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Built2Spec

Built to Specifications – Tools for the 21st Century Construction Site

H2020 Grant Agreement – 637221

D1.1 User, self-inspection, and quality checks requirements

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Executive summary

The **Deliverable D1.1** titled **"User, self-inspection, and quality checks requirements**" is a public document delivered in the context of WP1 and the tasks 1.1 and 1.3.

This work is part of the project on Tools for the 21st Century Construction Worksite (BUIL2SPEC) and is financed by the European Union under the Horizon 2020 Programme.

This Deliverable D1.1 aims to analyse the context of construction projects across various countries of the EU (partners countries), to identify the stakeholders and their issues, and to imagine which answers will be developed and tested during Built2Spec project. The outputs will result in basic requirements and use cases to feed the developments of work packages 2 to 6, and ensure that the developments of the project are in agreement with the actual needs of the market.

After a short general introduction (section 2), the results are presented in the sections 3 to 9 as follows.

Section 3 describes the methodological approach adopted to identify the needs of the stakeholders.

Section 4 presents the results of the analysis of: construction processes across Europe, stakeholders roles and issues, user needs and potential future solutions. These results represent the stakeholders/users' point of view.

Sections 5 to 9 present the current state of technological developments, the potential ways of improvement, and first outlines of new use cases and requirements. The results are presented separately for each technical field (thermal inspection, airtightness, indoor air quality, acoustic comfort, information management, smart material, 3D scanning and drones, and quality assurance). These elements of information are proposed by solution providers from Built2Spec's consortium.

Executive summary

1 TABLE OF CONTENT

Abbreviations

B2S = Built to Specifications

DOA = Description of Action;

CS = Communication Strategy;

WP = Work Package.

2 Introduction

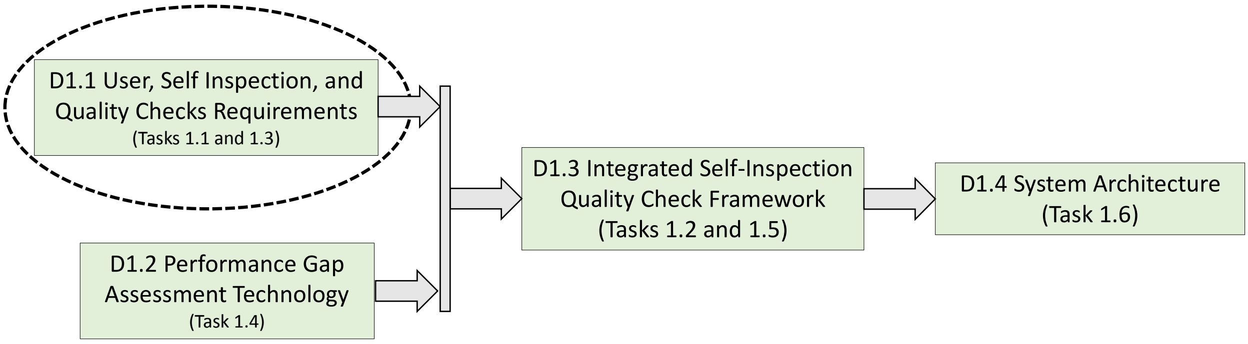

Fig. 1 Organization of deliverables and tasks of WP1

This deliverable gathers results from task1.1 (stakeholder workshops and user requirements) and task 1.3 (Energy efficiency and comfort related inspection and quality check requirements).

The objective of these tasks is to analyze the context of construction projects across various countries of the EU (partners countries), to identify the stakeholders and their issues, and to imagine which answers will be developed and tested during Built2Spec project. The outputs will result in basic requirements and use cases to feed the developments of work packages 2 to 6, and ensure that the developments of the project are in agreement with the actual needs of the market.

The information presented in this deliverable comes from various sources: bibliography, desk studies, internal expertise among B2S partners, and questionnaires/interviews/workshops carried out with professionals external to B2S consortium.

Section 3 describes the methodological approach adopted to identify the needs of the stakeholders.

Section 4 presents the results of the analysis of: construction processes across Europe, stakeholders roles and issues, user needs and potential future solutions. These results represent the stakeholders/users' point of view.

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3 Methodological approach to define user needs and quality check requirements

Section 3 describes the general method to identify the user needs (task 1.1) and propose requirements to improve energy efficiency and comfort conditions (task 1.3). The results are then presented in sections 4 (needs) and 5 to 9 (requirements, for each technical field).

3.1 Describing the construction process

Identifying precisely the user needs requires having a deep knowledge of the construction process. The various stages of this process must be defined from the definition of the project requirements by the owner/promotor, to the post-commissioning, operation, and maintenance of the delivered building.

For every stage of the construction process, the various steps/tasks implying a quality check must be described, as well as the involved stakeholders, their roles, the formats and structure of the information, flows, etc.

The construction process is described for several countries participating to Built2Spec: France, Germany, Italy, Spain, and United Kingdom. The results are compared, and the similarities and the differences are identified. Indeed, it is crucial to ensure that the outcomes of the different tasks of Built2Spec can be adapted to any European country.

In the scope of the Work Package 1 activities, as a starting point to identify the needs and which ones will be tackled by Built2Spec developments, we proceed to a mapping of the activities occurring during a construction project, along the stages identified previously. The main activities of interest are the ones related to auto-inspection tasks and quality checks. The activities are listed by all the partners of Built2Spec's consortium, each one benefitting from a specific background and point of view of a construction project. Indeed, a great number of stakeholders are represented in the consortium: owners, engineers, architects, manufacturers, site supervisors, software developers, technology providers, workers, users, academic research…

For each activity we produce a description of the following elements: position in the process (which stage?), short description of the normal process, related quality check, involved stakeholder(s), existence of legal requirements. The table (excel file) describing these activities includes more than 200 entries (1 for each activity/process).

Once the list of quality checks is obtained, it is easier to associate the needs collected from the stakeholders (methodology described in next section, results in section 4) and to identify on which parts the developments from Built2Spec will contribute to propose new solutions and requirements to improve the performance of construction projects (sections 5 to 9).

3.2 Identifying the user groups and collecting their needs

A user requirements' study has to help in answering the following questions:

- Which different quality checks need to be done and which quality checks has already been done in the different countries?
- Which background knowledge do the users have concerning quality checks?

- Which existing tools are they using? Which software knowledge has the user?
- Which are the most critical stages in the construction process, where quality checks should be done?
- Who could be the client of a collaborative construction management platform?

To obtain answers to these questions a methodology is proposed (next figure). One of the main issues is to allow the different groups of stakeholders to express freely their professional feedback, without their answer being influenced by the interviewer (B2S partner), for example by providing to them too many details about Built2Spec objectives and methods (resulting in a potential bias in the surveys).

The methodology is then applied in every country involved in the organization of Work Package 1 workshops.

The results of the application of the methodology are presented in section 4, and integrate the results from task 1.1.

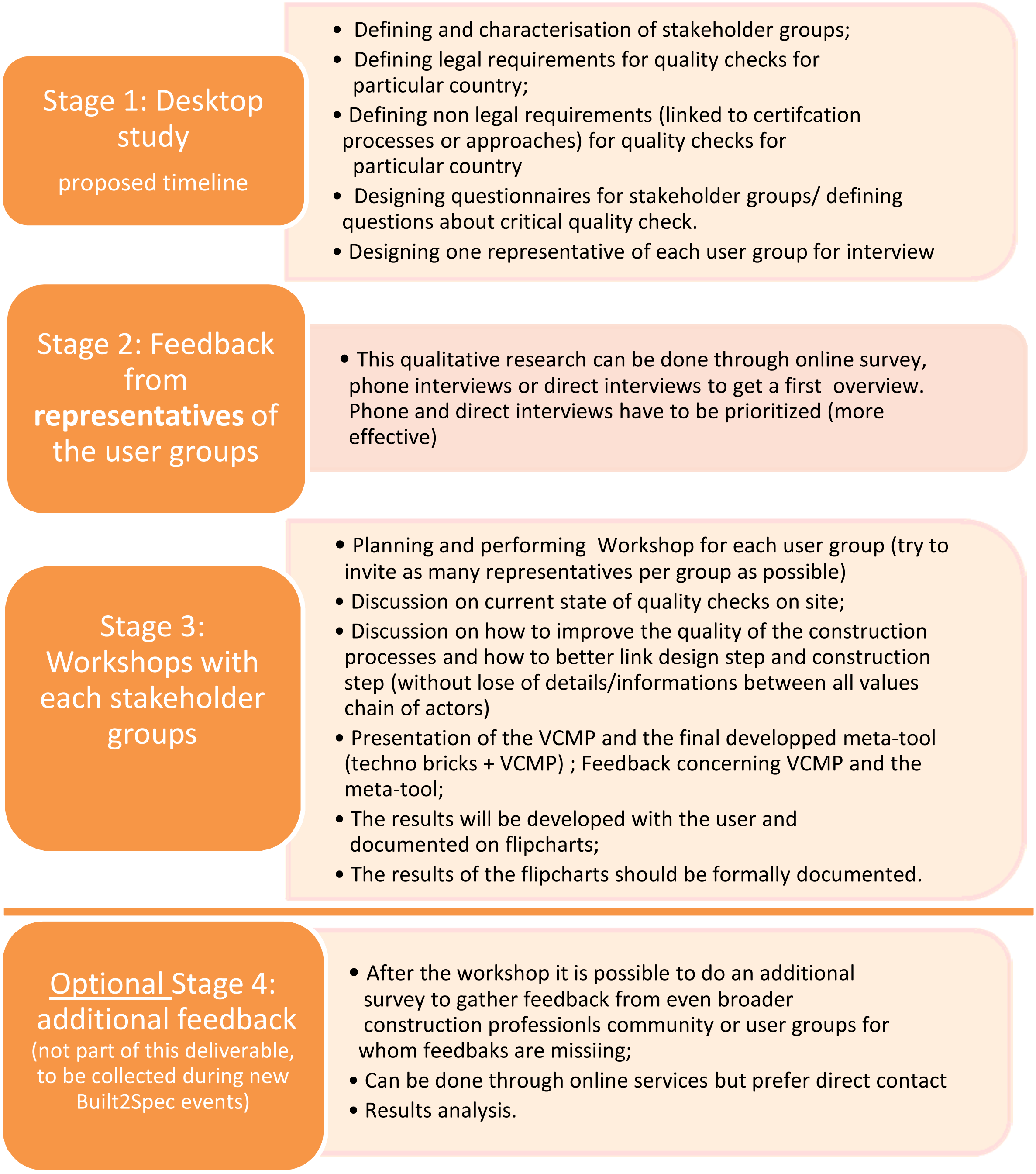


Fig. 2 Methodology to identify the user groups and needs

Methodological background for the suggested stages

Methodological background for Stage 1:
A desk research is carried out.
The main part of the desk research is realised by fill-in a questionnaire (one by country).
It is here important to define the end-users and the stakeholders groups. This desk study provides input to describe:

- Construction process contexts in Europe
- Stakeholders and challenges

Methodological background and optional guideline for Stage 2: Feedback from representatives of the user groups

For getting a first overview of the particular user needs in the context of quality self-inspections, the personal exchanges with several user groups help to find relevant information, which can also be of interest for the following workshops. A dialogue of generally 20-40 minutes is adopted.

Possible procedure:

- Select one user group, for example a worksite worker;
- Look for a potential partner of the Built2Spec programme;
- Preparing an interview guideline with relevant questions;
- Invite a worksite worker (or other selected user) for an interview;
- Get to know the role of this user group and try to develop a possible process of how self-inspections could be implemented in the daily work.
- Write down the results together with the partner;
- Summarize the results for a report for the individual customer needs.

Methodological background and optional guideline for Stage 3: Workshops with each stakeholder groups

1) There exists a hierarchy between some user groups. For example, the worksite worker and their supervisors or foremen. But we cannot plan several workshops for each user groups. This implies that we have to pay attention that everyone expresses his ideas and opinions during the workshop. Moreover, it is interesting to permit to each attendees to fill in a simple questionnaire at the end of the workshop. We can also imagine to make others interviews focusing on user groups who didn't give any or only few feedbacks during the WS (optional stage 4). As a result of this, the specific user requirements can be described.

2) In order to develop innovative products and services within the Built2Spec project, the qualitative group discussion, which will be generated within the workshop, seems suitable for getting the results that are needed for the project. In contrast to quantitative online surveys, the qualitative approach as suggested, allows the participants to interact with the moderator and the other participants to share develop new ideas.

3) We take advance of the fact, that the participants of the discussion can interact and inspire themselves within the conversation.

4) We generally don't present the built2spec project at the beginning of the workshop. We have to introduce the objective of the workshop which is to get the feedbacks of stakeholders on (non-exhaustive questions):

- how to improve the construction processes and enhance the quality
- how to improve the data/information sharing between people involved in the design step and people involved in the construction step.
- How to enhance the quality of the implementation
- What are their uses relative to quality assessment of the construction? Do they have quality assurance approach integrated in their construction projects?

Then, we can present our project and the different technological bricks and the future metaTool (platform+ Bricks) and ask them for their opinion/feedbacks.

The analysis of all feedbacks will help us to definitively define the user requirements.

Fig. 3 Workshop in Pessac (France, October 22nd 2015). What are the needs to improve quality in construction?

3.3 Selecting the issues to be tackled and defining the requirements for new solutions

The main issues are identified by implementing the methodology described in the previous section.

To precise these issues, the following questions are asked to the main stakeholders groups, during interview or dedicated workshops:

- What are the main mistakes observed on construction site and what are their impacts (thermal deficiency, bad IAQ, bad acoustic, energy consumptions, etc…)?
- What are the origins/sources of these mistakes? (bad choice during design, bad communication, lack of information, inadequate training/qualification, isolated decision making, etc…)
- What good practices can you observe?
- How to improve the quality during the construction stage?
- What needs to be checked and controlled? And which tools, technologies for self-inspection and future quality checks?
- Is there a clear need for self-inspection or quality checks solutions?
- In which technical fields? (Thermal, energy, acoustic, comfort, …)

- What are the objects to be checked (quality/airtightness/insulation of the envelope, implementation of components such as windows, etc.)? And which characteristics, performance values? (U-value of walls, VOC concentration, precise dimension of a room, etc.)
- Do self-inspection activities be easier with smartphone or digital tablet use?
- How to make the various stakeholders communicate with each other?
- In your projects (e.g. in IDDS approach or local equivalent), would you benefit from a common platform to exchange about the evolution of the project and its follow-up? Which data should be shared? Which format? Which control of the progress?
- Are the construction project management tools and information management/share tools necessary? Do you use them on your projects? (New forma, Bulldozair, Refurbify…) Do they satisfy your needs?
- Can recent technologies (such as BIM, drones, augmented reality, 3D scanning …) bring solutions to optimize the quality in construction and improve the communication between the stakeholders?

Based on the answers, recurrent observations will occur among the various stakeholders, thus allowing to identify the main user needs. To bring answers to these needs, several areas of expertise are identified and tackled by Built2Spec's implementation plan. In sections 5 to 9, technical details will be provided for each technical field in order to define requirements for the developments to be done in order to bring a response to the needs previously identified. Several steps are needed to define this first approach of requirements: identification of business as usual solutions, current limitations as regards the actual needs, possible ways of improvements, first schematic requirements and use cases. The Built2Spec partners involved in the technical developments (Work packages 2 to 6) will contribute in proposing these first requirements, which will be then enhanced and developed in the corresponding work packages.

Some of the technical fields are directly related to energy and comfort (e.g. thermal inspection techniques, airtightness, acoustic quality checks), others are also related to energy and comfort performance, but more indirectly (e.g. information management, quality assurance, smart materials). Sections 5 to 9 will then integrate the results from task 1.3.

4 User needs for improved auto-inspection and quality check applied to construction processes

4.1 Construction process contexts in Europe

4.1.1 Overview of construction processes across Europe and similarities

A construction project is composed of several stages, which can be described differently, with different levels of details, depending on which country is considered.

For example the next figure presents the main stages generally observed during a construction process.

Fig. 4 Typical example of main stages of a European construction process with tender (e.g. RIBA work stages)

To identify specific needs in order to propose adequate developments and solutions, it is necessary to enter much more in details in the description of the processes of a construction project.

The typical construction processes of several partner countries are described in details. Stages, stakeholders and interactions between both of them are described in the format of a workflow chart. The next figures show an example of one detailed construction process work flow in the case of France. More detailed examples of workflows are presented in annex (Italy, Netherlands, Spain).

Fig. 5 Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 1/4

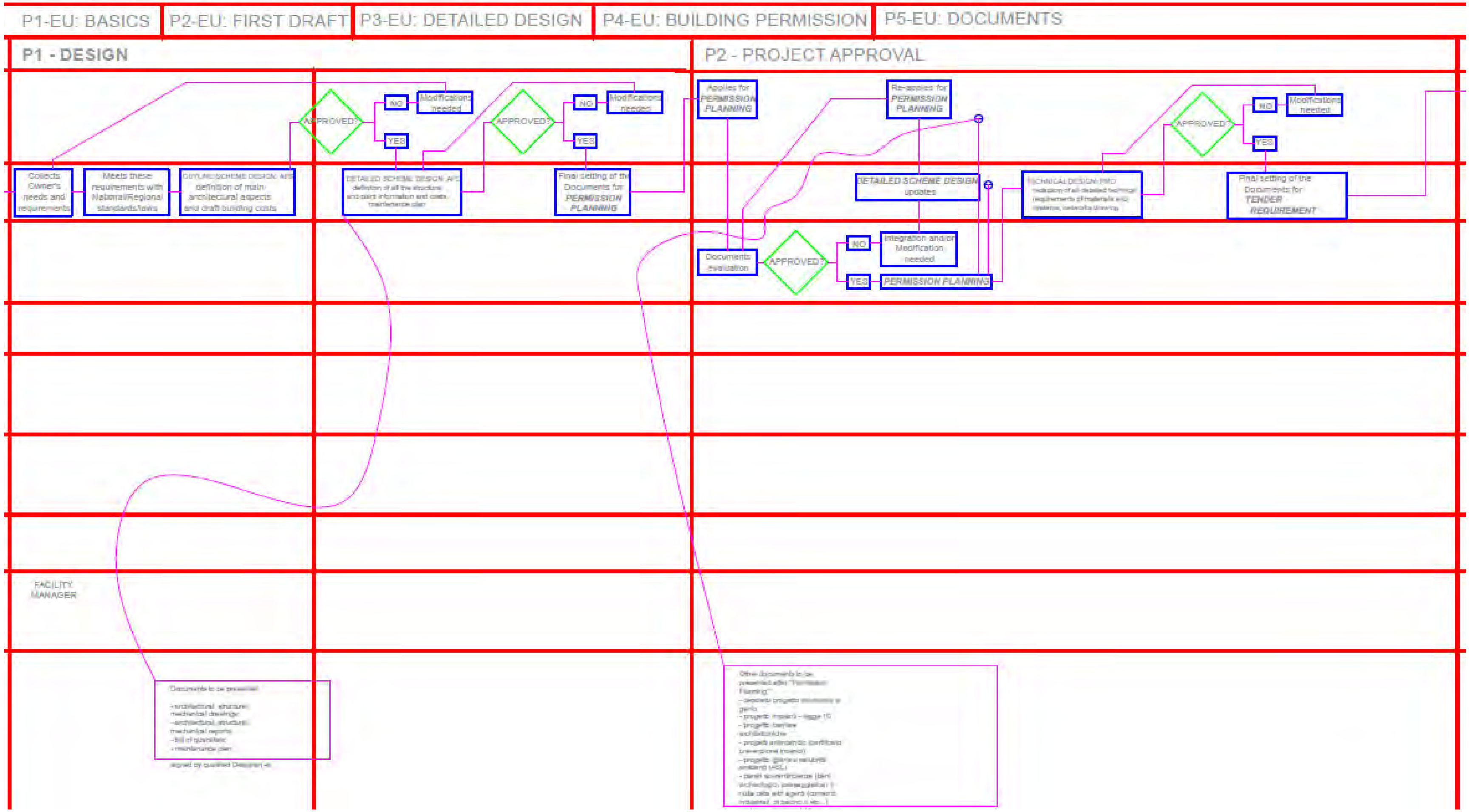


Fig. 6 Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 2/4

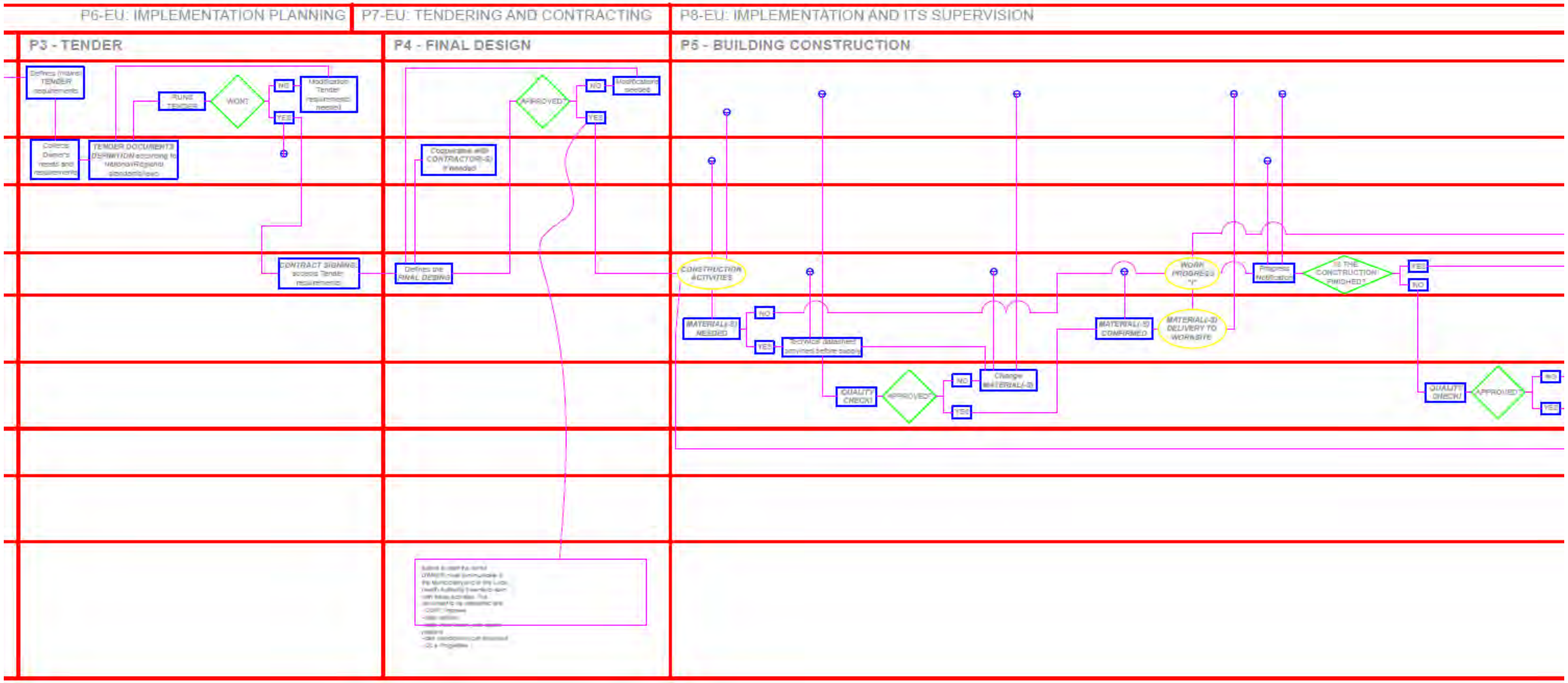


Fig. 7 Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 3/4

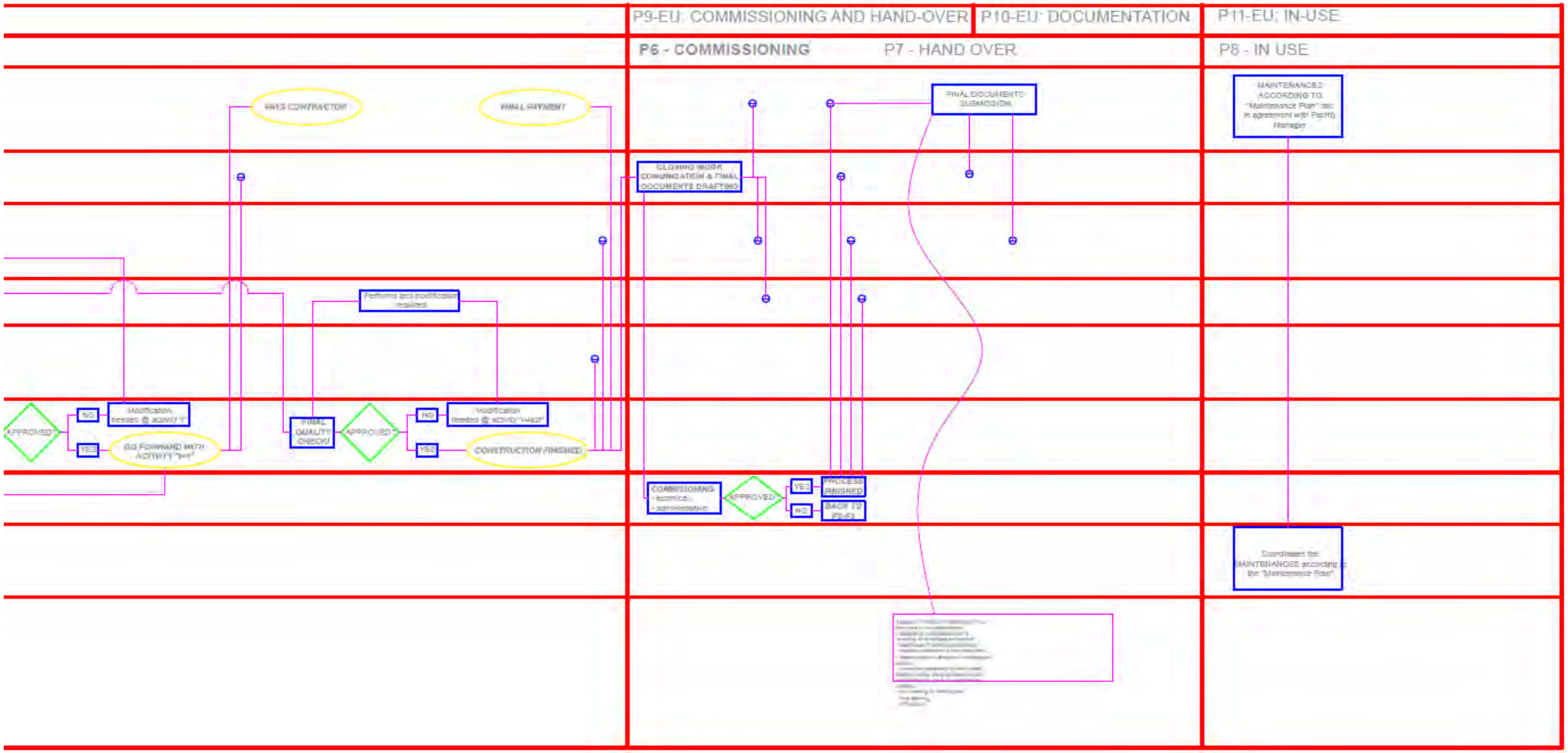


Fig. 8 Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 4/4

When comparing the construction process workflows from various UE countries, we observe strong similarities between them, with the same general phases: requirements by the owner, design, tendering, selection of the contractors, implementation, commissioning and handover.

Nevertheless some differences subsist. In the case of the French context for example:

- Importance of the **"programming" phase**. The programming phase, when the "*Maître d'Ouvrage*" (owner or promotor) defines the main outlines and requirements of the project (surfaces, main objectives), seems to be carried out in a more formal way in France than in some others countries. As a consequence, in France it is considered as an integrant part of the construction project stages whereas in others countries it is not mentioned as a construction project stage but as a prerequisite.
- **Role of the architect**. In France the main architect often takes several roles on, where different persons/entities would be involved in others countries. More precisely, the main architect is often both the chief designer, the tendering supervisor, and the main responsible of the implementation of works (*Maître d'oeuvre*).
- Architecture **contest stage and design**. In some cases, especially for large public projects, the chosen procedure corresponds to an architecture contest, where several design teams are competitors. The selection is usually carried out after the outline design (*esquisse* stage), but sometimes more details are asked, corresponding almost to more advanced stages of design (*avant-projet*). Then one team is selected to go on with the detailed design.

After a first analysis, **we observe that the differences between the countries about their construction process, even if having some impact on the way to carry out the project, do not prevent from identifying common situations and needs in terms of auto inspection and quality checks**.

4.1.2 Building Information Model (BIM) flow related a construction project

With the appearance of Building Information Models, powerful tools now exist and are being improved in order to accompany a construction project from the very early stage of design to the operation of the building.

The existing tools are developed in order to ensure that all the stakeholders involved in the design stage can read and write information on interoperable formats, representing most of the details of a construction project. These tools are being adapted to the context and stakes of each stage and can be considered as a prerequisite condition to check that what is implemented on the construction site is in agreement with the design. When necessary the BIM should allow to represent the updated information of the building when modifications have occurred.

BIM tools are essential for the implementation of integral design and delivery approaches. They are indispensable in the approach proposed by Built2Spec, by their capacity to represent spatially any kind of information. Please note that the IDDS aspects are to be developed in task 1.2 and deliverable 1.3.

Next figure represents a typical BIM approach developed in combination with the stages of a construction project.

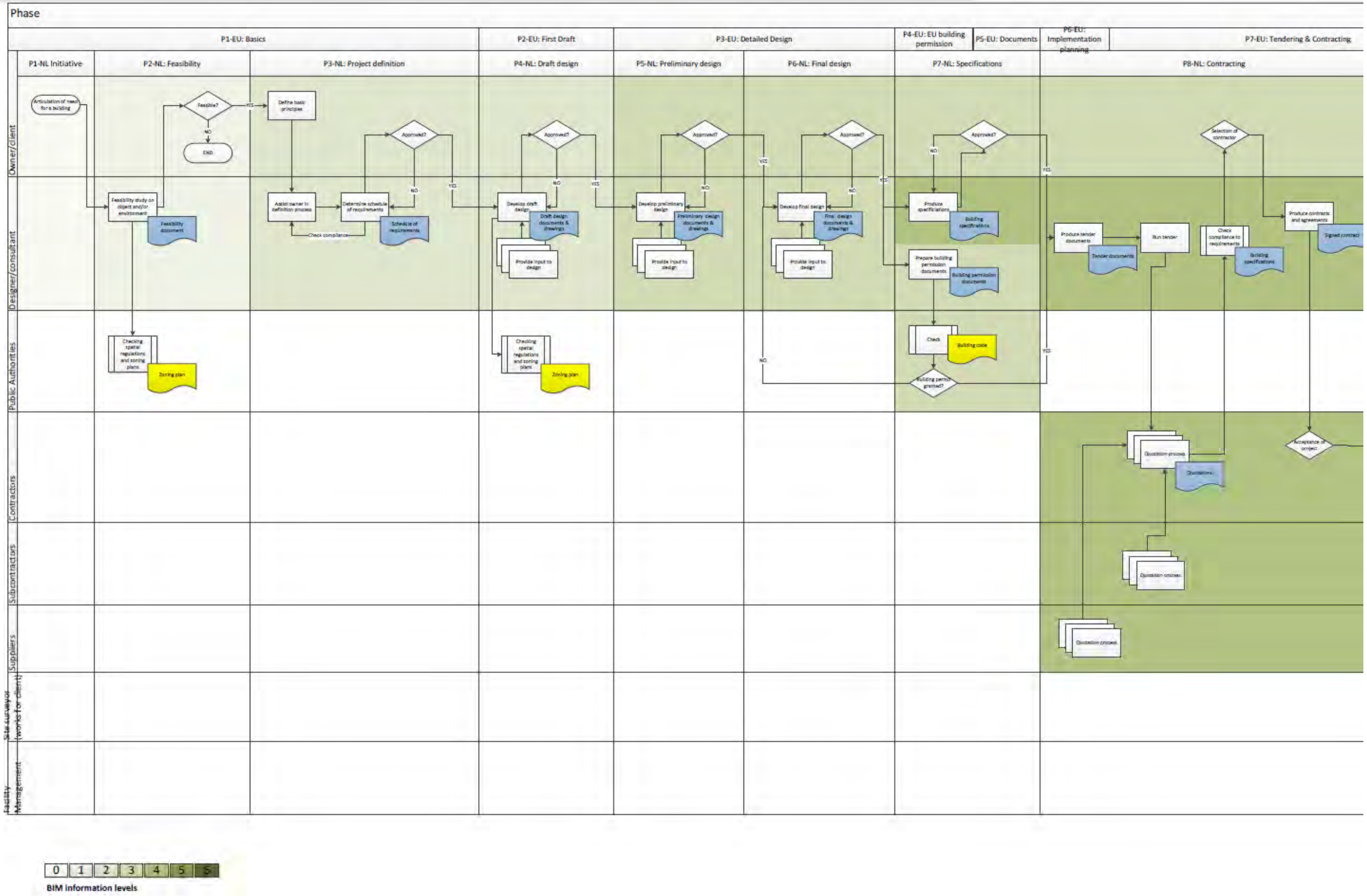


Fig. 9 Detailed BIM workflow (raws for stakeholders, columns for stages). 1/2

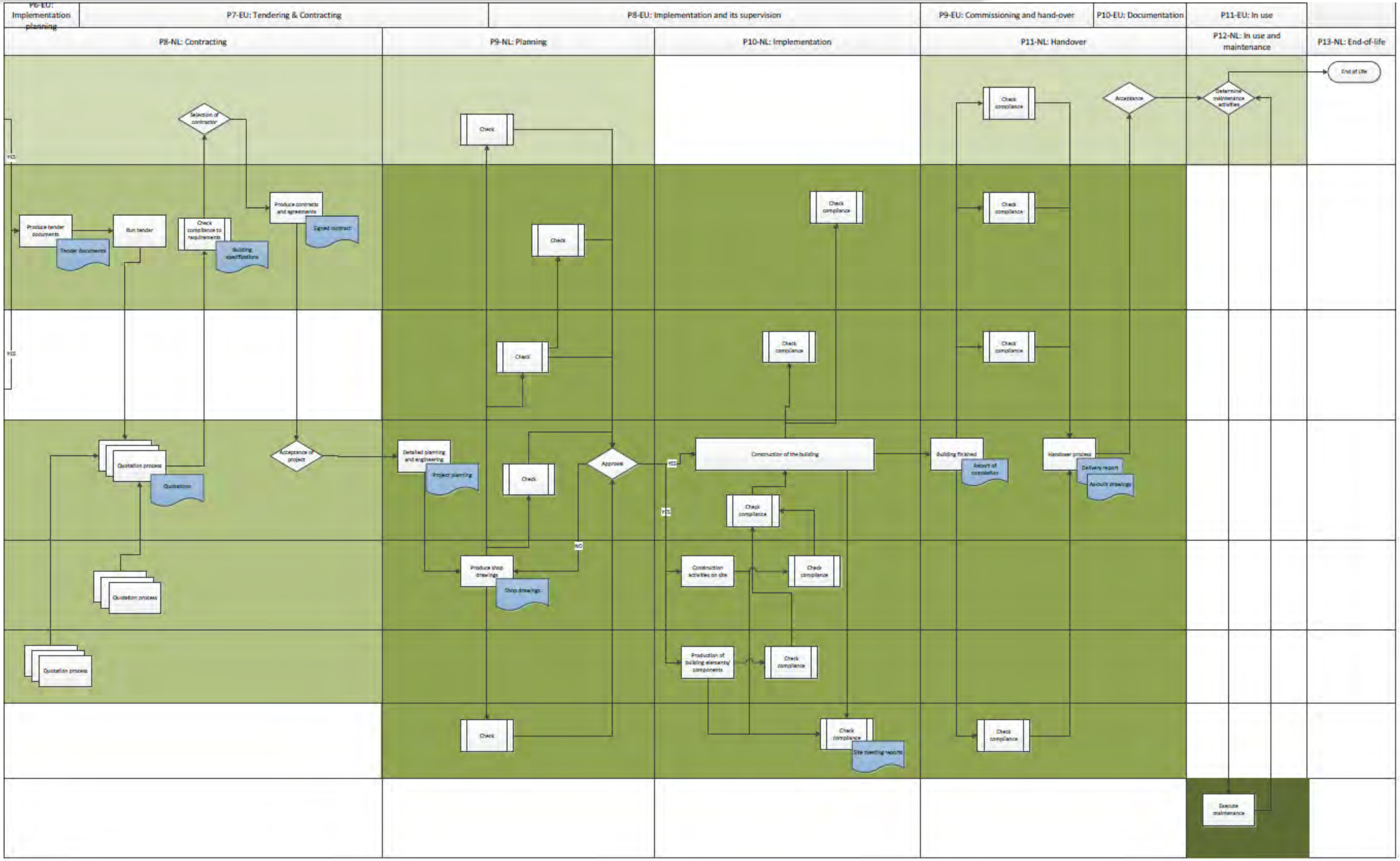


Fig. 10 Detailed BIM workflow (raws for stakeholders, columns for stages). 2/2

4.1.3 Retrofitting case

The workflow corresponding to a retrofitting context is slightly different from the ones applied to new buildings. However, most of issues to be tackled are similar. Some of the main differences are:

- Opportunity to carry out quality checks prior to design and implementation,
- Limited information and/or difficulty to access it (e.g. exact description of wall layers components)
- Specific technical solutions to be implemented.

The following figure describes the main stages of a retrofitting workflow.

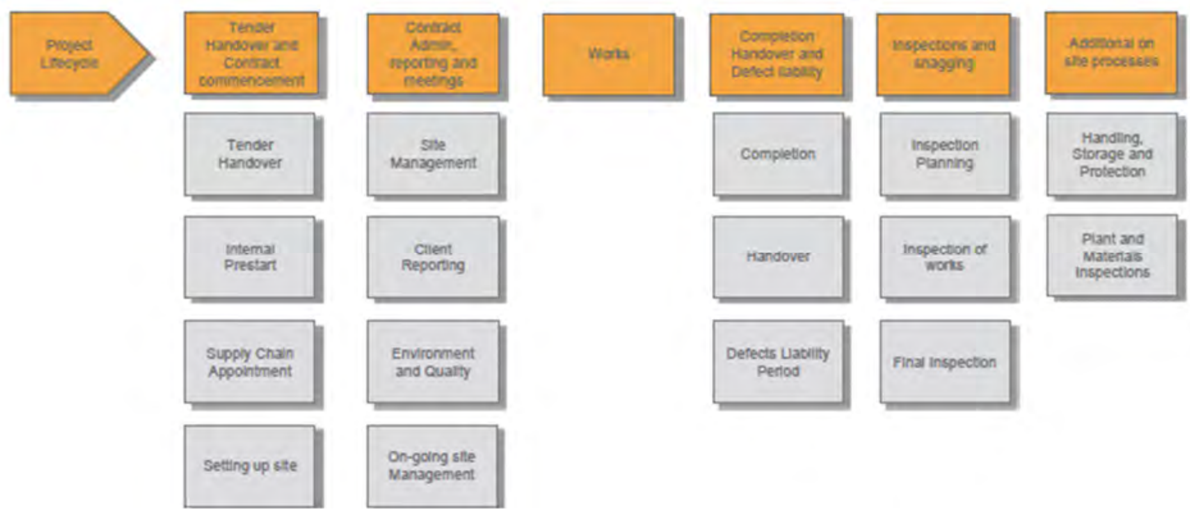


Figure. 11 Schematic workflow in retrofitting context (example for the UK)

4.2 Stakeholders and challenges

The relevant stakeholders groups and target users are outcomes of the desk study previously described in section 3.

Different groups of stakeholders interact with the construction project. They have different roles, at different moments, and also specific objectives and constraints. The different roles are usually similar from one country to another, even if some terms are sometimes difficult to translate precisely (e.g. *maître d'ouvrage*, who represents in the French context the entity who defines the need, the objectives, the budget, but is not necessarily the future owner himself).

A detailed analysis of the stakeholders has been carried out by each Work Package 1 partners, the main results are available in the surveys that have been carried out. Here is an overview of the different roles and stakeholders groups in the context of the Spanish regulation that can be extrapolated to all countries as a typical organization of actors in a construction project:

The actors named AGENTS in Spain, are defined by law according to the LOE "La Ley 38/1999 de 5 de noviembre, de Ordenación de la Edificación "_"Law 38/1999 of 5 November, Building Management" in its chapter III . All the definitions have been extracted and translated into English from this regulation.

The table below thus shows the most representative example of the complexity of the legal framework.

Table 1 Stakeholders obligations and regulation in Spain

ACTOR	DEFINITION	OBLIGATIONS
Promoter/ Developer	*It will be considered promoter any individual or legal entity, public or private, individually or collectively decides, promotes, plans and finances, using its own resources or outside, the building work for themselves or for their subsequent sale, delivery or transfer to third parties under any title.*	*a) To hold on the solar ownership authorizing him to build on it.* *b) Provide the documentation and background information necessary to draft the project and authorize the project supervisor subsequent amendments to the project.* *c) Manage and obtain the required licenses and administrative authorizations and sign the minutes of receipt of the work.* *d) Subscribe safe under Article 19. e) LOE. Provide the acquirer, if any, as built documentation, or any other document required by the competent authorities.*
Designer	*The designer is the agent commissioned by the developer that, according to the relevant technical and planning regulations, drafted the project.*	*a) Being in possession of the qualifying educational and professional qualifications of an architect, technical architect, engineer or technical engineer, as appropriate, and meet the conditions required for the exercise of the profession.* The qualification enables architect for projects of all types of buildings and all kinds of interventions. (New buildings, existing buildings, urban planning, structures, facilities…) The other qualifications, enable them to undertake specific interventions in buildings or building typology (see Article 2 LOE) *b) Prepare the project according to the regulations and what is established in the contract and return it, with visas if they were mandatory.*

		c) To agree, where appropriate, with the promoter partial hiring collaborations.
Builder	*The builder is the agent that assumes contractually with the promoter, the commitment to implement human resources and materials, own or others, works or part of works according with the project and the contract.*	*a) Execute the project work according to the applicable legislation and the instructions of the construction director manager and the director of the execution of the work, to achieve the quality required in the project.* *b) Have a degree or professional qualification that enables to fulfil the conditions required to act as a builder.* *c) Appoint the site manager to assume the technical representation of the builder in the work assuring that their qualifications or experience should be adequately trained in accordance with the characteristics and complexity of the work.* *d) Assign the human and material resources required in the works.* *e) To issue the subcontracting of certain parts or facilities of the work within the limits established in the contract.* *f) Sign the minutes of the commencement of works and the minutes of receipt of the work.* *g) To provide the necessary data to construction manager director for the development of the as built documentation.* *h) Subscribe the guarantees provided for in Article 19 LOE*
Construction manager director	*Is the agent, as part of the SITE TECHNICAL DIRECTION, manages the development of the work in technical, aesthetic, urban and environmental aspects, in accordance with the defined project, building license and other required approvals and conditions of the contract, in order to ensure their suitability for the intended purpose.*	*a) Being in possession of the qualifying educational and professional qualifications of an architect, technical architect, engineer or technical engineer, as appropriate, and meet the conditions required for the exercise of the profession.* The qualification enables architect for direction of all types of buildings and all kinds of interventions. (New buildings, existing buildings, urban planning, structures, facilities…) The other qualifications, enable them to undertake specific interventions in buildings or building typology (see Article 2 LOE) *b) Check the setting out and the adequacy of the foundation and structure projected to the geotechnical characteristics of the land.* *c) To resolve the contingencies that may occur in the work and list them in the Order Book and Assists precise instructions for the correct interpretation of the project.* *d) Prepare, at the request of the promoter or with its agreement, any changes in the project that may come required by the progress of the work, provided that they are adapted to the regulatory provisions referred to and observed in the project.* *e) To sign the minutes of minutes of the commencement of works and the final certificate of work and form the partial certifications and final settlement of the units of work performed, with visas if they were mandatory.* *f) Develop and sign the documentation of the work performed, for delivery to the promoter, with visas if they were mandatory.* *g) listed in Article 13, in cases where the Construction manager director and the works execution director is the same professional, if this option is chosen, in accordance with*

		Referred in paragraph 2a) of Article 13.
Works execution director	*Iis the agent as part of the SITE TECHNICAL DIRECTION, assumes the technical function of directing the material execution of the work and to control* ***construction quality*** *and quantity and quality of what is built.*	*a) Possession of the academic and professional qualifications and meet the conditions required for the exercise of the profession.* *When the works to be aimed at the construction of buildings for the uses indicated in group a) of paragraph 1 of Article 2, the academic and professional qualifications will be* ***technical architect (building engineer)****. It is also the enabling qualification for the works of the group b) directed by architects.* *In other cases the works execution director position can be performed indistinctly by professionals with the degree of architect, technical architect, engineer, or technical engineer.* *b) Check the reception of the construction products in the construction works, ordering the testing and accurate testing.* *c) Directing the material execution of the work checking stakeout materials, proper execution and disposal of construction elements and facilities, according to the project and with the instructions of the construction director manager.* *d) Include in the order book and Assists precise instructions.* *e) To sign the minutes of the commencement of work and the final certificate of work, and develop* *And signing the partial certifications and final settlement of the units of work performed.* *f) Collaborate with the other actors in the elaboration of the as built documentation, providing the results of controls executed.*
The entities and laboratories for quality control of the construction works.	*They are* ***entities of QC of construction works*** *those trained to provide technical assistance in verifying the quality of the project, materials and execution of the work and its facilities according to the project and the applicable regulations.* *They are* ***testing laboratories for quality control of the construction works*** *those trained to provide technical assistance, by conducting tests or service tests of materials, systems or facilities of a building work.* .	*a) Provide technical assistance and deliver the results of its activity to author custom agent, and in any case, the director of the execution of the works.* *b) Justify the capacity of human and material resources needed to perform the contracted work properly, if necessary, through the appropriate official accreditation from the legal authorities.*
Product Suppliers	*1.* ***Product suppliers*** *are considered manufacturers, wholesalers, importers or sellers of construction products.* *2.* ***Construction product*** *is product manufactured for permanent incorporation into a work including materials, semi-finished items, components and works or part of them, both completed and under implementation.*	*a) Making the supply of products according to the specifications of the order, responding to their source, identity and quality as well as compliance with requirements, if any, established by the applicable technical regulations.* *b) Provide, where appropriate, instructions for use and maintenance of the products supplied,* *As well as the corresponding quality guarantees for inclusion in the documentation of the work performed.*
Owners and users		*1. The obligations of the owners are to keep the building in good condition through proper use and maintenance, as well as*

		receive, preserve and transmit the as built documents and insurance and guarantees. *2. The obligations of users, whether or not owners, are, the proper use of the building or part thereof in accordance with the instructions for use and maintenance in the as built documents.*

The interaction between each stakeholder group and the construction project has already been represented in the construction project workflows (previous section and first annexes). The interactions between the stakeholders can be represented in many different ways, depending on the line of interest and the point of view.

The following scheme is a simple proposal from a quick analysis, positioning the user and the owner at the centre of all the interactions.

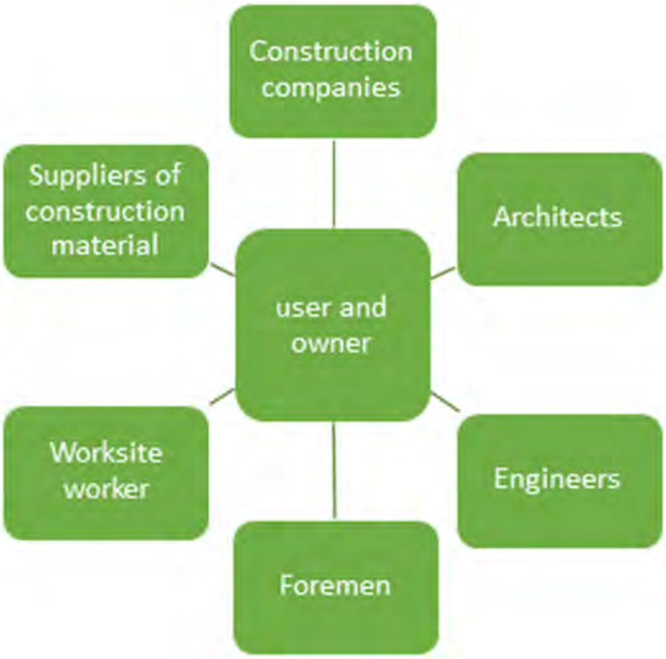


Fig. 12 Representation of the main stakeholders groups

Here is another representation of the stakeholders groups, classified according to their main relation with the different stages of the project.

Table 2 Distribution of stakeholders among the main stages of a construction project, depending on their main role

PROJECT INITIATION	PROJEcT DESIGN AND IMPLEMENTATION	PROJECT RELATED GROUPS
1) Owner and investor	2) Designer, architect	8) Facility Management
		9) Public Offices
	3) Technology Planers	
		10) Building user
	4) Worksite supervisor (including site workers)	
	5) Quality assurance: 5a: energetic, 5b other certificates	
	6) Construction companies	
	7) Material and Component suppliers	

We observe that the interactions between the stakeholders are sometimes complex and difficult to represent. This analysis emphasizes the need for adapted collaborative tools to facilitate and concentrate the communications between all the stakeholders. This need goes well beyond the existence of BIM tools to represent the building itself and all its components. The collaborative tools could integrate communication flows, control and validation procedure, different types of formats, follow-up and history of the construction project, etc. The next sections of this document aim at precising the needs and requirements related to these collaborative tools.

In a general approach, we could locate the main key problem areas across a construction process as follows:

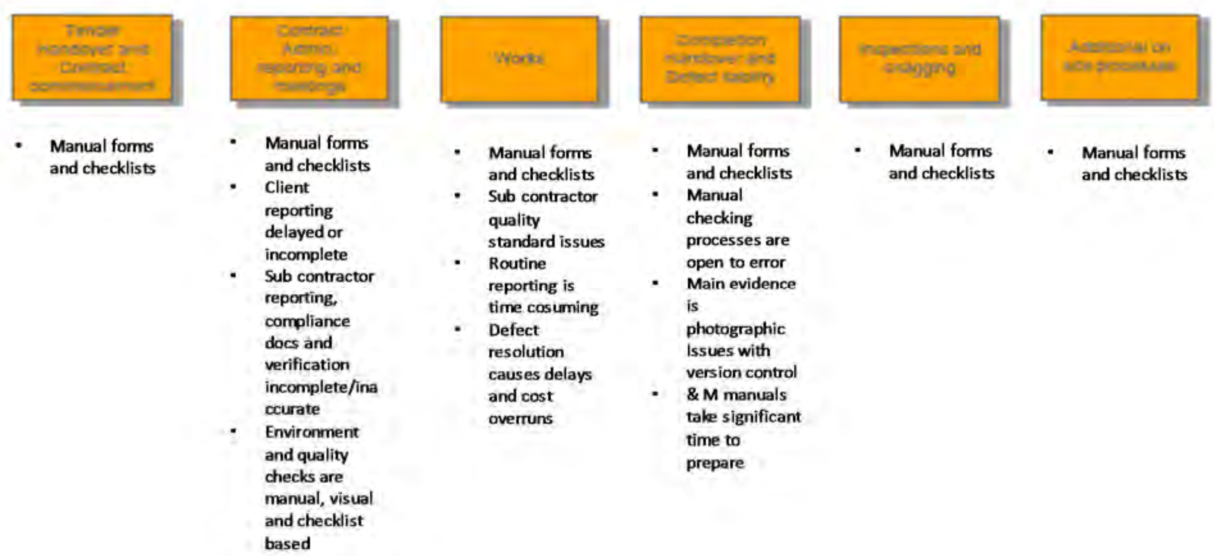


Fig. 13 Key problem areas of a construction process

More specific issues can be identified, as presented in the table below (source: Closing The Gap project, Zero Carbon Hub). In the scope of the questionnaires answered by all the participants of Work Package 1, each partner has assessed the criticality of each issue, and provided explanations/comments. The complete results are available in the questionnaires, which served as essential sources of information for this report.

Table 3 Specific issues during a construction process (source: Closing The Gap project, Zero Carbon Hub)

Issue*	Category
Limited understanding by planners or funders of the impact of phasing or aesthetic requirements on performance and energy related targets.	Land acquisition, concept design and planning
Limited understanding by concept design team of impact of early design decisions on performance and energy related targets.	
Inconsistent setting of standards and targets between local authorities (methodology/level) leading to increased complexity of solutions.	
Limited guidance, modelling tools and standards available to evaluate and review issues associated with energy performance at early design stages, including overheating.	
Inadequate understanding and knowledge within design team (buildability, thermal detailing, tolerances, construction systems and materials, site conditions, SAP and energy issues, performance).	Detailed design
Lack of integrated design between fabric, services, renewables and other requirements (e.g. due to lack of specialist input).	
Lack of communication of design intent through work stages, e.g. due to discontinuities in design team, specialist involvement or general work contract structure.	
Lack of suitable design tool that incorporates compliance check.	
Design team not communicating sufficient information regarding critical energy performance criteria of components to procurement team.	
Insufficient design information provided for building fabric, potentially leading to critical decisions being left to contractor/sub-contractor at construction phase.	
Insufficient design information provided for building services, potentially leading to critical decisions being left to contractor/sub-contractor at construction phase.	
Product and system design issues, e.g. concerns about robustness of product design, systems design issues.	
Manufacturer information lacking critical energy performance detail, relating to either building fabric or services.	Procurement
Inadequate consideration of skills and competency requirements at labour procurement (fabric and services).	
Product substitution at procurement without due regard for performance criteria.	

Issue*	Category
Procurement team lack of understanding of critical energy-performance related criteria.	
Tender documentation not containing up-to-date requirements or trade specifications.	
Lack of designer input available to site if issues arise, e.g. due to type of contract.	**Construction and commissioning**
Sales or year-end/interim build targets driving programme delivery - putting labour out of sequence and potentially compromising construction quality.	
Frequently changing site labour limiting ability for lessons to be shared or learnt.	
Construction responsibilities for energy performance unclear, lack of collaborative working, e.g. services penetrating air barrier.	
Product substitution on site without due regard for impact on energy performance.	
Lack of adequate quality assurance on site and responsibility for QA, e.g. due to site managers being overly reliant on sub contractors' QA processes, variability in processes, lack of supervision, reliance on Building Control.	
Lack of understanding in sales team of impact of changes, e.g. customer add-ons which affect SAP.	
Lack of ability to identify some products on site/in situ, e.g. by operatives or for QA or audit purposes.	
Poor installation or commissioning of services, e.g. due to installation guidance or design drawings not followed, lack of manufacturer installation and/or commissioning guidance.	
Short term fixes and improvisations on site without understanding of long-term impact, e.g. mastic for achieving required air pressure test result.	
Full design information or installation guidance produced but not available on site.	
Site management - inadequate consideration of sequence of trades and activities on site, later phase work undermining previous works.	
Lack of site team energy performance related knowledge and skills and/or care.	
Accredited Construction Details 'tick box' culture, i.e. recorded in SAP but not built on site.	
Poor installation of fabric, e.g. due to installation guidance or design drawings not followed.	
Lack of robust verification of planning requirements and standards at completion.	Verification

Issue*	Category
Lack of robust energy-performance related verification, reliance on third-party information (e.g. by Building Control or warranty providers).	
Commoditised third-party schemes not independent or checks not adequate (including Competent Persons Schemes).	
Lack of Building Control enforcement ability relating to energy efficiency legal requirements.	
Lack of clarity over documentary evidence required or acceptable for energy efficiency and other regulations applying.	
Limited tests and agreed protocols available for in-situ fabric performance measurement.	Testing
Limited tests and agreed protocols available for in-situ services performance measurements, including for system performance.	
Concern over consistency of some test methodologies and interpretation of data and guidelines.	
Limitations of air-pressure testing methodology (QA, robustness of third party certification, protocols).	
Lack of suitable end-of-line overall performance test to validate energy calculation models, products and building fabric.	
Tests not replicating or accurately taking into account dynamic effects, e.g. solar gain, microclimate, wind speed, weather effects.	
Limited tests and agreed protocols for innovative/less mainstream products and services.	
Commercial pressures leading to optimistic SAP input assumptions.	Energy modelling tools and conventions
Concerns about accuracy of aspects of the SAP calculation model and assumptions, e.g. thermal mass, hot water, ventilation, overheating, cooling, lighting, thermal bridging, weather, solar shading, community heating, particular technologies.	
SAP conventions not adequate, comprehensive or reflective of site conditions.	
As-built SAP not reflective of actual build.	
Lack of transparency and clear outputs for verifiers to check modelling assumptions (including designers to verify material performance assumptions, building controllers and others).	
Infrequent or insufficient audits of SAP assessors by licensing organisations.	
Concern over competency of SAP assessors (accuracy of data input, following of conventions, validation of assumptions, provision of design and specification advice).	
Issues surrounding use of calculation procedures related to U-values and Psi-values or associated Standards.	
Limited as-built test data used in SAP calculations (only air-pressure testing).	

Issue*	Category
Limited ability to include new technologies in SAP calculations.	
Concerns about the robustness or lack of overheating checks outside SAP.	

**Issues from "Issues list" (source: Closing the gap: End of term report. Zero Carbon Hub. 2014). http://www.zerocarbonhub.org/current-projects/performance-gap*

We can observe that the problems to be addressed involve most of the stages of a construction process. However the implementation/works stage is probably the one with the larger potential for improvement, as relatively few innovations have been brought to what happens on the construction site (whereas design, commissioning or operation stages have recently benefitted from a large number of technological improvements).

4.3 Users meet solution providers: from workshops to a Built2Spec community

Once the stakeholders and their main issues are listed, it is possible to ask them about their needs in order to improve the performance of the building all over its construction process.

The needs are gathered in several countries by means of paper work (desk study, questionnaires) and oral communication (workshops, interviews).

4.3.1 Workshops towards the Built2Spec stakeholders community

Several workshops have been organized in several countries, aiming at gathering a large variety of stakeholders and collecting their needs (before imagining potential solutions). These workshops are the first step of the constitution of the Built2Spec stakeholders' community, composed of professionals eager to test and implement innovative solutions to tackle the issues they regularly face during construction projects. Built2Spec communication activities and new events to come will be as many opportunities to keep informed and involved the members of this community, and make it grow at the same time.

Four workshops are shortly presented in the next sub-sections: Italy, UK, France, Spain. A 5th workshop is planned for April 2016 in Germany.

4.3.1.1 Workshop in Italy

Fig. 14 Italian workshop, November 27th 2015, Pescara

About 80 attendees participated in the Built2Spec workshop on November 27th 2015 in Pescara, Italy, comprising designers, construction companies and representatives from local municipalities.

„We had a real great and successful workshop", said Daniele Bortoluzzi from R2M. „The audience was really interested in our project and we hope that fruitful cooperations can be established in the future." The workshop organisers submitted a survey to the attendees to collect information on user requirements.

Considerable data have been collected during the workshop to be integrated in the project analysis of the user needs.

A demonstration of the potential of the Virtual Construction Management Platform has been carried out during this event, organized by DE5, R2M, VRM.

4.3.1.2 Workshop in the UK

Fig. 15 UK workshop, November 17th 2015, London

The UK workshop took place in London on 17th November 2015. The specific aims of this workshop, arranged by Lakehouse and BSRIA Ltd, were to:

- Understand the quality-related issues observed or experienced within the construction industry from a representative stakeholder group,
- Define, assess and understand the quality checks and controls used within the house building process pre, during and post construction.

A total of 30 people attended the event, comprising a mixture of representatives from housing associations, universities, architects, house-builders, local authorities, building professionals, charities and other relevant not for profit research organizations.

The quality issues reported by the workshop participants covered a range of themes including:

- Lack of skills, knowledge, training and awareness.
- Lack of communication, collaborative work and integrated design.
- Roles and responsibilities.
- Lack of continuity – changes made during design, during construction and post construction.
- Insufficient information.
- Cost and time constraints.
- Supply chain issues.
- Technical issues – pre-construction stage.
- On-site issues.

- Policies and other barriers to work.
- Lack of testing, commissioning and handover.
- Lack of aftercare and occupant behavior.

4.3.1.3 Workshop in France

Fig. 16 French workshop, October 22nd 2015, Bordeaux

The French workshop took place in Bordeaux on 22th October 2015. Organized by NOBATEK and CREAHd, it aims to launch a discussion with stakeholders of the building construction sector on "How to improve the quality of the construction process?" The following questions were discussed:

- What are the main issues?
- What needs to be checked and controlled?
- What tools and technologies for self-inspection and quality checks are needed?
- Improving the communication: which needs, feedbacks and solutions?

A total of 40 people attended the event, representing all categories of stakeholders from housing associations, universities, architects, building professionals, constructors, building owners.

4.3.1.4 Workshop in Spain

Fig. 17 Spanish workshop, June 26th 2015, Barcelona

Project partners OHL, EURECAT and VRM organised a workshop for over 20 construction stakeholders at EURECAT's office in Cerdanyola del Vallès (Barcelona) on June 26th 2015.

After a presentation of the tools and the virtual construction management platform developed in the Built2Spec project, the attendees discussed the users' needs regarding the future platform and filled in individual surveys.

As main conclusions we can highlight that experts agree that using control systems and tools integrated in a virtual platform will be a good way to organize and share information, and facilitate monitoring and verification of the work.

Built2Spec tools offer a great potential not only to check completed work, but also to diagnose existing buildings, even during its use for maintenance or improvement purposes.

Experts involved in the construction process believe that it is essential to perform construction activities correctly, or in order to avoid the emergence of problems and the likelihood of a performance gap between design and as-built.

4.3.2 Synthesis of user needs across Europe

The next table present an overview of the main needs, organized by type of stakeholder, and resulting from the various sources of collected data: desk study, questionnaires, workshops. Beyond the question of the needs, the stakeholders were also asked about how they imagine Built2spec developments can provide a solution**. This table probably represents the main output of task 1.1, resulting from the synthesis of a large number of stakeholders from many different countries**.

The suggestions collected here present the point of view from the user of the solution (architect, worker, etc.). Next sections (5 to 9) will present which solutions could be brought to the stakeholders and satisfy their needs, with the point of view of the solutions provider.

Table 4 Synthesis of the user needs and their expectations across Europe

User group	What are the user needs?	Which aspects of the buid2spec platform can serve it ?
Architects	• Handle all the documents on site • Make documents modification • Take note during the surveys • Review all the design documents • Having the contracted specifications and the last versions of drawings at hand. • Contact details and access to the correspondence • Access to the current norms and regulations • Documentation of the communication • Prompt communication • Easy to obtain, open, and real time data about the real performance of the construction , structure and facilities systems • Ongoing validation of both thermal and acoustic properties as the building progresses • Documented quality checks with regard to 'as-built' geometry etc.	• Possibility to use his/her smartphone/tablet on site to review the technical reports and drawings allowing him/her to make modification according to the situation needed on site. • Including into the platform a CAD app to make drawing modification/updates. • Including app able to catch photos and take notes on them. • Including editor to modify text file. • Integration with BIM could be useful to have a real view of the whole process. • Clear structure Online access to the documents and drawings Aids to facilitate better orientation (which part of the drawing am I considering at the moment?). • Object related structure of contact data, ordered according to the trades and linked to the contracted specifications • Access to a server of the norms Overview of the current norms • Access to internet/email and storage of the email in the project folder in the specific trade file • B2S technologies can serve to obtain this data in an easy way, and to compare the real performance of the building, allowing stakeholders to know when and where to intervene if necessary • . Efficient management of material specifications to ensure an accurate 6D BIM model
Engineers	• Handle all the technical documents and reports on site	• Including app allowing him/her to access on to structural/plan numerical model to verify local or global situation and or make modifications/updates if need. I.e. create a link to a server where all these numerical model are stored and are ready to "run".

User group	What are the user needs?	Which aspects of the buid2spec platform can serve it ?
	• Take note and review/update the technical documents • Having the last version of drawings and calculations • Contact details and access to the correspondence • Access to the current norms and regulations • Easy to obtain, open, and real time data about the real performance of the construction , structure and facilities systems • Ongoing validation of all structural details to include checks on reinforcement quantity, size spacing etc. Checks on structural steel connections ie. number of bolts, size etc.	• Including app able to catch photos and take notes on them. • Including editor to modify text file. • Online access to the documents and drawings • Access to internet/email and storage of the email in the project folder in the specific trade file • Access to a server of the norms • Overview of the current norms • B2S technologies can serve to obtain this data in an easy way, and to compare the real performance of the building, allowing stakeholders to know when and where to intervene if necessary • Extremely accurate onsite 3D imaging capturing intricate structural details and comparing with the intended
Construction companies	• Final design choices approval (e.g. each material or component to be installed is selected by the contractor and needs approval from the designer/owner) • Handle all the documents on site • Document and quantify the progress of the construction works to justify payments based on work progress • Review all the design documents • Be aware of the worksite current situation • Easy to obtain, open, and real time data about the real performance of the construction , structure and facilities systems • 4D BIM capabilities essential in conjunction with project management software • 5D BIM capabilities in order to manage costs efficiently	• Integrate into the VCMP a sheet to document with photos, sketch and/or simple drawing the progress of the work, note and so forth the works progress day-by-day. • Integrate into the platform a check list of the material to be used "floor-by-floor" avowing mistakes during the assembly. Moreover it helps to manage the worksite space organization keeping it safe and clean. • Link to installation manuals, standards/requirements, material datasheet and Supplier contact. • Creating a communication system (e.g. chat) with all the actors for quick question. • B2S technologies can serve to obtain this data in an easy way, and to compare the real performance of the building, allowing stakeholders to know when and where to intervene if necessary • Ongoing comparison of actual progress to predicated to ensure project completion within the expected timeline

User group	What are the user needs?	Which aspects of the buid2spec platform can serve it ?
	throughout the entire construction stage	
Client, project owner	• Having updated and contracted specifications at hand • Having access to the correspondence • Monitor the work progress • Be aware of the worksite current situation	• Logging into platform Owner should be able to have a dedicated part regarding the progress of the works (with photos, notes etc.) and the main documents. • An "approval check list" should also be present for any modification needed on site. • Online access to documentation
Worksite workers	• Having updated and contracted specifications at hand • Have a timetable for the activity • To work in a safety way	• Create a database with all the final technical documents (drawings, etc). • Include a detailed and editable Gantt Chart into platform to check what to do and update with the works progress. • Allow the workers to upload photos, take notes documenting the progress of the work and/or underlining errors or the need of modifications. • Control the location of the workers in the worksite to improve their safety
Worksite supervisors	• Having updated and contracted specifications at hand for surveys • To supervise the work progress • Easy to obtain, open, and real time data about the real performance of the construction , structure and facilities systems • Construction as per design specifications	• Create a check list with the quality/quantity checks to be performed on site during the survey; • Create a calendar for periodical on-site inspection. Email alarms can be generated to advise all the actors about this events. • Possibility to compare designed with build – take photos, add notes and so on when necessary. • Possibility to create a geo-tagged photos during the survey. • Create automatic email alarms when something is wrong or bad build. • Including into the platform a CAD app to make drawing modification/updates • B2S technologies can serve to obtain this data in an easy way, and to compare the real performance of the building, allowing stakeholders to know when and where to intervene if necessary
Managers	• Management issues • To handle the construction works • Having the last version of drawings and calculations • Contact details and access to the correspondence	• A database containing all the documents for site, technical and administrative management. • Online access to the documents and drawings • Access to internet/email and storage of the email in the project folder in the specific trade file • B2S technologies can serve to obtain this data in an easy way, and to compare the real performance of the building, allowing stakeholders to know when and where to intervene if necessary

User group	What are the user needs?	Which aspects of the buid2spec platform can serve it ?
	• Easy to obtain, open, and real time data about the real performance of the construction , structure and facilities systems	
Quality supervisors	• Quality check; i.e. compare designed with build. • Supervising that works are done in the correct way • Having the last version of drawings and calculations • Contact details and access to the correspondence • Easy to obtain, open, and real time data about the real performance of the construction , structure and facilities systems	• Having updated and contracted specifications • Possibility to compare designed with build – take photos, add notes and so on when necessary. • Create automatic email alarms when something is wrong or bad build. • Create a SCORE for the quality survey could be useful (e.g. 0 = bad works; 10 = excellent work). • Online access to the documents and drawings • Access to internet/email and storage of the email in the project folder in the specific trade file • B2S technologies can serve to obtain this data in an easy way, and to compare the real performance of the building, allowing stakeholders to know when and where to intervene if necessary
Facility managers	• Have access to reliable information such as real “as built” • To check easily the correct execution of the facility network • Having the last version of drawings and calculations • Contact details and access to the correspondence • Easy to obtain, open, and real time data about the real performance of the building and facilities systems • 6D BIM Model containing all relevant information	• Give them access as “real built”. • Online access to the documents and drawings • Access to internet/email and storage of the email in the project folder in the specific trade file • B2S technologies can serve to obtain this data in an easy way, and to compare the real performance of the building, allowing stakeholders to know when and where to intervene if necessary • Smart materials, thermal techniques, air tightness and acoustic techniques • Access to comprehensive BIM for project visualisation

Additional groups :		
Property owner	• Having updated and contracted specifications at hand • Having control of the work progress. • Be aware of the worksite current situation	• Online access to the documents and drawings, and current situation of work site
Construction product suppliers	• Having an exact list of materials (concerning both quality/technical properties and quantity) to be delivered to the worksite • Having the last version of drawings and calculations • Contact details and access to the correspondence • Assurance of their products being used according to the specifications	• The VCMP should contain all the updated documents coming from the worksite work progress, thus an efficient plan for the materials supply can achieved. This help the supplier to managed all the shipment activities avoiding delays, errors and so forth. • Online access to the documents and drawings • Access to internet/email and storage of the email in the project folder in the specific trade file • Smart materials, thermal techniques, air tightness and acoustic techniques – reassurance of the correct properties of building materials • BIM of their products accessible for industry • Imagery techniques for continuous inspection of construction progress and quality reassurance
Public/local authorities	• Periodical on-site inspection • Having updated and contracted specifications at hand for administrative check • Having access to licenses	• Adding photos, notes, sketch about the progress of the works (e.g. taken/made by Contractors, Owner, Worksite supervisor/director) can avoid on-site inspection • About the administrative check, having into the platform a dedicated check list can saving time and make the process more efficient and avoid mistakes and/or forget to check few documents required. • Link from the platform to local authorities information about licences and legal requirements
Building control	• Check the progress of the work on worksite with periodical survey; • Update the “cost report” based on the work progress.	• Integrating into the platform a part concerning the costs will avoid on site survey with consequent time and money saving. In fact Contractor can take photos and add notes day-by-day and document in near real time the work progress simply by using a tool into the VCM Platform. In this way the “cost report” can easily updated and reviewed standing in office.
Funding organisations	Best value for money	Summary reports on the construction process and materials used
Users/Inhabitants	• To enjoy the facilities with a certain comfort • High quality construction	Summary reports on the construction process and materials used Access to comprehensive BIM for project visualisation and future renovations

	• Buildings designed and constructed according to standards and regulations	
Designers	• Check the requirements sent to the Contractors • Having updated and contracted specifications at hand at any time.	• Integration of the VCMP with BIM. • Link to installation manuals, standards and requirements. • Create a materials database. • Check list of the all documentation to be provided to the Local Authority for the project approval.

As a conclusion, the main types of solutions to be tackled by Built2Spec are the following ones:

- **Codified template forms and checklists**
    - Reduce errors and delays
    - Reduce manual checking
    - Support verification of sub contractors
    - Improve sub contractor compliance and so improve payments
- **Technology supported quality checking** (e.g. integrated measuring tools and data capture)
    - Reduce time spent and errors made
    - Capture potential defects sooner
- **Automated data sharing and communications**
    - With customers
    - With supply chain
    - With key 3rd parties – e.g. building control

The exchanges that occurred to collect all the information presented in this section (workshops, interviews, questionnaires) are **a key part of the process to constitute the Built2Spec community**: an international collective of stakeholders eager to develop and implement new self-inspection techniques and quality check methodologies on construction project and buildings.

The following sections aim at describing for each technological field or topic: the **state of art context, the main barriers, the expected future solutions, and how Built2Spec could provide some of these solutions**. Based on these elements, Work Packages 2 to 6 will deal with proposing the precise requirements to be adopted in order to develop the new solutions. All the solutions will be tested at limited scale in these work packages and then at more realistic scale in Work Package 7 (pilots).

5 Requirements: Thermal performance of the envelope

There are several ways for assessing the thermal performance of a wall or an envelope. Here we focus essentially on non-destructive remote sensing techniques, involving most of the time infrared thermography.

5.1 Business as usual thermography inspection and quality checks

Building fabric inspection is one of the oldest thermography applications, and is still one of the most common uses of thermography. But it is not widely adopted as a mean of demonstrating compliance with building codes or energy efficiency regulations. Barriers to the use of thermography include: limited temperature difference, non-steady state conditions builders' reluctance to reveal faults in completed buildings. Built2Spec aims to increase the use of thermography for demonstrating compliance or the need for improving thermal insulation in new buildings and refurbishment projects by promoting the use of advanced thermal analysis and easy survey methods.

Thermography was first used for building inspections in the1970s, and, in 1972 a report (Paljak and B. Pettersson, 1972) was published in Sweden showing thermal images of artificially created faults to assist in identification of faults. Following this report an International Standard, ISO 6781, was published. The European and British Standards follow this standard closely as do standards in other countries. At the time of writing the International Standard is being revised and updated. The scope covers testing to identify irregularities but not the determination of thermal transmittance. In fact it specifically identifies that only differences greater than 50 % or at best 25 % in thermal transmittance can be detected by the method. The standard sets limits on environmental conditions that are quite stringent and prevent compliant surveys for approximately 7 months each year in the UK latitudes of roughly 50-60°N (more or less at other latitudes).

Building thermography is recommended or required in some countries for new buildings and significant refurbishments. Infrared cameras have been improved enormously since the 1970s with increased sensitivity, ease of use, and sophisticated onboard analysis at the same time at a reduced prices. There is a wealth of experience that is passed on through organized training, but standards and codes of practice have not kept up with developments in practice or technology. In particular, severity assessment and acceptance criteria are rarely stated in Standards or Codes of Practice, surveys relying on the judgment of the thermographer. These advances combine to produce an opportunity for increasing the use of thermography in checking compliance with building energy efficiency requirements.

There is a good case for thermal imaging every new building and every building on which major work has been done. In the UK for example, from reports on buildings that have been surveyed approximately 30% have significant anomalies that would affect the thermal performance through the life of the building. There are thought to be in the region of 100 thermographers in the UK who claim to be able to do surveys of buildings. However only 10 have registered as Category 2 Building thermographers on the voluntary UKTA Register.

Thermal imaging is usually not required by Building Regulations. It is sometimes recommended as an option. Thermal imaging of old buildings prior to refurbishment and buildings on completion is used to contribute to Sustainability Assessments under BREEAM. Thermal imaging is also written into the Specifications for many developments on request from the owner, developer or project manager as a means of checking that the building meets their requirements.

In some buildings the emphasis is on avoiding condensation on internal surfaces and a surface temperature factor or thermal index is used. Surveys of older buildings are also useful in finding sources of heat gain or loss that need to be addressed in refurbishment. The BREEAM Domestic Refurbishment Technical Manual gives credit "Where Thermographic surveying and Airtightness testing have been carried out at both pre and post refurbishment stages." The BREEAM UK New Construction non-domestic buildings technical manual 2014 gives credit for testing "the integrity of the building fabric, including continuity of insulation, avoidance of thermal bridging and air leakage paths is quality assured through completion of post construction testing and inspection. Dependent on building type or construction, this can be demonstrated through the completion of a thermographic survey as well as an airtightness test and inspection."

The lack of acceptance criteria and restricted environmental conditions has limited the adoption of thermal imaging in compliance checking for new and refurbished buildings. This project aims to address the barriers to adoption to maximize the benefits that can be obtained from thermal imaging of buildings.

Over 90% of building inspections are qualitative in that they use the skill and judgement of the thermographer to assess the existence, severity and cause of any anomalies that appear in a thermal image. This approach relies on the availability of sufficient skilled and experienced thermographers to assess all the new and refurbished buildings. All surveys are aimed at detecting missing insulation, thermal bridges and air movement. Some also test for locations of air leakage.

Table 5 Building thermography survey methods

Method	Exterior front	Exterior roof	Exterior other walls	Interior wall surface	Interior floor	Interior ceiling	Severity	Quantify heat loss	Air leakage
Street view	*						?		
Aerial		*							
Typical compliance	*		*	*	*	*			
TI Compliance	*		*	*	*	*	*		
Co-heating test	*		*	*	*	*	*	*	*
Proposed Built2Spec	*	*	*	*	*	*	*		*

A number of semi-quantitative methods are used by a few thermographers to provide an objective assessment of buildings and any anomalies found. A method of assessing dwellings based on a thermal image of the side facing the road has been used on many thousands of houses, usually funded by Local Authorities as part of their commitment to energy efficiency. Accuracy in assessment of these surveys is subject to the internal temperature being the assumed level and emissivity being typical. The analysis software has, in most cases, been able to detect and allow for windows, which are known to have a different emissivity from most opaque building materials. This method is very limited in scope and accuracy. In the past, aerial surveys from fixed wing aircraft or helicopters have been common, but these also suffer from large uncertainties due to poor resolution, uncertainty in emissivity, lack of knowledge of internal temperatures and having a poor view of walls. For internal surveys it is possible to be reasonably accurate in quantifying the severity of thermal anomalies in a structure and some of the methods are described in more detail below.

5.2 Identification of needs for improved quality checks

Principles – environmental conditions and how they affect detectability of anomalies

Heat transfer through a building wall, for example, is affected by the thermal resistance of the structure, the thermal resistance of the boundary layers and the environmental temperature on each side as shown by

$$Q = A\ \Delta T/(R_i + R_s + R_o) \quad (12.8)$$

Where Q is the heat transferred, **A** is the area of the surface through which the heat is transferred, R_i is the thermal resistance at the interior boundary, R_s is the thermal resistance of the combined layers of structural members, and R_o is the thermal resistance of the outside boundary.

The resistance of the boundary layer depends on radiative and convective heat exchange so the local air speed has a great influence on its value. It is conventional in building energy assessments to lump the convective and radiative heat transfer coefficients together into one 'boundary layer resistance' value applicable to 'normal' environmental conditions as detailed in ISO 6946:2007[i]. On the outside of walls air speeds are typically much higher than on the inside 1 m/s to 10 m/s compared with 0.25 m/s inside. Consequently there are separate external and internal boundary layer resistances. It is also conventional to use 'environmental temperature' in these assessments. This is defined as

$$T_a/2 + T_r/2$$

where T_a= air temperature and
T_r= radiant temperature

Reason for doing internal surveys

In a compound structural element the difference in environmental temperature occurs across the components of the total thermal resistance in proportion to their resistance values. Typically R_i might be 0.12 m²K/W, R_s 3.83 m²K/W and R_o 0.05 m²K/W giving a total, R_t of 4.0 m²K/W, and a U value of 1/Rt = 0.25 W/m²K. If there is a 10 K temperature difference across the wall this will result in 0.3 K across the internal surface resistance, 0.125 K across the outside surface resistance and the remainder across the structure of the wall. If there is a defect in a part of the wall, for example reducing the resistance of the structure is reduced to 0.3 m²K/W the outer surface temperature will rise 0.92 K and the inside surface drop 2.2 K. The difference in surface temperature on the inside is much greater than on the outside so the thermal image of the inside will show the defect more clearly than that of the outside. However this could be affected by the position of the insulating layer within the structure.

Wind effects on surveys

If the wind speed on the outside of the building increases the outside surface resistance drops so that at wind speeds more than 10 m/s it is only one quarter of its value at 1 m/s and the same defect would only produce a 0.2 K rise in temperature compared with the good section of wall. The thermographer would struggle to detect such a small difference.

More detailed treatment of external surface resistance can be found in ISO 6946, which includes the surface resistances listed in Table 3 at different wind speeds. These factors also apply to surface resistance in other thermography applications. Both electrical and mechanical thermography can be affected by high air speeds, for example in external electrical and ventilation plant room surveys.

Table 6 Values of R_o at various wind speeds

Wind speed	*Ro*
1	0.08
2	0.06

3	0.05
4	0.04
5	0.04
7	0.03
10	0.02

Factors influencing thermal radiation

ISO 6946:2007 states that at external surfaces it is conventional to use the external air temperature, based on an assumption of overcast sky conditions, so that external air and radiant temperatures are effectively equal. This ignores any effect of short-wave solar radiation on external surfaces, dew formation, radiation to the night sky and the effect of nearby surfaces. Other indices of external temperature, such as radiation-air temperature or sol-air temperature, may be used when such effects are to be considered.

On a clear night the sky radiant temperature can be as low as -50 °C with an air temperature well above zero. This has resulted in underestimation of heating requirements and many buildings being supplied with inadequate heating systems. This is particularly severe where the roof forms a large proportion of the total exposed fabric as in large single storey buildings. The roof is typically exposed mainly to the sky, which can have this low radiant temperature. Walls are typically exposed to radiative heat exchange with other walls, and ground, which may have a temperature closer to air temperature. Underestimates of heat loss of up to 10 % can be shown in buildings with a large roof area and low air leakage rate compared with using a more accurate measure of external ambient temperature. Although thermographers rarely try to make quantitative assessments of building heat loss it is important to understand the heat exchange processes to which their subjects are exposed.

Conversely solar radiation, both direct and diffuse must be considered when undertaking daylight building surveys. Most thermographers are aware of this problem and avoid surveys in sunny conditions. It is also important to consider sky temperature in cloudy, diffuse sun conditions. For any objective assessment using external surveys cloudy conditions are essential to minimise the effect of sky conditions.

Errors due to incorrect setting of emissivity or reflected apparent temperature

Having the wrong reflected apparent temperature, RAT, set in the analysis software can lead to significant errors in displayed temperature that depend on the object temperature. Using a radiant thermal model the errors have been estimated and example is shown in Fig. 18 for a RAT setting of 20°C when the RAT is really 25°C

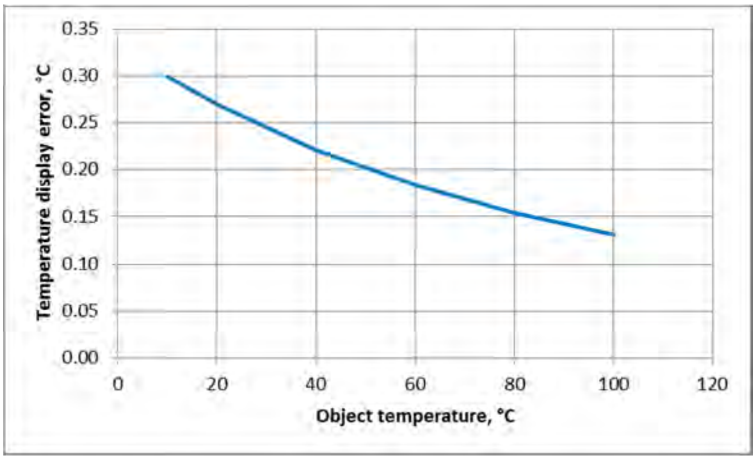


Fig. 18 Temperature display error due to 5K error in RAT

Setting the emissivity wrongly can lead to even larger errors. The radiant thermal model has been used to estimate the effect of setting the wrong emissivity for an object at 40°C with emissivity of 0.95 in a 25°C environment. It can be seen from Fig. 19 that setting the emissivity wrong by just 0.05 can lead to an error of 4°C in the displayed temperature.

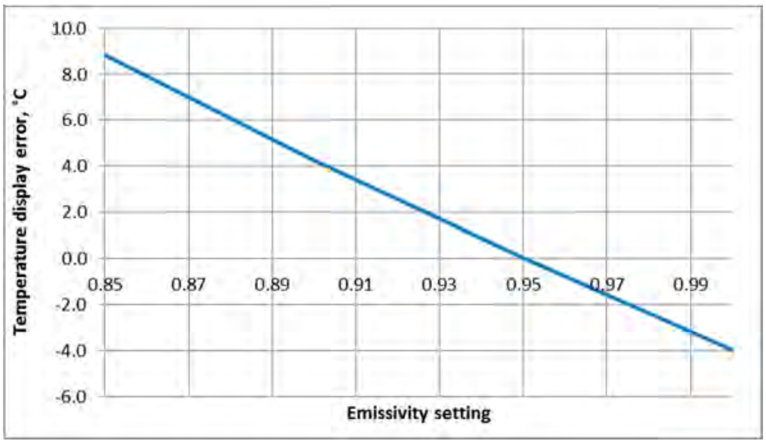


Fig. 19 Temperature display error due to emissivity setting error

The technical limitations of the current business as usual result in **a current difficulty to provide quantitative and repeatable results, hence the impossibility to obtain a reliable and complete thermal assessment** of an envelope by the mean of non-destructive and affordable techniques.

5.3 New quality checks solutions and requirements

Two complementary methods are imagined (one qualitative and one quantitative). Some potential use cases are also presented.

5.3.1 Proposed Built2Spec "Qualitative" Thermal Self inspection during construction process

Thermal testing of buildings on completion is a common method of compliance checking, but many people involved in this testing complain that it happens too late in the construction process. A method of testing thermal performance of completed elements before completion of the building is needed so that remedial works can be undertaken without jeopardizing the construction program.

This proposed survey method involves thermal imaging of internal surfaces of external fabric elements soon after they are installed. It is anticipated that for such tests the usual conditions for a good thermographic survey will not be present. To overcome this shortcoming acquisition of data related to the construction materials is vital to allow comparison between observed thermal patterns and expected thermal behaviour.

The method is not intended to replace compliance testing because the uncertainties in this method are significantly greater than the normal compliance test where the building maintains a reasonably steady 10K temperature difference across the whole building fabric.

The proposed method is based on reverse modelling to predict deviations from the design from changes in the surface temperatures. The method will be developed during the project, but essentially it consists of:

1. Use a suitable infrared camera, see Notes
2. Determine necessary period, T, for thermal history data based on thermal capacity of fabric elements, 1 – 24 hours
3. Measure site conditions over the period T:
    a. Internal temperature
    b. External temperature
    c. Solar radiation on surfaces
    d. Precipitation rate
    e. Wind speed
4. Position the data collector in front of the fabric element to be assessed and check the following:
    a. Location in 3 dimensions with respect to the building datum with accuracy ±dL[1]
    b. Orientation with respect to the building
    c. Acceptable field of view, eg full height of wall if possible
    d. Fabric element in front of the camera is external fabric
5. Proceed with thermal imaging:
    a. Measure RAT (Reflective Apparent Temperature) on both sides
    b. Measure distance
    c. Capture image
    d. Send image to cloud-based processing system
    e. Move to adjacent position to check the next section of fabric by moving in a suitable direction. Repeat until all areas of the selected fabric element have been assessed.
6. During the process or subsequently do analysis of the images:
    a. Identify which areas in the image are external building fabric from the building model or recognition of features from image data.
    b. Adjust image settings in accordance with RAT, air temperature, distance, emissivity
    c. Calculate the critical surface temperature from $\mathbf{f_{CRsi}}$ internal and external environmental temperature
    d. Count the number of image pixels that are below that temperature
    e. Calculate the area covered by each pixel from distance, number of pixels in focal plane and lens optical properties
    f. Calculate area of anomaly from pixel count and pixel area
    g. Repeat for all images
    h. Calculate total area of building surface inspected
    i. Calculate percentage represented by areas below the critical surface temperature.

    Is this percentage acceptable – if yes the test is passed

Notes:

Thermal History: Thermal storage in the building elements affects surface temperatures. 'Heavyweight' elements store more heat and take longer to reach equilibrium temperature so when you are assessing thermal performance from surface temperature you need to know what temperatures the element has been exposed to in the past. For most building elements this period, T, is between 1 and 24 hours.

[1] The value of dL, the accuracy of location needs to be determined during the project

Infrared camera specification:

Number of pixels: There is a trade-off between the number of pixels in an image, the distance from the object, the lens optics, and the size of anomaly to be detected. Current practice in building thermography is that they system should reliably identify anomalies that are 10mm x 10mm. This implies that each pixel in the image must relate to approximately 3.6mm x 3.6mm on the object if an accurate measurement of temperature is required.

Therefore a camera that has a focal plane array of 80 x 60 pixels can effectively cover an area of 286x214mm but a camera with 640 x 480 pixels can cover an area of 2286x1714mm.

It is anticipated that this test will be performed by a site worker, close to the building element recently completed. This means that a camera with a relatively small number of pixels will be appropriate for this test.

Pixels	60	80	120	180	240	360	480	640
Length, width, mm	214	286	429	643	857	1286	1714	2286

Sensitivity: Infrared camera sensitivity is usually expressed as NETD, Noise Equivalent Temperature Difference. It states the apparent temperature difference caused by electronic noise in the imaging system. Effectively it is the smallest temperature difference that can be measured by the system. Typical values are between 0.03 and 0.2K. The uncertainty in the assessment will be affected by this value

Accuracy: Accuracy of temperature measurement is important if you are using several different temperature measurement devices in the assessment. When all measurements are made with the same instrument the systematic errors will be cancelled out as temperature differences are calculated.

Uncertainty: The uncertainties involved in this method depend on a range of factors which will be evaluated during research. It is anticipated that the greatest contribution to uncertainty will come from:

a) Temperature difference, which mainly influences convective heat exchange at surfaces
b) Accuracy of input thermal properties
c) Radiative heat exchange, which is generally less well understood than convective

5.3.2 Quantitative thermal inspection method

The qualitative method previously described is qualitative in terms of characterization of the thermal performance of a wall (e.g. no absolute U-value) but could be used quantitatively in terms of % of surfaces and statistical variation a thermal index for example. It could be used on large parts of the building for a general diagnosis. It could be done before retrofitting, after construction works, or during their implementation.

Besides, some developments in R&D environments aim at developing quantitative methods, which could allow to assess the thermal characteristics of a building (e.g. U-value). These methods are usually based on the association between thermography measurements, complementary measurements (hygrothermal conditions, radiative conditions, wind, well-known emissivity sample, etc.), and modeling (e.g. reverse method to identify thermal parameters). Moreover the integration of the results into direct modelling tools allow to produce new results/indicators, such as the impact on energy consumption of an anomaly in the U-value of one wall. These approaches usually imply larger temporal sets of measurements (over a certain duration) in order to gather more information about the behavior of the wall/envelope in reaction to a solicitation (e.g. solar radiation or heating). The need for measurements over a duration that is coherent with the characteristic time of the involved thermal processes results in more advanced protocols, more difficult to apply on a complete building.

Thus we can imagine to apply the quantitative methods in a complementary approach to the qualitative one. Whereas the qualitative approach allows to check the general behavior and heterogeneities of the envelope, the quantitative method could be applied to a typical, representative or singular element of the envelope. The use of direct modelling could then allow to obtain an assessment of the impact on the thermal performance of the building (for example to check if the guarantee of performance is still valid, in spite of a problem on the insulation).

Both methods will be developed and tested in work package 2.

5.3.3 Thermal inspection use cases examples

Here are a few examples of short descriptions of use cases about thermal performance quality checks.

- **Quality check for thermal bridging of the external envelope**

Here are the different stages of the use case:

- The architect's construction details and specifications for minimising thermal bridging of the external envelope are integrated into the BIM of the project.
- The site operatives use their mobile device to access these thermal bridging details, specification, calculations links and information videos when they are working on those parts of the external envelope where thermal bridging has been identified as critical
- The subcontractor and operatives complete the construction of the various thermal bridging details and record the bar code and photos of the materials they use. QUALITY CHECK.
- A thermal imaging camera is used to take thermal images of the details to analyse the performance of the constructed detail and compare it to the design calculations and simulation images. QUALITY CHECK.
- Any remedial action is taken and the work and detail photographed and thermal images assessed. QUALITY CHECK.
- The EoU (Evidence of Use) App prompts all operatives on site to take photos of any detail being constructed, or worked on, which impacts on the thermal bridging performance of the external envelope. QUALITYCHECK.
- All accidental compromises of the thermal bridging details are photographed, logged and flagged to site management and the appropriate foreman or subcontractor is notified so that remedial repairs can be organised. QUALITY CHECK.
- All repairs to thermal bridging details are photographed and thermal images analysed when completed. QUALITY CHECK.
- On completion thermal images are taken of all the critical thermal bridge details, thus enabling the assessment of the energy performance of the whole of the external envelope.

➢ **Quality check for wall insulation installation on site**

Here are the different stage of the use case:

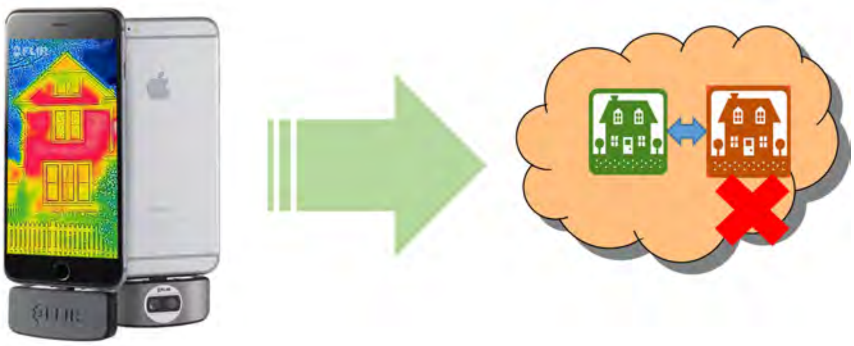
- Supplier receives order via B2S and deliver it to the worksite: e.g. "rockwool";
- Contractor receives confirmation of delivery and can start the work. Scanning the material ID it will be linked to a page that show "how to", "best practices" and "tech data sheet". During the work it can take pictures and save it into the platform to prove the quality of the work!;
- During the survey scanning the RFID (attached to the wall) Surveyor access to the "designs" and he/she can compare "as built" according to the Contractor pictures,… (see above).
- If BIM and GPS are used RFID can be redundant but it can be still useful during operation for a quick access to construction data.

Fig. 20 Schematic representation of the information flows between the use case stages (virtual platform on the left)

➢ **Checking thermal performance of structure using a suitable infrared camera and networked processing**

Here are the different stages of the use case:

- Measure site conditions for suitable period
- Position the camera and data collector in front of the area to be assessed
- Collect location data
- Collect thermal image
- Send data and thermal image to building model in the cloud
- Compare thermal image with result of dynamic thermal model
- Move to new location and repeat



6 Requirements: Air tightness performance

6.1 Business as usual inspection and quality checks

The building airtightness describes how leaky the thermal envelope of a building is. It determines the cooling or heating energy loss through cracks and gaps in the building envelope, the indoor air quality as well as the building life span. It is important to understand the airtightness level of buildings.

Current business as usual inspection method is the blower door technique, which has been set out by European and North American standards, such as EN 13829, CGSB (149.10-M86) and E779-10. The quality checks using blower door unit include measuring building leakage rate in a range of high pressures, and quoting the leakage characteristic at a certain pressure difference. This pressure difference, adapted differently in different countries and regions, mainly includes 4 Pa, 10 Pa, 50Pa (typical), 75Pa and 100 Pa. In order to make it easy to compare for different buildings, the leakage rate is usually normalised by building parameters such as the internal volume or envelope area, in the form of permeability and air change rate.

6.2 Identification of needs for improved quality checks

Air leakage, as a consequence of poor construction detailing and workmanship, has a direct impact on the thermal performance of buildings and can lead to significant energy wastage (typically 13%-33% of overall consumption). For this reason many EU countries have introduced airtightness requirements, normally quoted as the air permeability or changes per hour at a given pressure difference (typically 50 Pa). The blower-door pressurisation test has been used globally for many years as the method of assessment. However, it can only produce reliable results at pressures much higher than that found in natural infiltration, is seen to be sensitive to wind at low pressure, time consuming to set up and carry out, costly, and requires bulky equipment. Furthermore, the need for trained operatives means it is rarely used until the final commissioning stages, when it is often too late to remediate any significant differences between design and performance (which can exceed 50%).

The UNOTT 'pulse test' (abbreviated as "APU") for airtightness could help reduce the performance gap between design and commissioning by enabling quick checks (typically a few seconds) and remediation to be carried out during the construction process for both new and retrofitted buildings. The technique, which is proven to be quicker, cheaper, and more accurate than the conventional blower door technique provides a portable and easy to use solution. It could fundamentally shift the existing airtightness testing market from a small scale specialist commissioning service to one where construction workers can undertake airtightness assessments themselves.

6.3 New quality checks solutions and requirements

- **Related user**

Due to the fact the airtightness test can be significantly deskilled, the potential end users of APU can be expanded from specialized testing companies with trained operatives, to the market where a construction worker can undertake airtightness tests for quick checks during construction and retrofitting process.

- **Related process**

The APU works by subjecting the building envelope to a known volume change in a short period of time. This generates a flow rate through the adventitious openings, which in turn creates a pulse in the internal pressure characteristic of the building's leakage. A period of quasi-steady flow is established during the pulse that directly gives the leakage characteristic at low pressure, and after adjustment to still air conditions and a small correction for the effective flow rate arising from compressibility of the air, the result can be plotted or read in the same way as the steady technique. The method negates the effects of wind and buoyancy at low pressures, reduces inertia effects associated with unsteady flow and minimises variation of the pressure difference during the test period.

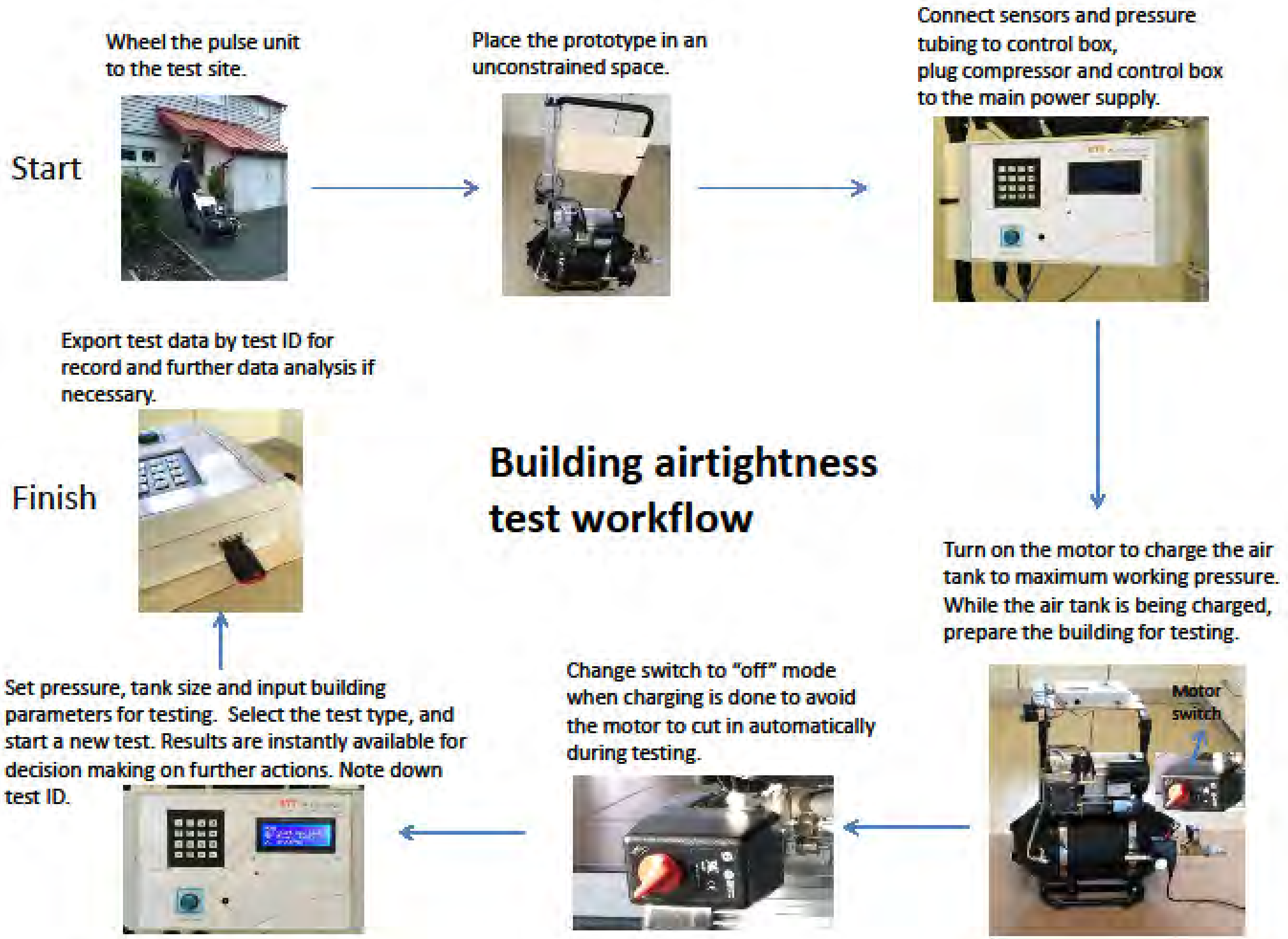
The related process consists of the following two parts.

a. Prototype preparation:

- Wheel the APU onsite and place it in an unconstrained space to allow the released air to expand freely and avoid the released air to be reflected back to the prototype.
- Connect the air releasing section to the tank if it has to be disconnected during transportation. PTFE tape must be applied to the thread to make sure the connection is secure and airtight.
- Connect the APU to the main power socket and switch on the pump to charge the compressor;

Figure 21 Setup of APU onsite

A simplified workflow of airtightness test using APU is shown on the next page.


Start
Wheel the pulse unit to the test site.
Place the prototype in an unconstrained space.
Connect sensors and pressure tubing to control box, plug compressor and control box to the main power supply.
Turn on the motor to charge the air tank to maximum working pressure. While the air tank is being charged, prepare the building for testing.
Motor switch
Change switch to "off" mode when charging is done to avoid the motor to cut in automatically during testing.
Set pressure, tank size and input building parameters for testing. Select the test type, and start a new test. Results are instantly available for decision making on further actions. Note down test ID.
Export test data by test ID for record and further data analysis if necessary.
Finish
Building airtightness test workflow

b. Building preparation:

While the APU is being charged automatically, prepare the building according to airtightness testing standard in each partner country in order to maintain a short overall testing time.

- **Units**

"Air leakage rate, V4", m^3/s;
"Permeability, Q4", $m^3/h{\cdot}m^2$;
"Effective leakage area, ELA", cm^2;
"Air change rate, ACH", h^{-1};

- **Benchmark values**

The benchmark values of the building airtightness, specified by current national standard or regulation in different partner countries, are listed in Table 7.

Table 7 Information of airtightness test in the Built2Spec partner countries

Country	Permeability or Air change rate		Pressure difference (Pa)	Property type
Germany	3.0 (Natural ventilation) 1.5 (Mechanical ventilation) 0.6 (Passive house)	h^{-1}	50	Domestic dwelling
Ireland	10	$m^3/m^2{\cdot}h$	50	Domestic dwelling
Switzerland	0.75	$m^3/m^2{\cdot}h$	4	Domestic dwelling
Spain	50 (Southerly, warmer area) 27 (Northerly, cooler area)	$m^3/m^2{\cdot}h$	100	Domestic dwelling
France	0.6 (single family house) /0.8 (Multi-family building)	$m^3/m^2{\cdot}h$	4	Domestic dwelling
Italy	10	$m^3/m^2{\cdot}h$	98	Schools
Netherlands	0.2	m^3/s	10	Domestic dwelling
	0.2 per 500 m^3	m^3/s	10	Non-residential building
United Kingdom	10	$m^3/m^2{\cdot}h$	50	Domestic dwelling

- **Frequency of reporting**

The test results are reported in each test run.

- **Outlier values**

The repeatability of current pulse unit in various housing and environmental conditions is ±10%, any values outside this range would be regarded as outlier values. However, repeatability within ±5% is achievable in an ideal condition. The feature of removing outlier values during measurement will be added to the firmware in future development.

- **Data format**

The data is reported in CSV file, consisting of three sections: “DETAILS”, “RESULTS” and “RAW DATA”. The information that is useful for Self-Inspection platform are listed in “DETAILS” and “RESULTS”.

- **Evidence**

.Please refer to the conference papers and patent ID below for the evidence of this technique.
Paper 1: “ A NOZZLE PULSE PRESSURISATION TECHNIQUE FOR MEASUREMENT OF BUILDING LEAKAGE AT LOW PRESSURE”;
Paper 2: “Field trialing of a new airtightness tester in a range of UK homes”;
PCT application number: PCT/GB2015/051901.

Here is an example of short description of use case about air tightness quality checks.

- **Quality check for the airtightness of the external building envelope**

- The architect’s construction details and specifications for the airtightness of the external envelope are integrated into the BIM model of the building.
- The site operatives use their mobile device to access these airtightness details, specification, links and information videos when they are working on any part of the external envelope to ensure their work is correct
- The airtightness subcontractor and operatives complete the installation of the airtight layer and record the bar code and photos of the materials they use. QUALITY CHECK
- A diagnostic air pulse test is completed to check the performance target will be achieved. QUALITY CHECK
- The EoU (Evidence Of Use) App prompts all operatives on site to take photos of any detail being constructed, or worked on, which impacts on the airtight layer of the external envelope which is highlighted in the details and BIM model. QUALITY CHECK
- All penetrations of the airtight layer for structure or services are sealed with the appropriate airtightness seal, tape, mastic or adhesive and photographed on completion and before the work is covered up by a following trade. QUALITY CHECK
- All accidental “punctures” of the airtight layer are photographed, logged and flagged to site management and the appropriate foreman or subcontractor is notified so that remedial repairs can be organised. QUALITY CHECK
- All repairs to the airtight layer are photographed when completed. QUALITY CHECK
- The final airtightness test results output data are sent directly to the VCMP project folder in the cloud. QUALITY ASSURANCE
- Remedial airtightness sealing and testing is completed as necessary to achieve the target level of airtightness. Repeat the 2 previous actions. QUALITY ASSURANCE

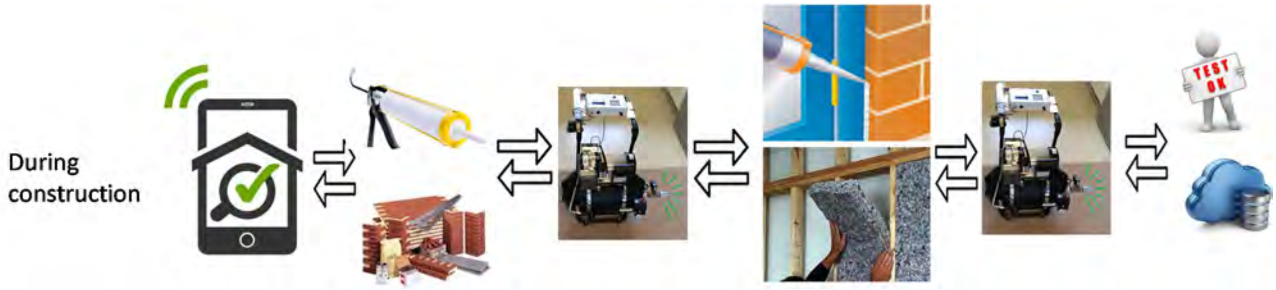


Fig. 22 Schematic representation of the airtightness quality check use case

7 Requirements: Indoor air quality

7.1 Business as usual inspection and quality checks

The assessment of the indoor air quality (IAQ) involves generally the measurement of comfort parameters (temperature, relative humidity), of compounds concentrations indicating air confinement (carbon dioxide, etc.), and of pollutants concentrations (volatile organic compounds, particulates, etc.).

An analysis of the guides present in the literature and of the current regulations showed that it is necessary to follow in priority the concentration of the following volatile organic compounds (pollutants) in order to assess the IAQ: formaldehyde, benzene, naphtalene, trichloroethylene, tetrachloroethylene, fine particulates, nitrogen dioxide, acrolein, acetaldehyde, toluene, xylene, 1,2,4-trimethylbenzene, 1,4-dichlorobenzene, ethylbenzene, 2-butoxyethanol, styrene, and TVOC (Total Volatile Organic compounds). It is also necessary to follow the concentration of the pollutants related to wood material such as the hexanal, the α-pinene, the limonene, and the delta-3-carene. Besides, carbon monoxide has to be assessed. Carbon dioxide could be assessed in order to measure the air confinement of the room but it is not of primary importance. Fine particles concentrations (PM 2.5 and PM10) have to be measured as they also could affect significantly the health of the occupant. This last measurement could also allow verifying the performance of the ventilation system. Monitoring the concentration of nitrogen dioxide (NO_2) can be relevant to assess the performance of the filtration system regarding the pollutants coming from the outside.

Depending on the nature of the compounds monitored, different measurement techniques are used. Generally, all the volatile organic compounds (VOCs) concentrations and the NO_2 concentration will be monitored by using IAQ normative methods which are basically passive metrology solutions. The basic principle of these solutions is to absorb a maximum of pollutants on the surface of a material presenting a very high specific surface area *via* the diffusion phenomenon. This material is left in the room for 5 days. In consequence, the result obtained corresponds to the average exposure over 5 days. These normative solutions are two-step methods, the first step being the adsorption of these pollutants on a porous material on site, and the second step being the analysis of these pollutants by chromatography in an off-site laboratory. Finally, **this process can take several days or weeks to be completed.** As the sampling time is very long (5 days), it is not possible to measure the TVOC concentration using these methods as the absorbent can be saturated and there is also an adsorption competition between the different compounds. In order to measure the TVOC concentration, active methods following the norm NF ISO 16000-6 (2012) are used. The air is pumped and the VOC are trapped on a tube composed of an adsorbing material. As for the passive methods, the pollutants are analyzed in a second time in a laboratory. These methods are then also time consuming and they also present the drawback of requiring the **use of bulky equipment**. These actives method are also used for the measurement of PM 2.5 and PM10 concentrations which are adsorbed on the filters at the entrance of the pump. CO and CO_2 concentrations can be measured by using non-dispersive infrared diffusion sensors (NDIR) that allow a real-time and a continuous measurement.

7.2 Identification of needs for improved quality checks

Recently, it has been proven that the IAQ could affect the occupants' health and this issue is also now addressed by new building concepts and approaches such as LEED, BREEAM, and HQE, which include IAQ performances targets to satisfy. Generally, buildings designers put very little effort on this topic and focus more on energy issues addressed by these approaches. However, attitudes tend to change as countries policies are also beginning to integrate this IAQ issue in new regulations. For example, in France, there is now a regulation which obliges the control of the IAQ of a certain category of building, those opened to the public.

Despite the emergence of new standards and regulation concerning the Indoor Air Quality matter, the IAQ is never tested during the construction process. It is only measured during the commissioning phase of the building. All the studies on IAQ found in the literature agree that most of the VOCs present in the indoor air are emitted by products present inside the building. Thus, a study conducted in five European cities in public buildings and individual houses in 2008 has put forward the influence of building materials emissions on indoor air quality. This is especially true for new buildings or buildings containing new furniture. Besides, it has also been proven that some compounds are exclusively emitted by building construction materials (acetone or formaldehyde, etc.). It was also shown by a study in Finland, that a dwelling designed and furnished with low-VOC materials had better indoor air quality both before and after 5-month occupancy. **Therefore, there is a real need to know, anticipate and control the emissions of building materials and to control thereafter the quality of the air inside the building.**

The way to implement materials during the construction can have a major impact on indoor air quality in the building. Thus, it is necessary to be able to measure indoor air quality all along the construction process, with a portable and fast analyzer. **Business as usual quality check techniques** are either slow (take several weeks to be completed), or require the setup of bulky and costly equipment. In consequence, they **are not adapted to the required application yet**.

BLUE analyzers uses a non-dispersive infrared diffusion sensors (NDIR) able to detect a wide range of pollutant. They can be used for **this application as they allow a real-time measurement with a high accuracy. Then, it becomes possible to identify the nature of the pollutants instantly.** Moreover, this apparatus dispose of a source emission detection mode allowing **tracking the pollutants sources in the building** *via* the utilization of a probe**.** The ambition in BUILT2SPEC will be to develop a portable version of an **all-in-one analyzer**, combining BLUE technology for the measurement of the VOC concentration with other technologies such as the one developed by the start-up CAIRPOL for the measurement of fine particulates concentration (PM2.5 and PM10), and others for the measurement of comfort parameters. This analyzer will be designed and adapted for field operation by a construction technician. The weight will be reduced down to 5kg (from 15kg) and the volume down to 10 liters (from 22liters). This technology will give then fast results that will be delivered to the user through an adapted interface. These results can be then read by non-specialists field technicians, and the analyzer will provide real-time updates to the information system of the project.

With a properly documented database linking the materials used with potential pollution levels, it can be envisaged to track and correct the misuses of construction products during the building phase, and to fully assess the IAQ during the commissioning phase.

7.3 New quality checks solutions and requirements

- Related user

Due to its adapted interface, the BLUE analyzer can be used by trained operatives working for specialized testing companies as well as by non-specialists such as a person working on the construction site.

- Related process

- First, the area to be tested will be selected according to its relevance with the information we want to obtain (performance of the ventilation system, global IAQ at the end of the construction, etc.).

- Then, the BLUE analyzer is placed in this area and plugged to a power source. It can be operational in minutes. It can be controlled both locally *via* a tablet-based interface, and remotely. The results are displayed, and necessary measures are taken according to the results obtained.

- After the measurement, the analyzer is turned off and can be reused again instantly in another area without any maintenance needed (no consumables or parts replacements needed, no requirement for new calibration).

- Units

This analyzer measures pollutants concentrations. They will be expressed either in ppb or in µg/m^3.

- Benchmark values

The benchmark values of the pollutants concentrations, specified by current national standards and regulations are different from a country to another. They also vary depending on the chemical nature of the pollutant which is more or less dangerous for people health. The concentration threshold is also different depending on the exposition time: the threshold is higher for a short time exposition than for a long time exposition.

As the workers will be exposed for a short time period (few hours) whereas a habitant will be exposed for a long time period (several years), we need to take into account both thresholds in our project. In the following table, we summarize the most restrictive concentration values for each pollutant of interest for a short and a long period of exposition:

Pollutant name	Concentration treshold: long time exposition (µg/m^3)	Concentration treshold: short time exposition (µg/m^3)
Formaldehyde	10	30
Benzene	2	5
Naphtalene	10	50
Trichloroethylene	10	20
Tetrachloroethylene	1.380	250
Acetaldehyde	50	200
Toluene	300	15.000
Xylene	200	4.800
Styrene	250	2.000
1,2,4-trimethylbenzene	100.000	250.000
1,4-dichlorobenzene	1.000	122.000
Ethylbenzene	200	1.000
2-butoxyethanol	100	1.000
Acrolein	0.8	6.9
α-pinene	200	2.000
Limonene	1.000	1.0000
TVOC	1.000	3.000
NO_2	20	200
CO	10.000	60.000
PM 2.5	10	25
PM10	20	50

Table. Concentration values threshold for different time of exposition that will be taken into account in the calculation of the IAQ indicators

The TVOC values have been determined according to the values presented in the HQE certification that consider 5 levels of contamination:

- Level 1: if TVOC < 300 µg/m^3, there is no impact on the occupants' health (target value)
- Level 2: If 300 µg/m^3 < TVOC < 1.000 µg/m^3, there is no impact on the occupants' health, but we need to increase the ventilation of the room.

- Level 3: if 1.000 µg/m^3 < TVOC < 3.000 µg/m^3, few impacts can be observed on the occupants' health. This level can be tolerated for 12 months and measures have to be taken to find the pollutants sources. The room ventilation has to be increased as well.
- Level 4: if 3.000 µg/m^3 < TVOC < 10.000 µg/m^3, major impacts can be observed on the occupants' health. This level can be tolerated for maximum 1 month and measures have to be taken urgently to find the pollutants sources. The room ventilation has to be increased as well.
- Level 5: TVOC >10.000 µg/m^3, inacceptable concentration. People should enter only if they cannot avoid it, and they can only enter for short periods of time (hours) and the ventilation system has to be pushed at its maximum.

The guide values of the hexanal and of the delta-3-carene concentrations are not defined yet in the literature in a proper manner. This can be explained by the fact that the consideration of these pollutants is new and the data have not been published yet. They would be nonetheless monitored as they are an indicator of wood pollutants emissions.

Some pollutants values are subject to change in few years as they have just started to be taken into consideration recently and their guide values are not too much restrictive for the moment as their effect on health is still unknown. These values would certainly decrease with the publication of studies presenting the effect of these pollutants on human health. The indicators would have to be calculated again then.

- Frequency of reporting

A report will be established after each measurement.

- Outlier values

If the value is under the detection limit, it will simply not be taken into account by the apparatus. If the concentrations measured are very high compared to the threshold values, the experience will be repeated again to confirm the first one. If the values remain unchanged, the apparatus will be set on the "source emission detection" mode. In this mode, a probe will be attached to the apparatus and the pollutant presenting the highest concentration value will be selected. Several measurements will be then conducted in order to find the pollutant emission source in order to take actions.

- Data format

The data will be reported in a CSV file which can be sent by WIFI or LAN.

- Evidence

The analyzer has been recently certified by the "Laboratoire national de métrologie et d'essais" (recording number: LNE040002-0; LNE identification number: 30525-0; date: 01/12/2015) in the context of the national Environmental Technology Verification (ETV) program directed by ADEME (in coherence with the ETV program of the EU program). The verification statement report (called "Déclaration de verification ETV Blue X-FLR8) can be found following the link:

http://www.verification-etv.fr/upload/Le_programme_ETV/Declaration_ETV_Blue_X-FLR8_Blue_IndustryScience.pdf .

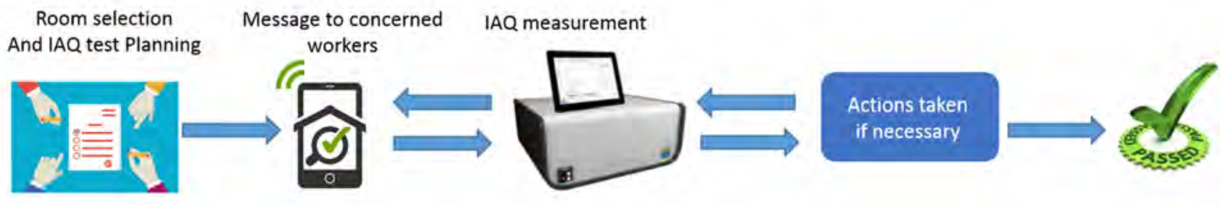
- Uses cases

The analysis of the indoor air is only relevant if there is no more important air leakage in the room studied. This analysis are then performed once all the walls, doors, insulation panels, and windows are installed. It has be determined that the analyzer could be used for the following use cases:

1. The verification of the ventilation system, and more especially of its cleanliness and of its performances (validation of the air inlet position, of the filtration system, and of the dimensions of the ventilation system)
2. The prevention of the damage on the workers' health and on the occupants' health all along the construction process
3. The verification of the influence of the introduction of furniture into the building
4. The qualification of the retrofitting influence on the IAQ. This test can be done following a request of the occupants who have noticed the apparition of odors in the building for example. It could also be set up systematically before and while the retrofitting phase. In this case, the aim would be to take action if the IAQ is strongly impacted by the retrofitting process such as the installation of panels to prevent the dust from reaching the building air inlet. This could also lead to the evaluation of the retrofitting action on the IAQ, and maybe to the creation of a new classification/label for retrofitting/construction sites.
5. The evaluation of the impact of the different construction or retrofitting phases/actions on the IAQ. We could for example add a function to the platform created in the B2S project. With this new function, we could ask each company which intervenes on the construction site to complete a survey where they will precise if they intend to introduce materials that could degrade the IAQ. This will then allow establishing a plan in order to prevent the degradation of the IAQ during the construction process.

Quality check

- A quality check planning will be decided and will be accessible by all the workers *via* a platform.
- A reminder is sent to the operative to test the IAQ as planned before, and will precise what is the purpose of the measurement and how to perform it.
- The IAQ will be controlled in the context of one of the four first use cases (validation of some equipment/materials, prevention of health damages, and qualification of a construction site). For each uses case, measurement protocols will be available on the platform. QUALITY CHECK
- If the IAQ values do not match the values required for each uses cases, it has to be noticed to the appropriate foreman or subcontractor. Actions have to be conducted until the IAQ measurement indicates the desired values (detection of emissions sources, increase of the ventilation, cleaning of the ventilation system, etc.). These actions have to be listed and pictures can be taken to illustrate the issue. This list of actions and pictures have to be reported in the platform QUALITY CHECK
- The final IAQ test output data are sent directly to the VCMP project folder in the cloud.



8 Requirements: Acoustic performance

8.1 Business as usual inspection and quality checks

Acoustic performance in residential buildings is perceived as one of the major environmental problems. To face this issue, most European countries have regulatory sound insulation requirements for dwellings and classificatory schemes.

Actually, acoustic quality checks are performed from international descriptors that evaluate airborne and impact sound insulation and are defined in ISO 717. These descriptors are derived from values measured according to ISO 140. Acoustic performance tests have to be performed in the last stage of the building construction and depending on the country it is mandatory or not.

Mobile devices and an OPL source are used in this project to check the airborne sound insulation of buildings.

8.2 Identification of needs for improved quality checks

Nowadays, most of the European countries check the acoustic quality of the building according to the performance. Only few countries sound insulation regulation and guidance involve also a prescriptive approach, where construction technical drawings are provided.

Moreover, the acoustic performance test must be realized by authorized acoustic consultants and are expensive measurements.

With Built2Spec portable acoustic measurement unit, quick tests can be carried out complementarily to traditional tests to gather better and faster information.

8.3 New quality checks solutions and requirements

- Related user
  The end user of portable acoustic measurement unit may be constructors and research centers.
- Related process
  - Room selection: Suitable rooms have to be chosen for the tests. The requirements of the rooms are delivered according to ISO 140.
  - Measurement procedure: Measurements are performed also with ISO 140 requirements. Mobile application guides us through the measurement protocol.
- Units
  - The acoustic unit to quantify sound insulation is the dB
- Benchmark values
  - One of the main problems regarding acoustic sound insulation performance is that, not only the benchmark values but also the acoustic descriptors change from country to country.
    Efforts are made by European Cooperation in Science and Technology (COST) to find a common framework in building acoustics throughout Europe.

    Anyway, knowing the building parameters, is possible to use relationships to translate from one descriptor to another.
    The benchmark values obtained from regulation in the partner countries are listed in Table 8.

Table 8 Acoustic descriptors and values for airborne sound insulation between dwellings

Country	Descriptor	Multi-storey housing (dB)	Row housing (dB)
France	D_{nTw}+C	≥ 53	≥ 57
Germany	R'_w	≥ 53	≥ 57
Ireland	D_{nTw}	≥ 53	≥ 53
Italy	R'_w	≥ 50	≥ 50
Netherlands	R'_w +C	≥ 52	≥ 52
Spain	D_{nTw}+C	≥ 50	≥ 50
Switzerland	D_{nTw}+C	≥ 52	≥ 55
United Kingdom	$D_{nTw}+C_{tr}$	≥ 45	≥ 45

- Frequency of reporting,
  Each test will be reported appropiately. One first test will be done in a selected environment and, depending the results, more tests will be performed in different parts of the building.

- Outlier values
  Outlier values have to be classified according to the following possibilities
  - A problem with the measurement procedure. Background noise, incorrect equipment position,
  - A problem with the building geometry. Wrong selection of the rooms
  - An indicator of an acoustic leakage.

- Data format
  Data will be reported as a raw text, including the sound insulation descriptor and room parameters
- Evidence

The use of mobile devices for acoustic measurements is reported in :

·Kardous, C. A., & Shaw, P. B. (2014). Evaluation of smarpthone sound measurement applications. JASA Express Letters .

·Robinson, D., & Tingay, J. (2014). Comparative study of the performance of smartphone-based sound level meter apps, with and without the application of a ½" IEC-61094-4 working standard microphone, to IEC-61672 standard metering equipment in the detection of various problematic workplace n. Internoise Australia .

On the other hand, an analysis of the omnidirectional parametric loudspeaker can be found in :

·Sayin, Umut, Pere Artís, and Oriol Guasch. "Realization of an omnidirectional source of sound using parametric loudspeakers." The Journal of the Acoustical Society of America 134.3 (2013): 1899-1907.

Here is an examples of short description of a use case about acoustic quality checks.

- **Sound insulation quality check**

Main stages of the quality check:

- Room selection: during building construction suitable rooms are chosen for the tests. The requirements of the rooms are chosen for the tests. The requirements of the rooms are delivered according to ISO 140.
- Measurement procedure: measurements are performed also with ISO 140 requirements. Mobile application guides us through the measurement protocol.
- All results with indoor positioning are linked to VCMP.

- **VCMP quality check for Acoustic Insulation Panel installation on site**

Main stages of the quality check:

- Supplier receives order, via B2S platform, to deliver the Acoustic Panel to the worksite.
- Contractor receives confirmation, via B2S platform, of delivery and can start the work. Scanning the material ID it will be linked to a page that show "how to", "best practices" and "tech data sheet" of the product.
- During and after the construction activities, the worker will take pictures and will save them into the B2S platform to prove the quality of the work.
- After construction activities, surveyor will carry out the Acoustic Quality control helped by B2S technologies. The technical acoustic data obtained in the acoustic test will be saved into the B2S platform.
- During the survey scanning the RFID (attached to the panel). Surveyor access to the "BIM model", "detail designs" and "acoustic requirements" and he/she compares "as built" according to the previous design and technical specifications

9 Requirements: Information management from the early design to the operation of the building, and smart materials

9.1 Business as usual information management and smart materials

During the various stages previous the construction works, a large amount of documentation is produced sequentially by the stakeholders, for example: requirements and objectives of the project by the promotor/owner, schematic design to detailed design by the design team and the architect, detailed implementation from each contractor.

After the construction, new documents are available (e.g. *Dossier des Ouvrages Exécutés* in France) to describe how the designed solutions have been actually implemented. But during the construction process, on the construction site, relatively few documents are produced or updated, whereas essential decisions and actions take place and have an impact on the final result.

In spite of the arrival of numerical formats for this documentation, the information is still difficult to access and disseminate from the construction site, mainly due to the physical environment of the construction site. Moreover, during the implementation of the construction works, the stakeholder are usually not present together at the same place at the same moment (except for construction site meetings) and the communication between them can face some barriers, resulting sometimes in a deficiency of coordination and non-quality.

Beyond the digitalization of the information, the recent developments in information and communication technologies offer new possibilities, not only to facilitate more direct communication between stakeholders (e.g. e-mail) but also to collect information about what happens on the construction site, in the building (e.g. connected sensors, smart materials).

Some smart materials developments deal with the capacity to make information accessible, by using the implemented material as the main vector of this transfer of information.

In business as usual approaches, the information is usually dissociated from the material (e.g. related documentation, technical description, available in documents that are not physically linked to the material) or is added after implementation of the material, with strong economic and technical constraints of deployment (e.g. intrusive sensors installed after the building component).

In the case of documentation (plans, technical documentation, detailed design documents), the needed information is generally accessible to every stakeholder involved in the construction, but not necessarily from the construction site itself.

Some major construction companies have recently developed online software platforms allowing sharing all the detailed design documents, in relation with each part of the construction (construction lot). Theoretically the information could be then reached online directly from the construction site via a connected mobile device, but in reality these platforms still lacks flexibility and lightness to be used by any involved stakeholder (from the site supervisor to the worker validating an autocontrol) and they are mostly used in the office. Moreover these platforms are not interoperable yet with the communication of data directly collected on site through smart materials.

9.2 Identification of needs for improved information management and smart materials

Every previously described technical field (thermal techniques, air tightness tests, acoustic inspection, etc) is concerned by information management solutions and procedures on the construction site. The current solutions have a large potential to be improved. This would finally result in large savings of time and a reduction of the risks to obtain an unsatisfactory result or performance.

The main needs to improve these information management solutions are the following ones:

- Need for a more automated collection of the information. Some parameters are needed to be measured or monitored on site in order to ensure the correct conditions or behaviour of the construction (e.g. Temperature measurement to avoid damage on fresh concrete).
- Need for a support in comparing the technical data sheets with the project specifications. This process is very time consuming (need to compare manually the information by referring to different documents) and often done in the office when there is no more the possibility to check details from the reality of the site.

More specifically, as concerns aspects that could be improved by smart materials, the needs can be expressed as follows:

- Need for a support in checking that the material implemented on site fits exactly with the one specified in the detailed documentation.

- Need for more direct tests on material, directly on construction site and not in laboratory (e.g. compliance with the expected mechanical properties)

9.3 New information management, smart materials, and 3D scanning solutions and requirements

The needs defined in the previous section can be tackled by different types of innovations. Here are the main types of innovation to be implemented in the next years in terms of information management and smart materials:

- Implementation of measurements devices to mobile devices already in use (smartphones/tablets upgraded with specific sensors such as thermography sensor).
- Integration of wireless sensors connected to software platforms in the cloud, enabling the monitoring of the construction, from any location.
- Embedded sensors in precast elements, allowing to check more precisely the behaviour of the component, and measurements that would not have been possible without damaging the structure.
- Collaborative software platform enabling the access and dissemination of a large variety of document, from the construction site, and between all the involved stakeholders (not only the site supervisor).
- Identification system for materials (e.g. RFID) enabling checking the complete technical details of the material actually implemented on site, and to compare with what was planned. This system could be integrated in a collaborative platform (see previous bullet point).

The collaborative platform mentioned in these bullet points represents one of the main developments to be carried out in the Built2Spec project, this is the main object of one dedicated work package (WP6). It will be later referred to as the **Virtual Construction Management Platform (VCMP)**.

Considering these innovations, it is possible to imagine more detailed cases of application (or **use cases**), by defining which solution is operated by which stakeholder, at which stage of the project, and by precising what are the input and output of the use of the solutions. In Built2spec approach, as the VCMP will be the central component in terms of information flows, there are a large number of associated use cases (whereas for the sections and technologies mentioned previously, there is sometimes only one use case associated). Here are a few examples of short descriptions of use cases about data management, smart materials, and 3D scanning.

- **Quality check for smart materials, i.e. precast concrete building elements with embedded sensors. Coupling with the VCMP.**

Main stages of the use case:

- Supplier receives an order via VCMP for a precast concrete structural building element, e.g. floor slab.
- Supplier's design team designs the slab, taking into account its structural and environmental performance. All slab design models & calculations are uploaded on VCMP.
- During the slab manufacturing process structural (e.g. vibrating wire strain gauges) and environmental (e.g. thermistors) sensors are embedded in the slab:
- Those sensors are embedded in both, the precast and in situ part, of the slab;
- The location of sensors matches the most critical points in the structural & environmental performance of the slab – based on the slab design models (numerical analysis & calculations) saved in VCMP.
- Those sensors continuously record data during the construction (starting with the concrete pour both in the precast concrete plant and on site) and operation phases of the building;
- The measured data from the sensors are analysed and compared to the design data - QUALITY CHECK (results available on VCMP):
- Temperature measurement of curing concrete ensures the actual concrete's strength matches the designed strength;
- Temperature measurement of concrete elements in operating building ensures better prediction of the building's energy consumption and thermal comfort of the occupants;
- Strain measurement allows for a long term comparison of stresses in the slab over its working lifetime, in order to ensure the slab is performing as designed.
- Additional laboratory testing results (structural & environmental) uploaded on the VCMP ensure the required properties of materials used on site - QUALITY CHECK

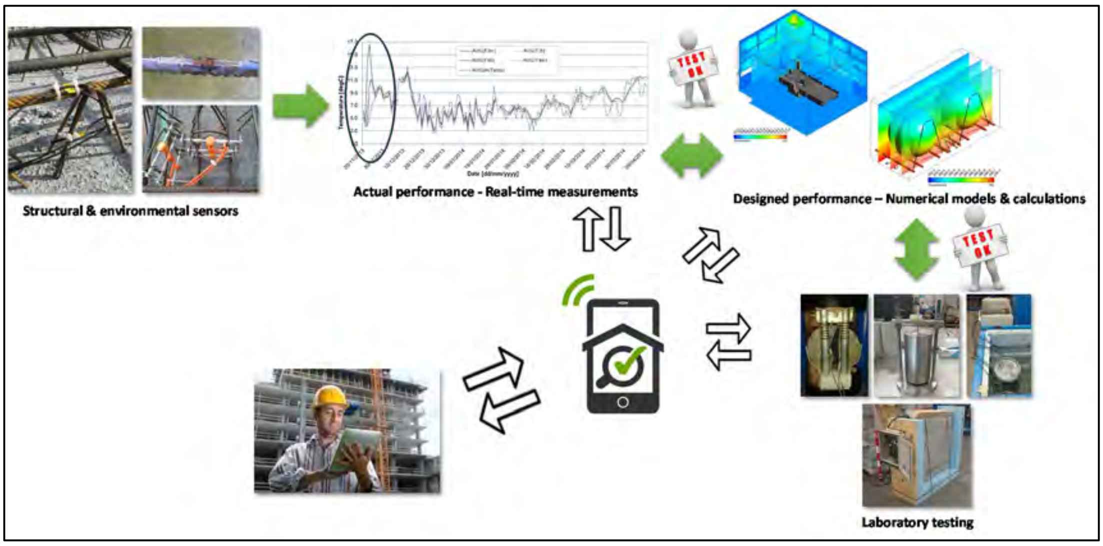


Fig. 23 Schematic representation of the communication flows between VCMP and the related actions

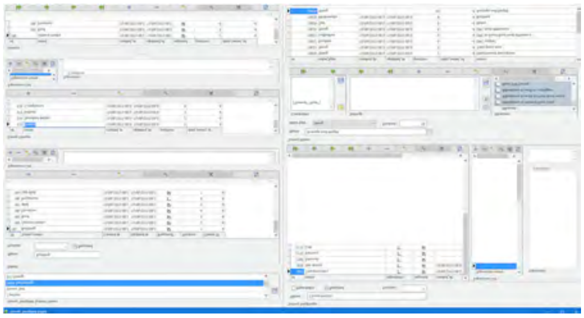
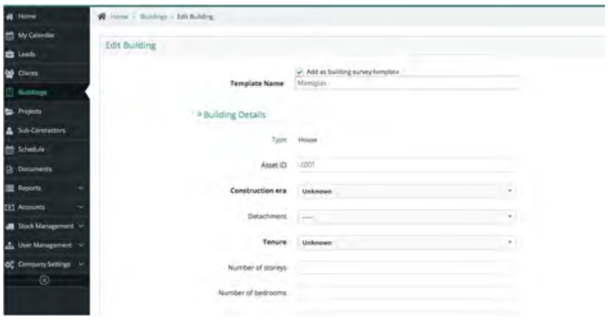
➢ VCMP "vigilance spots" integration and "visa" management

The main stages can be described as follows:

- The design team specifies during design "vigilance spots" to be followed-up when the contractors send detailed descriptions and implement their solutions on sites (e.g. insulation of the interface between roofs and facades, at the frontier between 2 lots and possibly 2 different contractors)
- The "vigilance spots" are integrated in VCMP and localised on BIM
- The contractors specify a technical response and technical details to comply with the "vigilance spots", to be integrated in the VCMP
- The design experts validate (or not) the technical proposal from the contractor, indicating a "visa" on the VCMP
- The site supervisor can inspect/check the list of "vigilance spots" directly on site, and validate them directly on the VCMP.
- If the site supervisor needs more information about the technical details, he can access directly the information updated by the contractor ("cahier de detail")
- If BIM is used to localize the "vigilance spots" the format of the data must be light enough to be managed from mobile devices (VCMP displaying limited information extracted from the BIM?)

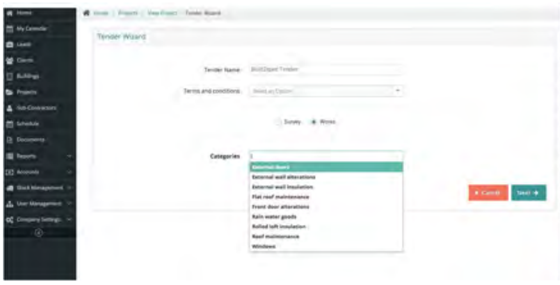
➢ **Survey management through the VCMP**

- Survey template creator: Build pre-configured property surveys using survey template creator
- Linked surveys: Different surveys for different onsite requirements. e.g specialised insulation survey, heating survey, mixed measure survey etc
- Completed building surveys can be saved as pre-populated templates. For faster surveys on similar buildings

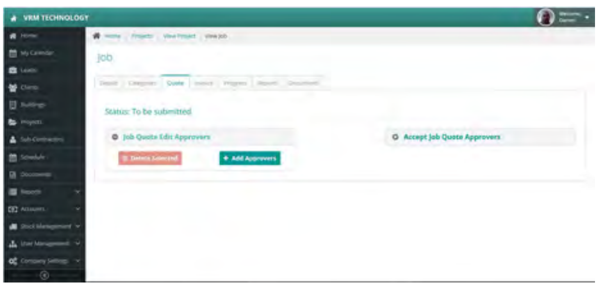
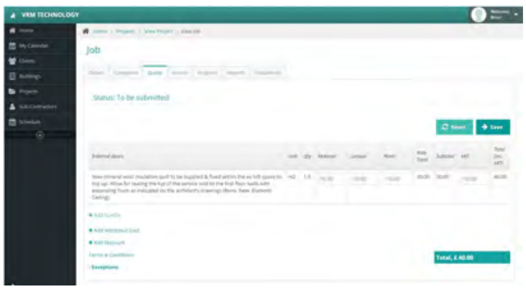



➢ **Tender creation and management through the VCMP**

- System is pre-populated with all required items of works, products, costs, units of measure etc
- Tenders may be created from scratch on a single property or a number of properties
- Self Inspection minimum requirements are created
- Suitable contractors and or sub-contractors are available via current ratings, location and standard costs
- Tender approval via single or multiple approvers

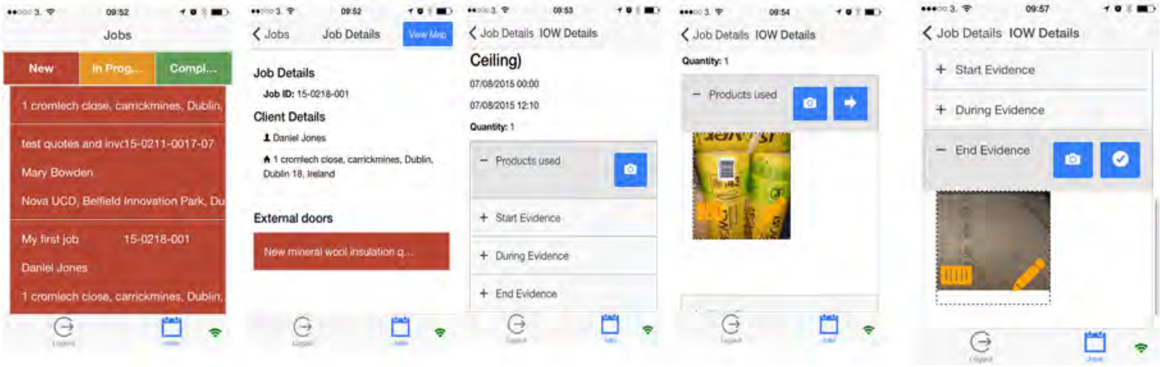



- Request for quotes or tenders created and sent to contractors
- Different type of approvers for quotes allowed. e.g approvenew quote, approve edit/update of quote
- Self Inspection minimum requirements are created
- Suitable contractors and or sub-contractors are available via current ratings, location and standard costs
- Tender approval via single or multiple approvers

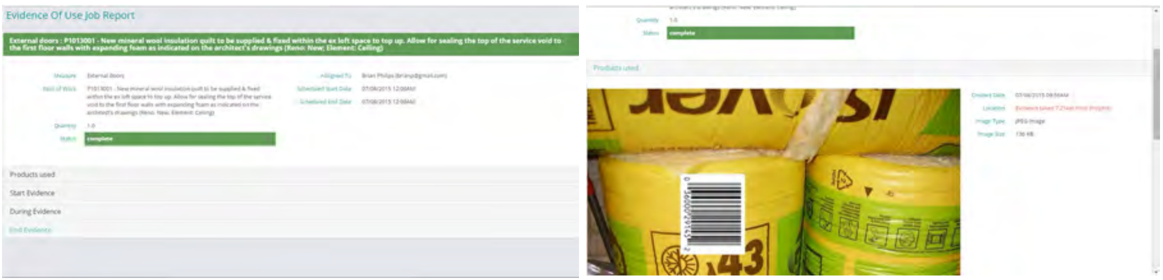



➢ **Self-inspection app and cloud**

- Work allocated via Schedule module
- Workers onsite use mobile apps to evidence work progress. Photos, GPS, Notes
- RAG (Red, Amber, Green) traffic lights show status
- Correct products matched via photo barcode scans



- Work progress sent back to cloud once connectivity available from mobile device
- RAG (red, Amber, Green traffic lights show status
- Correct products matched via photo barcode scans
- Evidence Reports
- GPS location of photos matched against agreed job location



➢ **BIM integration of unforeseen or unforeseeable events/elements on the construction site**

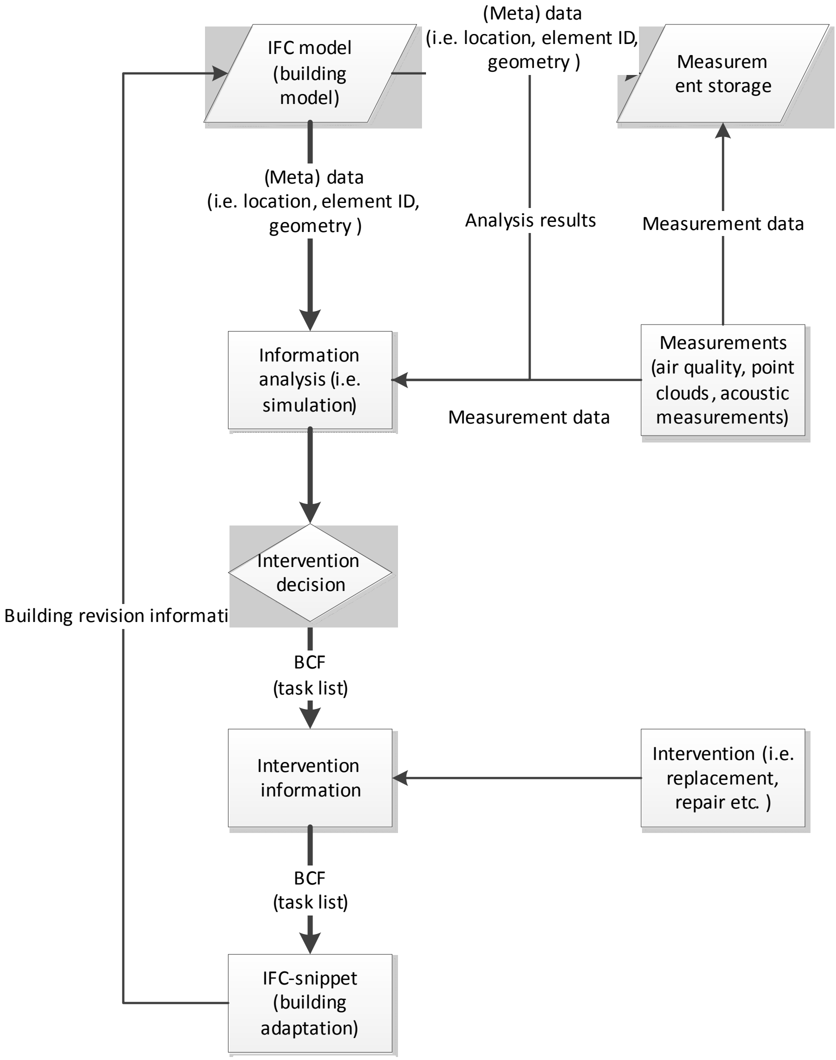
Here are the main steps:

- In some cases, the site supervisor will observe details that were not integrated in BIM (not foreseen or not foreseeable).
- In these cases there can exist a need to integrate this information very quickly in the BIM, and to assess the impact related to others details/constraints.
- The supervisor informs the BIM manager via the VCMP.
- The BIM manager/chief designer decides of which details should be "accepted" and integrated into the BIM, and which details should be "rejected" and corrected as planned.
- The modification of the BIM is accompanied by a notification on the VCMP and the site supervisor is informed
- Several iterations and exchanges between the construction site and the BIM may be needed in a very limited time to solve an issue. The VCMP is a good mean to accelerate this process

➢ **Measurement during construction leading to an intervention on-site**

Here are the main steps:

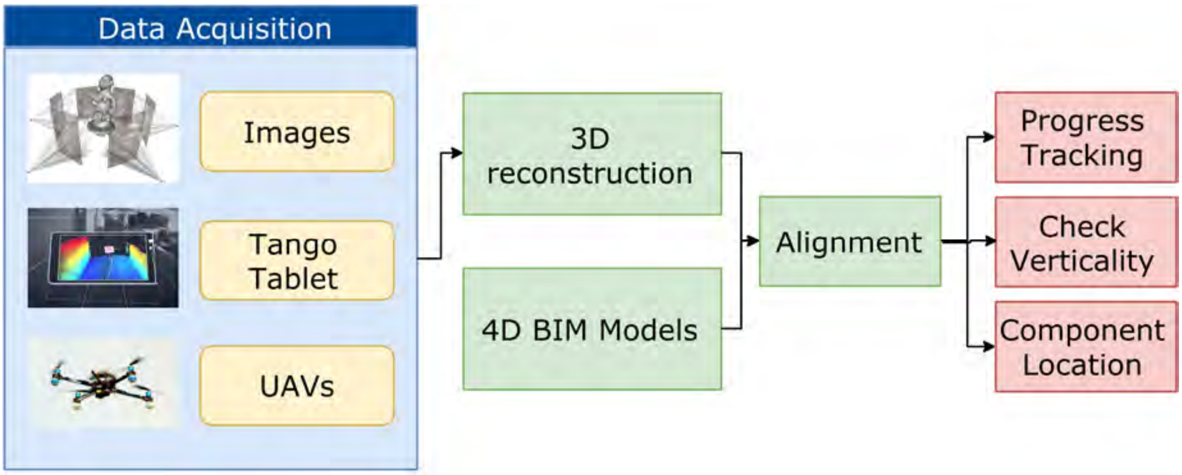
- A measurement is performed, the results are used in a simulation using the building model (or checked against a requirement)
- The component fails the test/simulation and the designer decides this is not acceptable.
- An issue is reported and an intervention/replacement/upgrade is executed by the contractor.
- The model is updated with an IFC-snippet (possibly after a new measurement/check)
- This entire process is tracked and managed by VCMP



- **Quality check for 3D reconstruction based on imagery, 3D scanning and drones techniques**

Main stages/steps of the use case:

- On-site data acquisition. It can be done in 3 different ways:
  - Images (passive sensor),
  - Google Tango Tablet (active sensor),
  - UAVs (drones)
- 3D Reconstruction pipeline (accuracy in the range of cm)
- Alignment and comparison against 4D BIM models, allowing:
  - Progress trackin
  - Check verticality/horizontality/angles of some components
  - Check correct location of some components



Annex A Typical construction process workflow in Italy

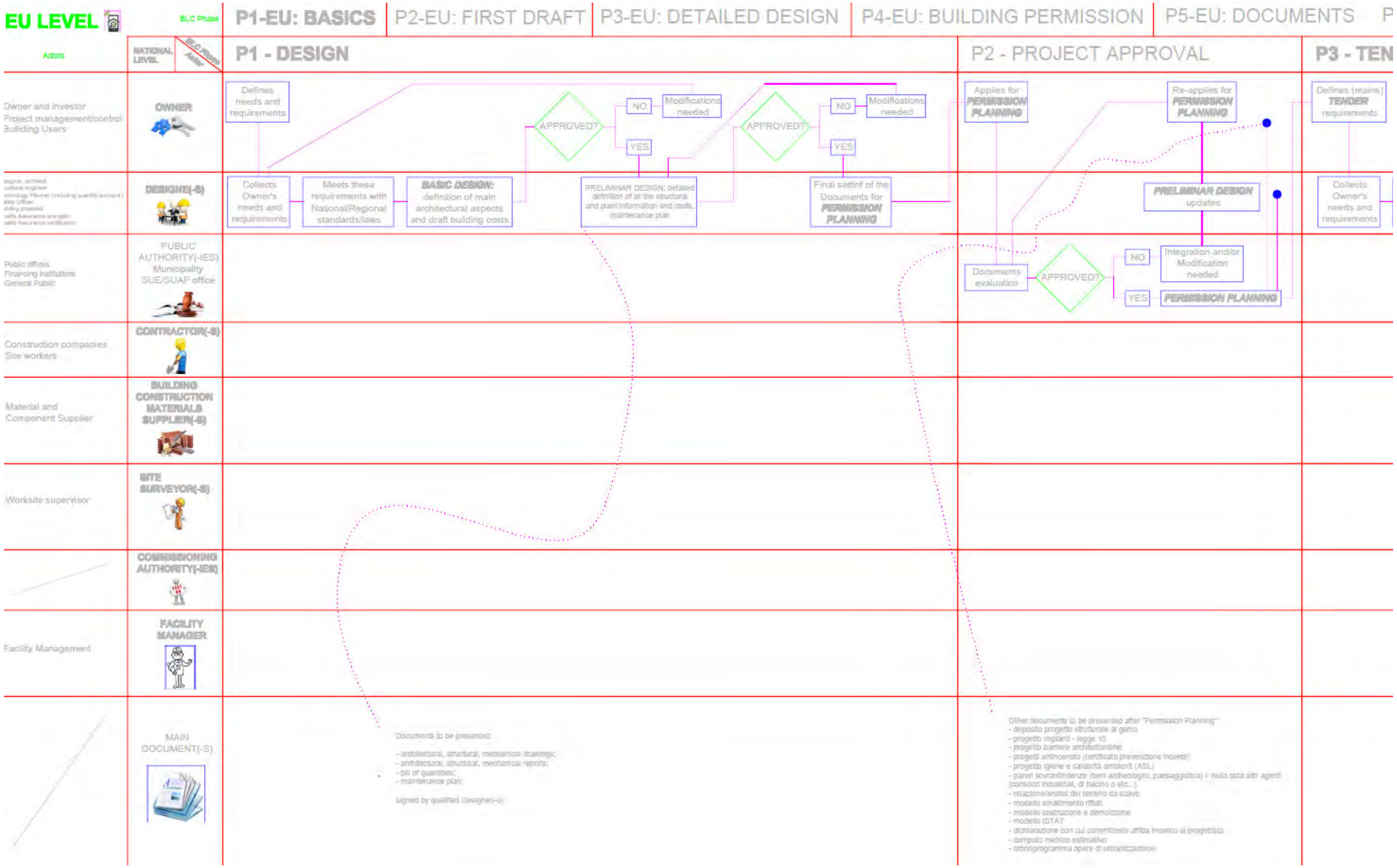


Fig. A Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 1/3

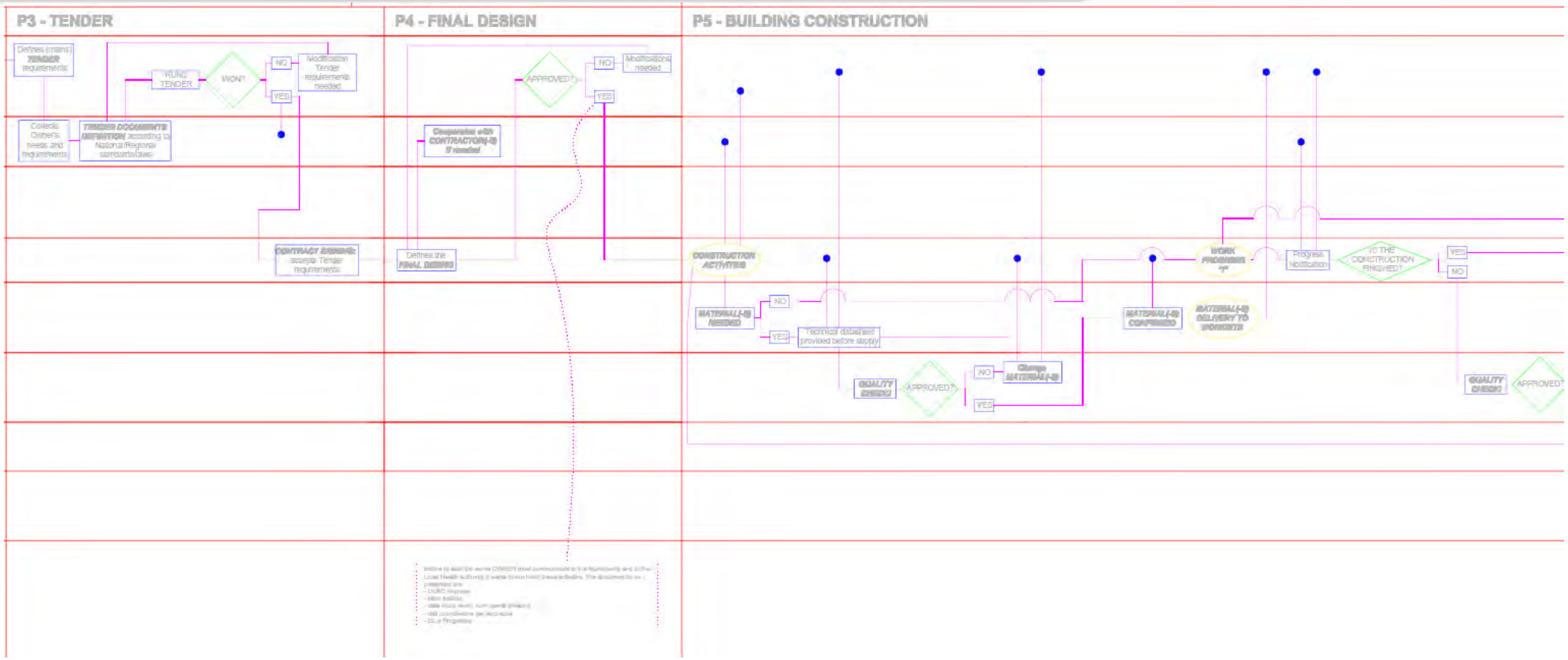


Fig. B Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 2/3

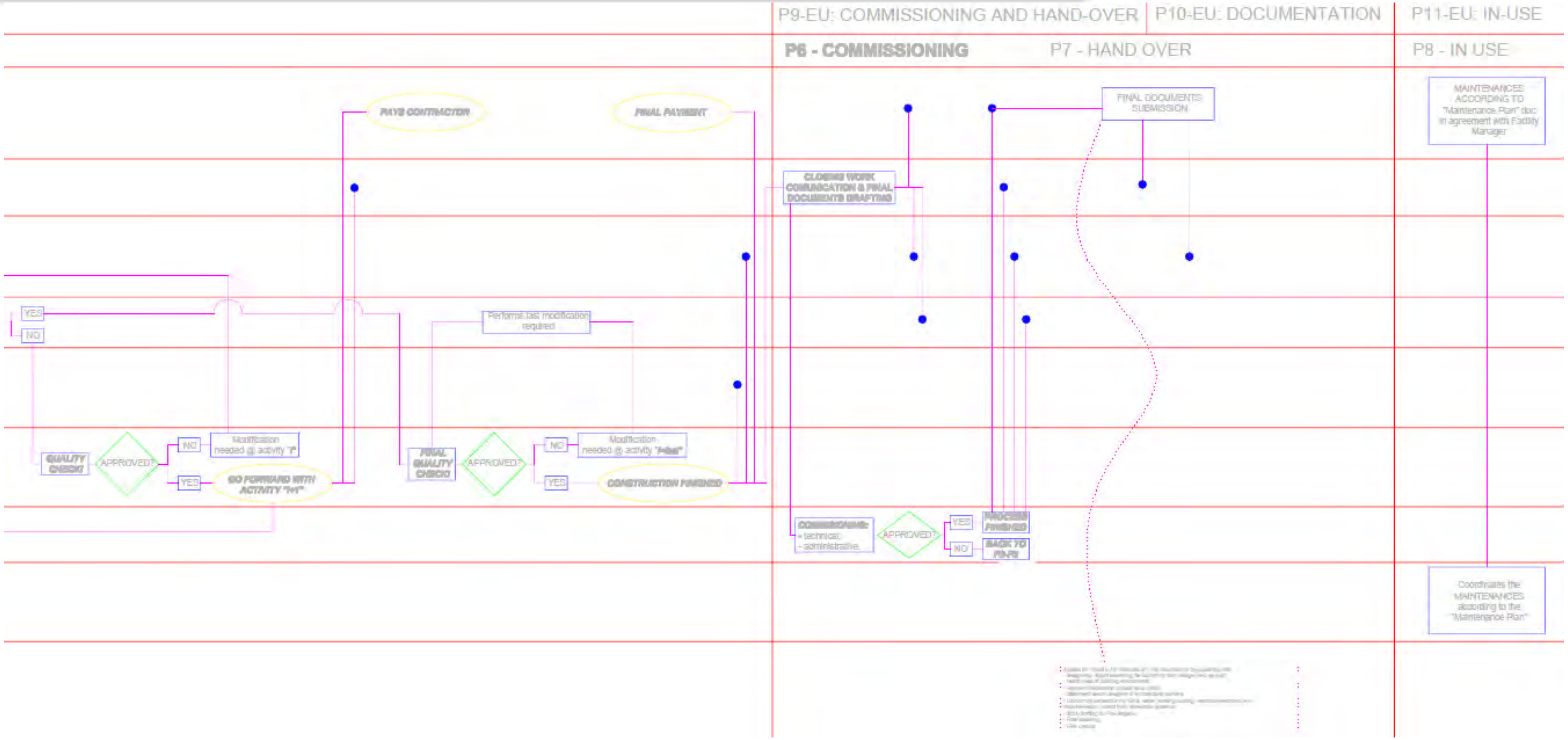


Fig. C Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 3/3

Annex B Typical construction process workflow in Netherlands

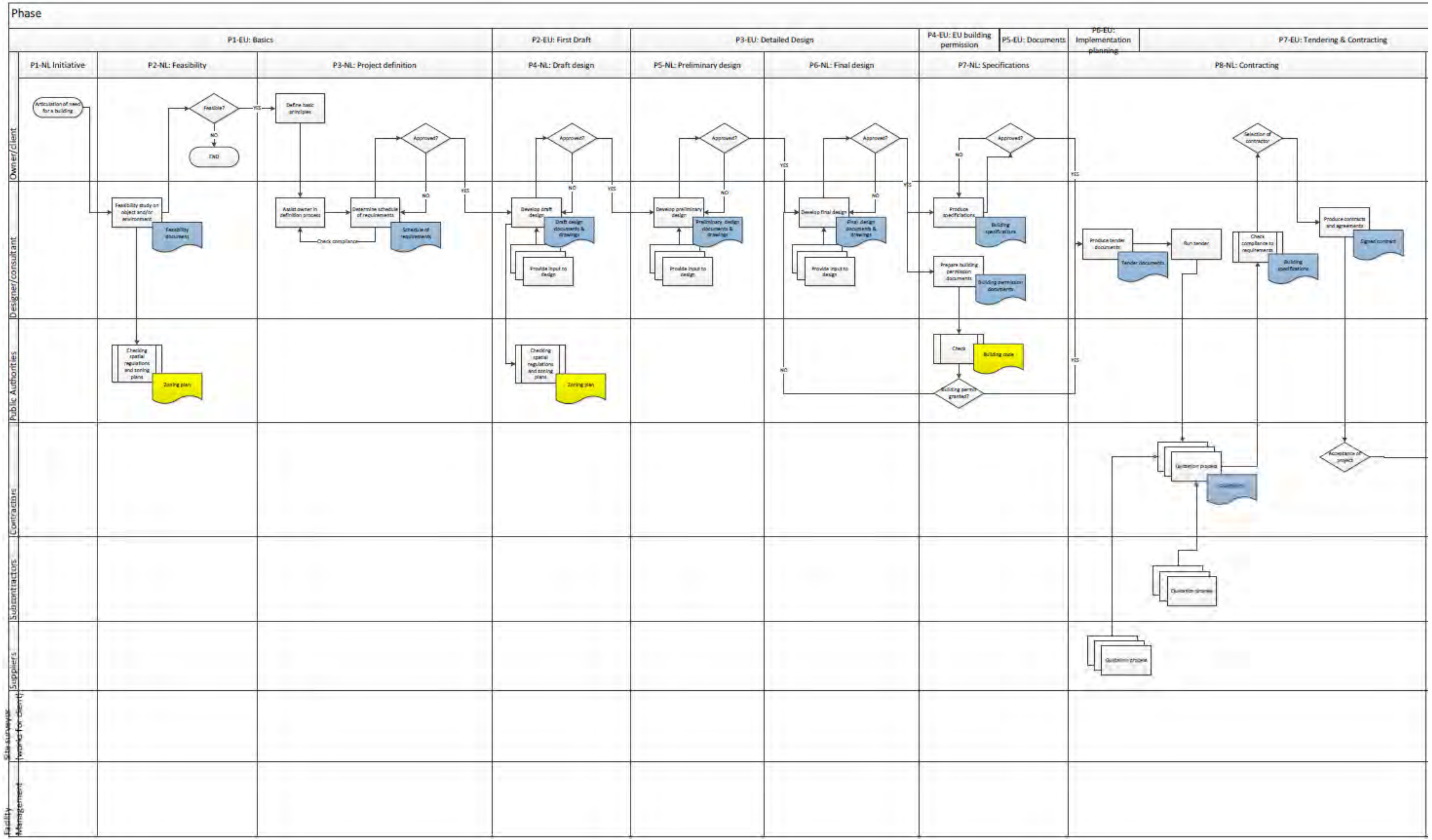


Fig. D Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 1/2

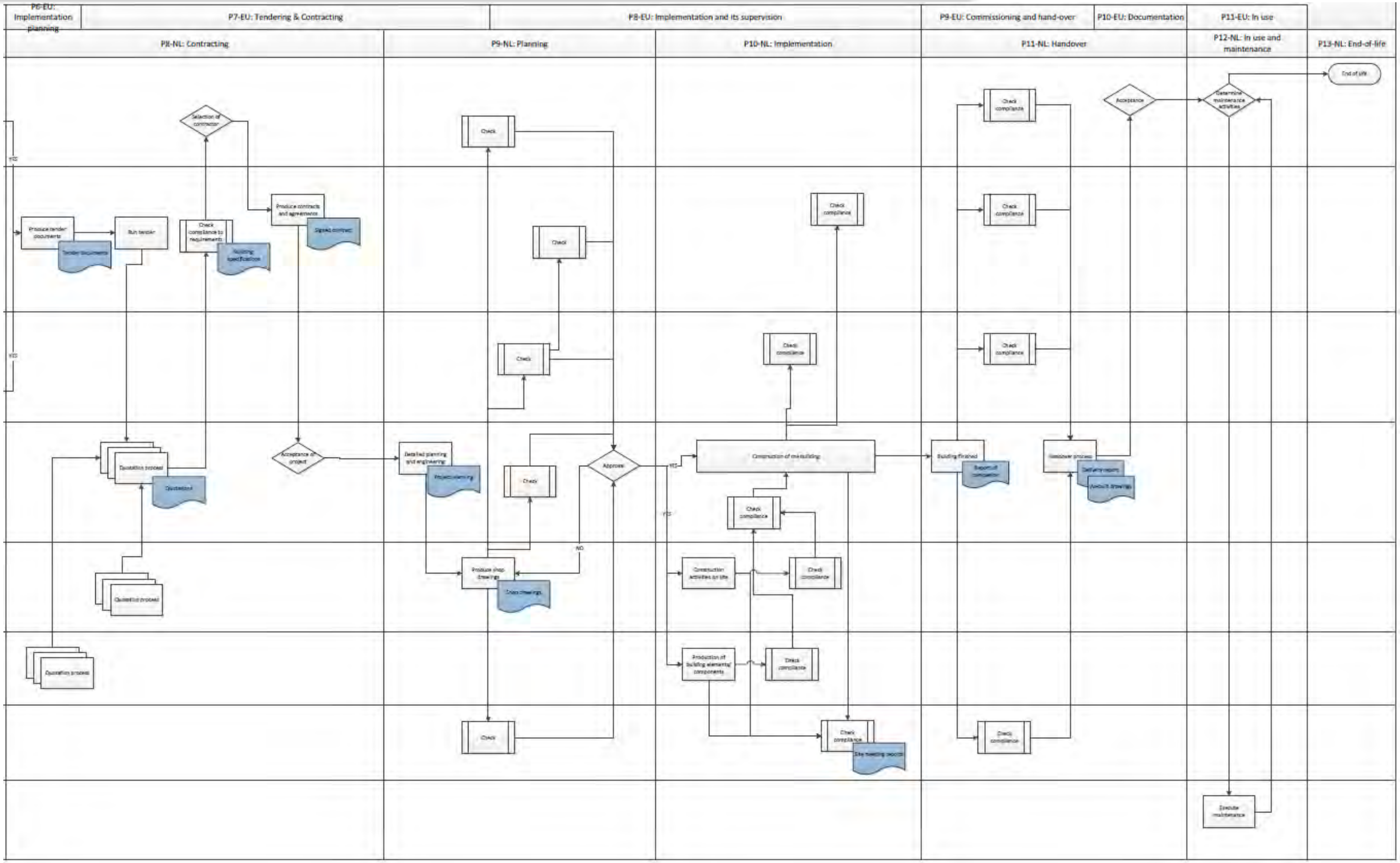


Fig. E Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 2/2

Annex C Typical construction process workflow in Spain

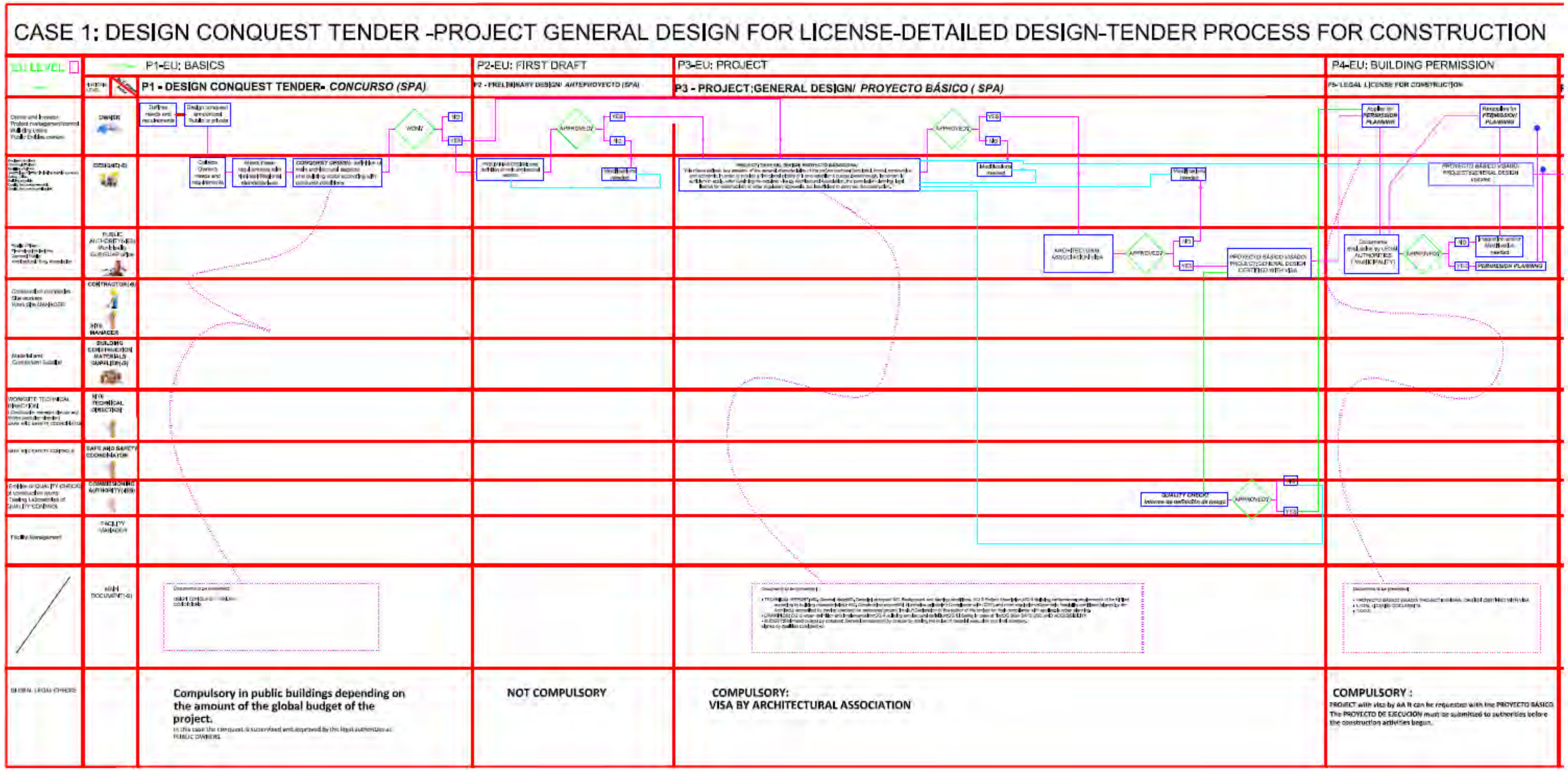


Fig. F Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. ¼

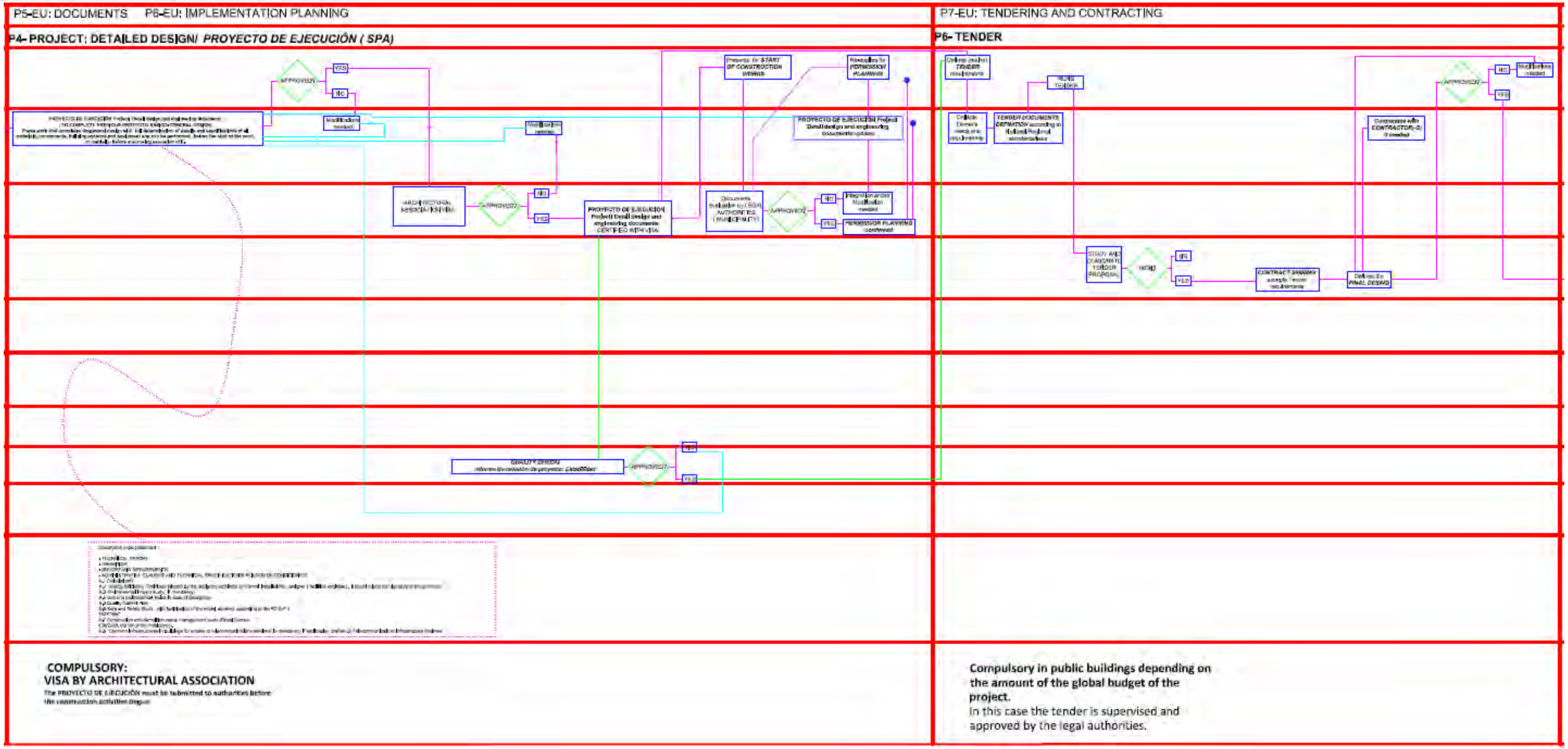


Fig. G Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 2/4

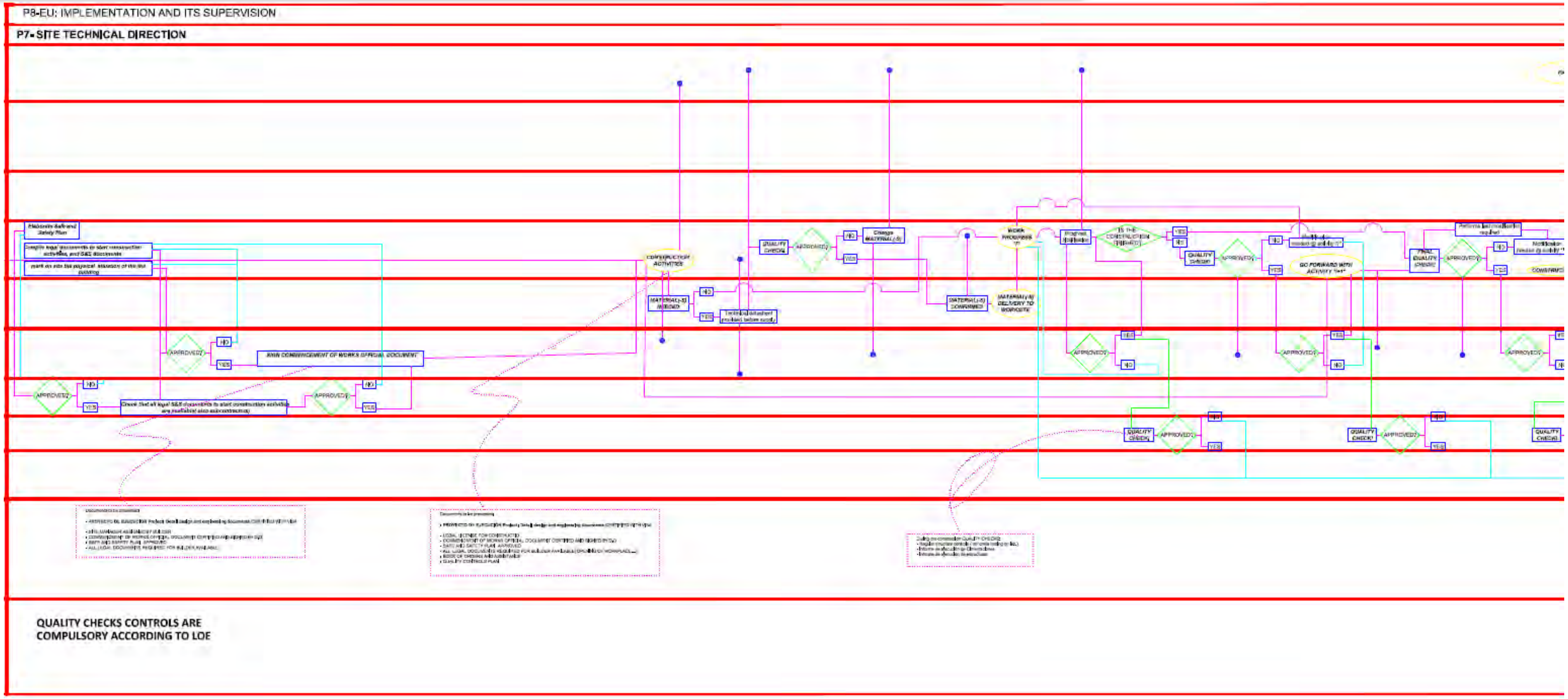


Fig. H Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 3/4

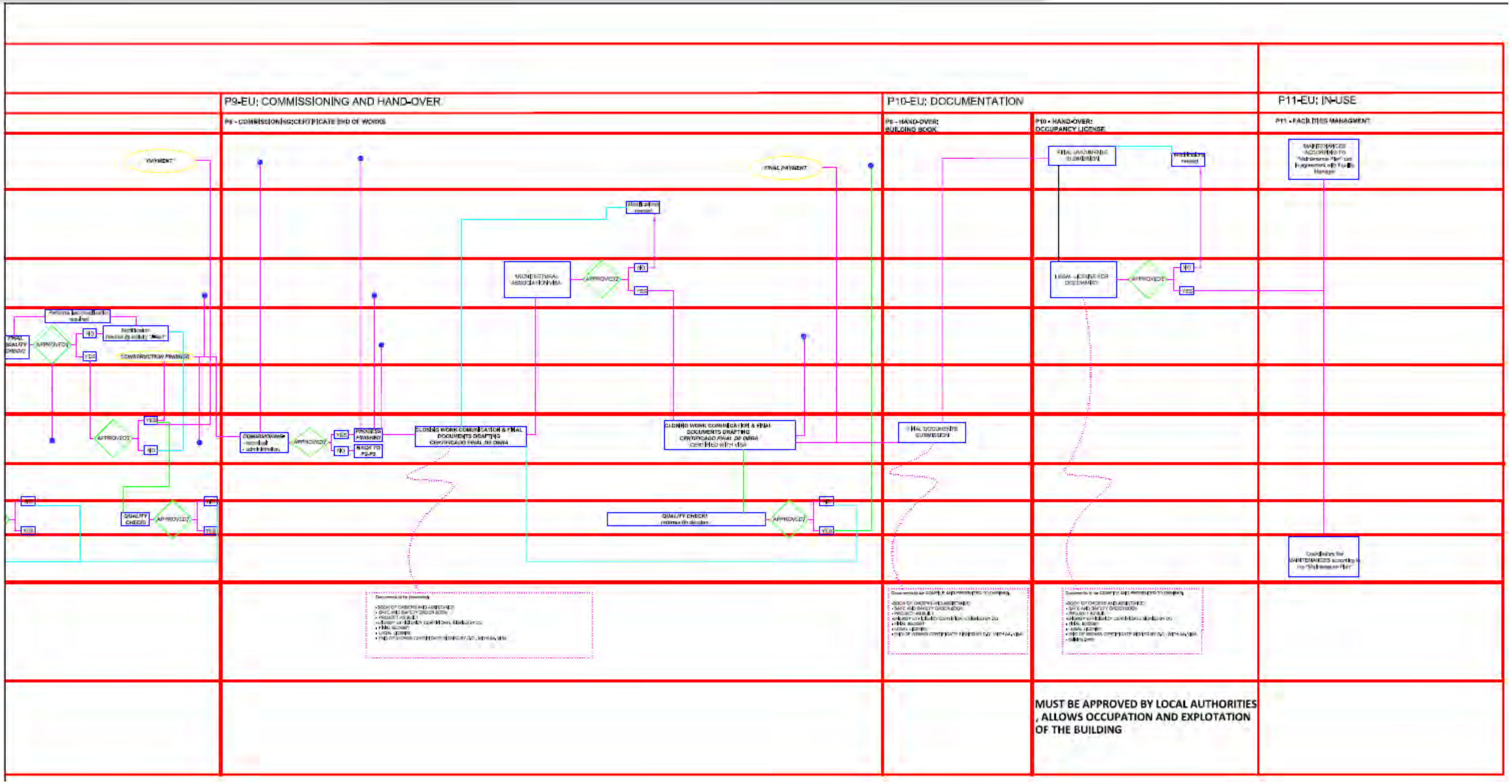


Fig. I Detailed construction process workflow (raws for stakeholders, columns for stages), including decision milestones. 4/4