most tested, and best-operationalized approach [32]. Many studies have been performed leading to changes in the originally proposed TAM model. In [33], the authors developed a model called combined TAM-TPB model which integrated the TAM and Theory of Planned Behaviour (TPB) while the two major upgrades of TAM were employed by Venkatesh and his co-workers, who defined:

- a new version of TAM – the so-called **TAM2** [34]**-** where new variables were considered to the initial TAM. More specifically, TAM2 encompasses social influence processes (subjective norm, voluntariness, and image) and cognitive instrumental processes (job relevance, output quality, result demonstrability, and perceived ease of use) as determinants of perceived usefulness and usage intentions; and
- the **Unified Theory of Acceptance and Use of Technology (UTAUT)** Mode [35]. This methodology considers four key constructs for UA, namely: performance and effort expectancy, social influence, and facilitating conditions. The methodology was developed in the framework of unifying the constructs of eight previous defined models (theory of reasoned action, TAM, motivational model, TPB, a combined theory of planned behaviour/technology acceptance model, model of personal computer use, diffusion of innovations theory, and social cognitive theory).

TAM has been used by researchers worldwide to understand the acceptance of different types of information systems. The various studies have tried to modify the TAM by adding new variables to it. The majority of the studies use surveys (most often custom ones) and questionnaires for data collection [36] that are, then, analysed towards providing user acceptance assessment output. A comprehensive review of the different approaches used and the respective application areas can be found in [37].

As regards TAM usage in the digitalisation of lean-construction industry, vey recently, Park and Park [30] analysed the factors of the TAM for Construction IT. They developed a research model based on Davis's TAM incorporating the traits of information accepters in the construction industry. The TAM for construction IT proposed in this study had five external factors (acceptance type, educational satisfaction, usage knowledge, usage enjoyment, and usage experience) and four internal factors (ease, usefulness, attitude, behavioural intention). The methodology was realised through surveys conducted mainly with the stakeholders of construction and engineering organizations located in Seoul. The methodology was proven to be adequate enough and very interesting results were reached on UA of information systems in the construction industry.

Apart from TAM, another methodology used for usability assessment is the System Usability Scale (SUS) [38]. SUS is a simple, ten-item scale giving a global view of subjective assessments of usability. SUS can be applied in assessing usability of various types of systems including systems used in industrial environments. In particular, ten Likert-scale questions are considered. Scoring is based on a 5-point Likert Scale from strongly disagree to strongly agree. These are:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

The results of an SUS survey are used to establish a satisfaction score, which ranges from 1 to 100. A score is generally considered 'good' from 75, and passable between 50 and 75. A score below 50 reveals serious customer satisfaction issues.

SUS has been considered as providing a high-level subjective view of usability. Therefore, it is often used in comparing usability between systems, even dissimilar ones. This one-dimensional aspect of the SUS is both a benefit and a drawback, because the questionnaire is necessarily quite general. A comprehensive review of the

SUS covering its early history from inception in the 1980s through recent research and its future prospects can be found in [39].

6.2 COGITO Assessment Methodology

The evaluation and assessment of UA in COGITO follows a stage-approach presented in Figure 3. It is structured around a user-centric design and agile software development process allowing for continuous feedback interaction with the final end-users of the solution. The process followed includes three stages:

- First stage includes mainly activities performed within T2.1 (and T9.2 - COGITO Living Lab Activities). It is focused on living labs activities and definition and analysis of target groups and end-user / stakeholder requirements (SRs).
- Second stage includes mainly the work performed within this task (T2.3) and incorporates: an assessment of the available methodologies found in the literature; the definition of the COGITO research model for UA evaluation; and the definition of the list of KPIs.
- Third and final stage includes: the refinement of the KPIs based on pre-validation, integration and testing results; the questionnaires creation aligned with UCs to be demonstrated in the pilot sites; the collection of feedback on questionnaires and log files of the system during demonstration; the analysis of data gathered and KPIs quantification leading to final user acceptance evaluation results. This stage will be performed mainly as part of the WP8 activities.

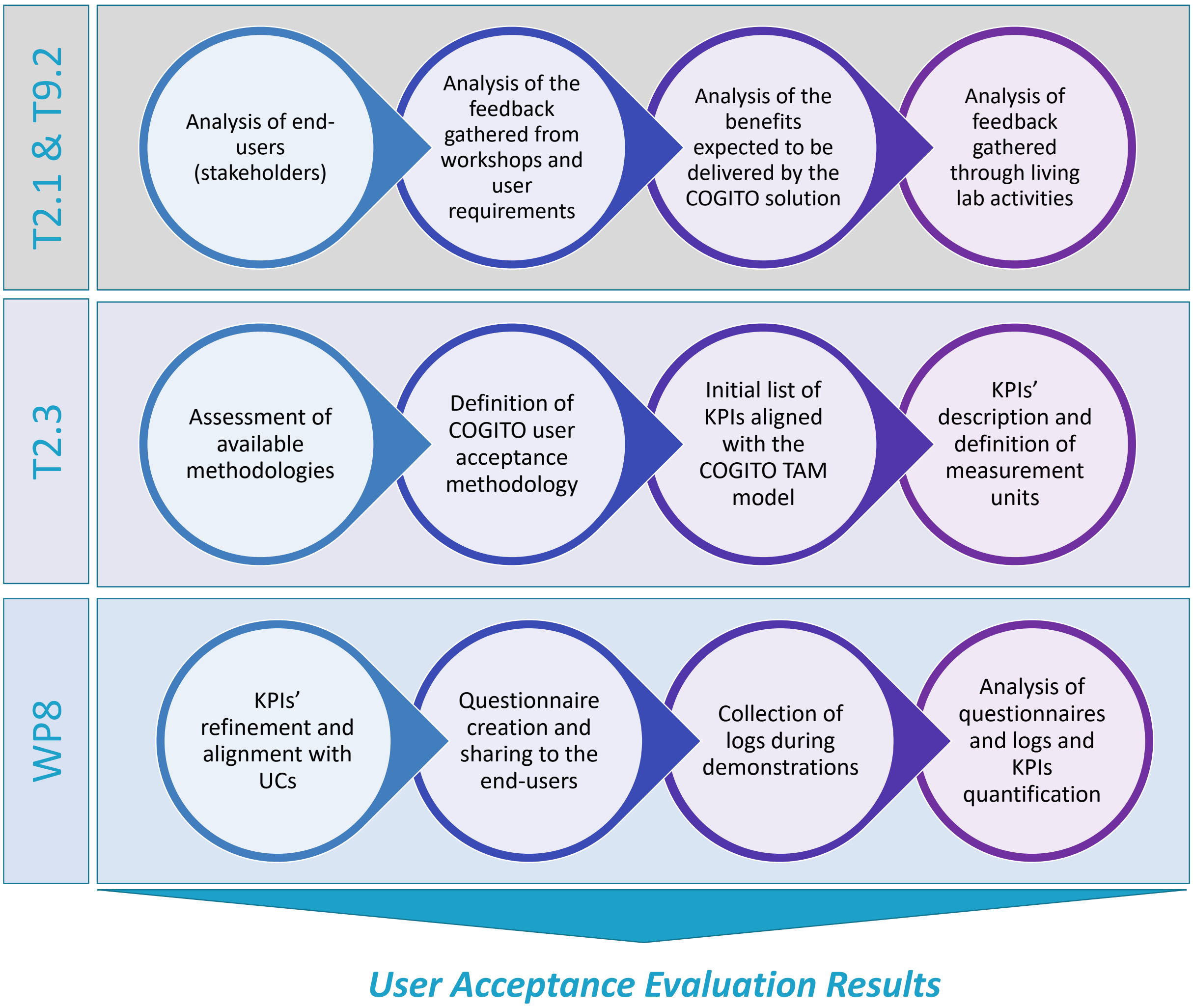


Figure 6-2: Steps of the COGITO user acceptance evaluation methodology and alignment with tasks and WPs

The assessment has been built on the TAM theory presented in Section 6.1 that correlates acceptance with the constructs of perceived usefulness and perceived ease-of use. The methodology has been customised to fulfil COGITO scope and objectives. Thus, TAM blocks will be considered while the objective usability will be added as an external factor. Given the provision of enhanced COGITO safety services, metrics of perceived safety are also determined, as well as the system's usability [40]. The COGITO model for UA evaluation based on TAM is illustrated in Figure 2.

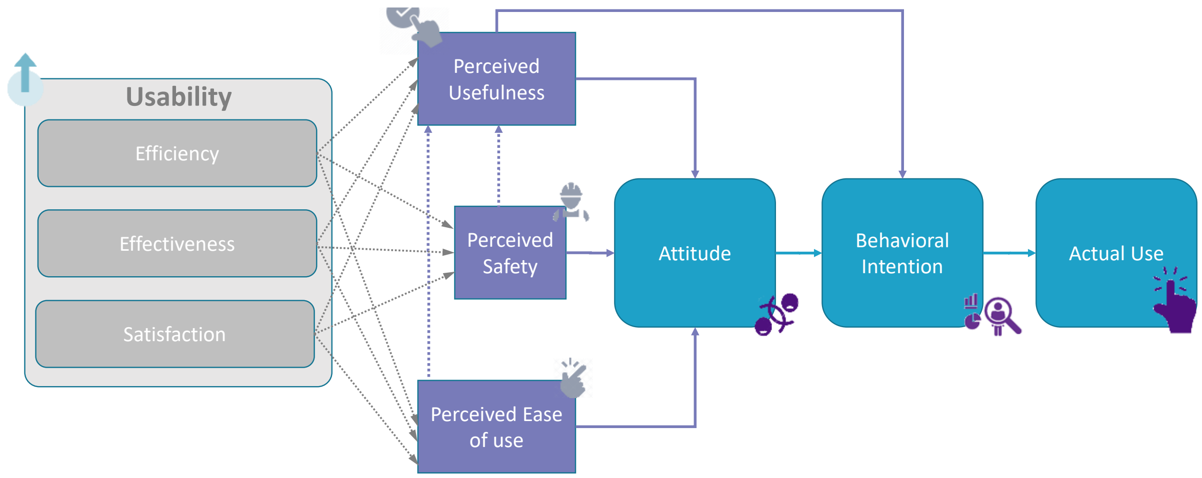


Figure 6-3: COGITO model for user acceptance evaluation

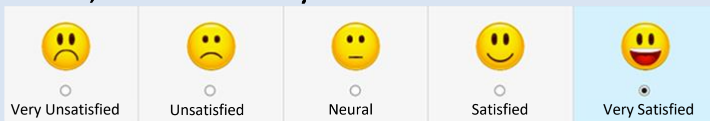
The methodology is primarily based on questionnaires. In particular, a complete set of questions addressing all metrics will be contained in a questionnaire that will be provided to the end-users. When possible, objectively measured KPIs addressing the system's usability and error handling capacity will be used. Unless otherwise defined, a set of questions/statements answered through a Likert-based scale [41] will be used to assess each identified metric. Questions/statements may need to be adjusted/slightly modified for evaluating user acceptance on the functionalities demonstrated in each COGITO Use Case (UC). This will be carefully considered once a first version of components has been developed and their interactions have been fully defined.

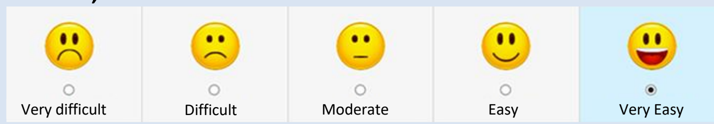
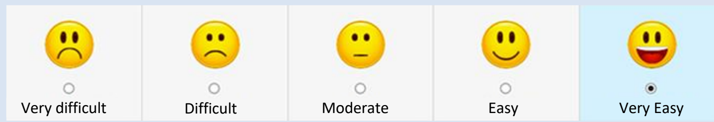
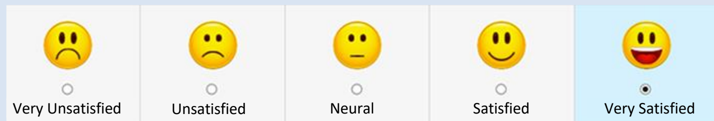
As regards usability assessment, KPIs influenced by ISO standard has been selected towards achieving an objective assessment (as opposed to the high-level subjective view of usability that can be provided by applying SUS).

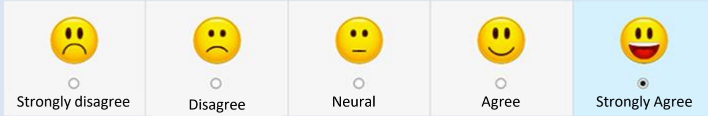
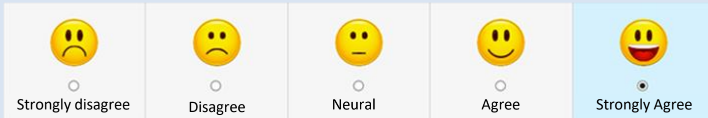
6.3 COGITO KPIs

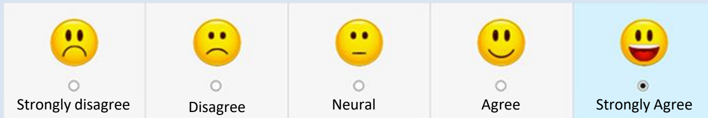
Table 6-1 summarises the UA KPIs along with their definition, units and method of measurement. Note that, in contrast to the previous KPI table, this one does not include a column 'UC', because these KPIs are to be applied across tools and do not relate to specific UCs.

Table 6-1 – User Acceptance KPIs

KPI	Name	Definition/Description	Units	Calculation Method
Usability				
KPI-UA-1	Completion Rate	This KPI indicates effectiveness and is defined as the number of tasks completed successfully relevant to the total number of tasks undertaken by a user.	%	This indicator is calculated through observation and analysis of system's event log files, where applicable (additional info can be gathered from questionnaires).
KPI-UA-2	Number of errors	This KPI indicates effectiveness and is defined as the number of errors (unintended actions, slips, mistakes, omissions) that a user makes while attempting a task.	unitless	This indicator is calculated through observation and analysis of system's event log files, where applicable (additional info can be gathered from questionnaires).
KPI-UA-3	Time-based efficiency	This KPI indicates efficiency and is defined as the time (in seconds and/or minutes) the participant takes to successfully complete a task.	Seconds /minutes	This indicator is calculated through observation and analysis of system's event log files, where applicable (additional info can be gathered from questionnaires).
KPI-UA-4	End-user satisfaction	This KPI expresses end-user / stakeholder satisfaction with COGITO in a convenient metric. It is presumed that a smart solution that is easy to use and understand will more likely satisfy users and will be more easily adopted than a difficult solution.	Unitless	A post-task question taking the form of Likert scale rating. **"Overall, how satisfied are you with COGITO?"** 
Perceived ease of use				
KPI-UA-5	Task level satisfaction	This KPI indicates satisfaction and is defined as a score of satisfaction of the user in their interaction with the solution.	Unitless	A post-task question taking the form of Likert scale rating. Its goal is to provide insight into task difficulty as seen from the participants' perspective.

				"Overall, this task was" 
KPI-UA-6	Learning process satisfaction	This KPI indicates satisfaction in the learning process of the COGITO system.	Unitless	A post-training question taking the form of Likert scale rating. It takes the form of Likert scale rating. Its goal is to provide insight into difficulty on learning how to use COGITO as seen from the participants' perspective. **"Overall, learning to use COGITO tools and services was:"** 
KPI-UA-7	Satisfaction when interacting with COGITO	This KPI indicates satisfaction when a user is interacting with the COGITO tools through the provided UIs. It attempts to evaluate the intuitiveness of the UIs and their user-friendliness.	Unitless	A post-training question taking the form of Likert scale rating. **"Overall, how satisfied are you with COGITO UI?"**  This KPI should be linked to each of the provided UIs.
Perceived Safety				
KPI-UA-8	Improvement on perceived safety	A psychometric scale rating of the improvement of perceived safety by utilising the H&S services of COGITO. The KPI attempts to provide a qualitative assessment from the user perspective on	Unitless	The user should provide feedback on the following statement after completion of demonstration of UCs relevant to H&S: **"Please rate the degree to which you agree with the following statement:**

		whether COGITO has provided added value as regards safety related aspects in their work.		**COGITO solution improves jobsite safety during a construction project realisation."** 
KPI-UA-9	Perceived trust	A psychometric scale rating of the perceived trust on the system. Perceived trust defines the extent to which the user believes that COGITO will assist them in achieving a goal even in uncertain and vulnerable situations.	Unitless	The KPI takes the form of Likert scale rating. The user should provide feedback on the following statement after participating in demonstration activities: **"Please rate the degree to which you agree with the following statement:** **I believe that COGITO can assist me in achieving a goal during my work execution even in uncertain and vulnerable situations."** 
Perceive Usefulness				
KPI-UA-10	Advantages for end-users	This KPIs defined the extent to which the project offers clear advantages for end users / stakeholders. The advantage can take many forms, for instance cost savings, improved quality, improved safety, etc. It is presumed that solutions which have a higher level of advantages to end users will be more likely to be adopted than solutions which have negative or no advantages.	Unitless	The inputs for this KPI will be the replies to questionnaires about the advantages they believe they have with COGITO. The following statements should be rated (individually): **"Please rate the degree to which you agree with the following statements:** - **I think that there is clearly an added value offered by the COGITO tool suite.** - **I think that COGITO usage improves productivity.**

				- **I think that COGITO usage improves projects' quality.** - **I think that COGITO usage improves construction project cost savings.** - **I think that COGITO usage facilitates the collaboration among different teams.** - **I think that COGITO usage optimises workflow management.** - **I think that COGITO helps me be more effective."**  The questionnaires/surveys will be answered by the end-users and be processed to elicit the user reception of the advantages offered by the COGITO solution.

7 Conclusions

The deliverable defines the COGITO evaluation methodology. Following a review of the goals of COGITO and its UCs, relevant performance assessment methods and KPIs, described in the literature and/or employed in industry, were reviewed and analysed for their relevance to the COGITO project. An initial list of KPIs was then put together by the technical partners and presented to the industry partners for feedback, considering the measurability, collectability and comparability.

The final list of construction performance KPIs is grouped in 6 categories: duration, cost, quality, safety, energy, and user acceptance. The first five specifically focus on construction performance and can be measured for both current practice and practice using the COGITO solution. In contrast, the user acceptance KPIs are solely applied to the application of the COGITO solution and are not compared against a baseline.

Overall, 55 KPIs are proposed for the first five categories, and 10 KPIs are proposed for UA. For each KPI, we have provided a description, the unit of the KPI, and the method to be employed to calculate it.

As mentioned in the document, extensions and refinements of the evaluation methodology in terms of chosen Use Cases (UCs) and KPI assessment method must happen once the specific test cases are confirmed and the types of activities that will be on-going during the validation periods are known. As a result, the list of KPIs and measurement methods proposed here will be revised in WP8, more specifically in T8.2 (COGITO ICT System Pre-Validation) and T8.4 (Demonstration of COGITO Tools on Construction Projects).

References

[1] COGITO, "D2.1 - Stakeholder Requirements for the COGITO Project," 2021.

[2] J. Won and G. Lee, "How to tell if a BIM project is successful: A goal-driven approach," *Automation in Construction,* vol. 69, pp. 34-43, 2016.

[3] ISO/TC 258, "ISO 21500 - Guidance on project management," ISO, 2012.

[4] ISO/TC 258, "ISO 21502 - Project, programme and portfolio management — Guidance on project management," ISO, 2020.

[5] ISO/TC 258, "ISO 21511 - Work breakdown structures for project and programme management," ISO, 2018.

[6] BIMERR, "D2.1 - Stakeholder Requirements for the COGITO System," 2021.

[7] Designing Buildings Wiki, "Key Performance Indicator (KPI)," Designing Building Wiki, 2021. [Online]. Available: https://www.designingbuildings.co.uk/wiki/Key_performance_indicators_KPI. [Accessed 14 June 2021].

[8] KPI Working Group, "KPI Report forThe Minister for Construction," UK Government, 2000.

[9] ISO/TC 258, "ISO 21508 - Earned value management in project and programme management," ISO, 2018.

[10] J. Teizer, "The Role of Automation in Right-time Construction Safety," in *2016 Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC)*, Auburn, USA, 2016.

[11] J. Hinze, S. Thurman and A. Wehle, "Leading indicators of construction safety performance," *Safety Science,* vol. 51, no. 1, pp. 23-28, 2013.

[12] G. Zwetsloot, "Key performance indicators," OSGH Wiki Networking Knowledge, [Online]. Available: https://oshwiki.eu/wiki/Key_performance_indicators. [Accessed 14 June 2021].

[13] OSHA, "Clarification on how the formula is used by OSHA to calculate incident rates," OSHA - US Department of Labor, [Online]. Available: https://www.osha.gov/laws-regs/standardinterpretations/2016-08-23. [Accessed 14 June 2021].

[14] [Online]. Available: https://sitemate.com/uk/resources/articles/safety/safety-kpi/. [Accessed 14 June 2021].

[15] M. R. Hallowell, S. Bhandari and W. Alruqi, "Methods of safety prediction: analysis and integration of risk assessment, leading indicators, precursor analysis, and safety climate," *Construction Management and Economics,* vol. 38, no. 4, pp. 308-321, 2020.

[16] F. A. Manuele, One the practice of safety, Wiley, 2013.

[17] W. M. Alruqi and M. R. Hallowell, "Critical Success Factors for Construction Safety: Review and Meta-Analysis of Safety Leading Indicators," *Journal of Construction Engineering and Management,* vol. 145, no. 3, 2019.

[18] J. Teizer, B. S. Allread, C. E. Fullerton and J. Hinze, "Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system," *Automation in Construction,* vol. 19, no. 5, pp. 630-640, 2010.

[19] P. Tiwary, "Energy efficiency and building construction in India," *Building and Environment,* vol. 36, pp. 1127-1135, 2001.

[20] S. Bükrü, M. Wolf, O. Golovina and J. Teizer, "Using field of view and eye tracking for feedback generation in an augmented virtuality safety training," in *ASCE Construction Research Congress*, Reston, VA, USA, 2020.

[21] H.C. Kim, "Acceptability Engineering: the Study of user Acceptance of Innovative Technologies," *J. Appl. Res. Technol.,* vol. 13, no. 2, pp. 130-237, 2015.

[22] D. Skoumpopoulou, A. Wong, P. Ng, and M. F. Lo, "Factors that affect the acceptance of new technologies in the workplace : a cross case analysis between two universities," *Int. J. Educ. Dev. Using Inf. Commun. Technol,* vol. 14, no. 3, 2018.

[23] A. Rasheed, O. San, and T. Kvamsdal, "Digital Twin: Values, Challenges and Enablers From a Modeling Perspective," *IEEE Access,* vol. 9, p. 21980–22012, 2020.

[24] J. C. Camposano, K. Smolander, and T. Ruippo, "Seven Metaphors to Understand Digital Twins of Built Assets," *IEEE Access,* vol. 9, p. 27167–27181, 2021.

[25] ISO/TC 159, "ISO 9241-11 - Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts,," 2018.

[26] ISO/IEC JTC 1, "ISO/IEC 25022:2016 - Systems and software engineering — Systems and software quality requirements and evaluation (SQuaRE) — Measurement of quality in use," 2016.

[27] J. Mifsud, "Usability Metrics - A Guide To Quantify The Usability Of Any System - Usability Geek," UsabilityGeek, [Online]. Available: https://usabilitygeek.com/usability-metrics-a-guide-to-quantify-system-usability/. [Accessed 17 May 2021].

[28] F. D. Davis, " A technology acceptance model for empirically testing new end-user information systems: Theory and results," 1985.

[29] J. Schöpfel and O. Azeroual, "Current research information systems and institutional repositories: From data ingestion to convergence and merger," in *Future Directions in Digital Information*, Elsevier, 2021, pp. 19-37.

[30] E. S. Park and M. S. Park, "Factors of the technology acceptance model for construction IT," *Appl. Sci.,* vol. 10, no. 22, pp. 1-15, 2020.

[31] K Warner Schaie Sherry Willis, Handbook of the Psychology of Aging, Elsevier, 2016.

[32] D. B. L. Ellis, Future Directions in Digital Information, Elsevier, 2021.

[33] S. Taylor and P. Todd, "Assessing IT usage: The role of prior experience," *MIS Q. Manag. Inf. Syst.,* vol. 19, no. 4, p. 561–568, 1995.

[34] V. Venkatesh and F. D. Davis, "Theoretical extension of the Technology Acceptance Model: Four longitudinal field studies," *Manage. Sci.,* vol. 46, no. 2, p. 186–204, 2000.

[35] V. Venkatesh, M. G. Morris, G. B. Davis, and F. D. Davis, "User acceptance of information technology: Toward a unified view," *MIS Q. Manag. Inf. Syst.,* vol. 27, no. 3, p. 425–478, 2003.

[36] C. Nadal, C. Sas and G. Doherty, "Technology acceptability, acceptance and adoption-definitions and measurement," in *ACM CHI 2019 Conference on Human Factors in Computing System*, 2019.

[37] P. Surendran,, "Technology Acceptance Model: A Survey of Literature vol. 2, no. 4, pp. 175–178, 2013.," *Int. J. Bus. Soc. Res.,,* vol. 2, no. 4, p. 175–178, 2013.

[38] J. Brooke, "SUS: a "quick and dirty" usability scale," in *Usability Evaluation in Industry*, London, Taylor and Francis, 1986.

[39] J. R. Lewis, "The System Usability Scale: Past, Present, and Future," *International Journal of Human–Computer Interaction,* vol. 34, no. 7, pp. 577-590, 2018.

[40] 5G-MOBIX Consortium, "D2.5 Initial evaluation KPIs and metrics," 2019.

[41] S. Jamieson, "Likert scale | social science | Britannica," [Online]. Available: https://www.britannica.com/topic/Likert-Scale. [Accessed 17 May 2021].

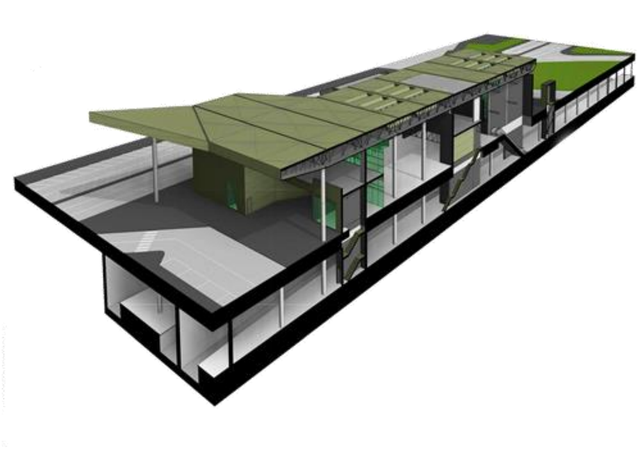
[42] M. Eriksson, V.-P. Niitamo and S. Kulkki, *State-of-the-art in utilizing Living Labs approach to user-centric ICT innovation - a European approach,* 2005.

[43] R. Agarwal, S. Chandrasekaran and M. Sridhar, "Imagining construction's digital future," McKinsey & Company, 2016.

[44] P. Chapman, "The Energy Costs of Materials," *Energy Policy,* vol. 3, no. 2, pp. 47-57, 1975.

[45] ISO/TC 59, "ISO 16739-1 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries (ISO 16739:2013)," ISO, 2016.

[46] ISO/TC 163, "ISO 13790 - Energy performance of buildings — Calculation of energy use for space heating and cooling," 2008.



COGITO

CONSTRUCTION PHASE
DIGITAL TWIN MODEL

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