Paper ID APEN-MIT-2021_173
Applied Energy Symposium: MIT A+B
August 11-13, 2021 • Cambridge, USA

Using Living Labs to tackle innovation bottlenecks: the KTH Live-In Lab case study

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Abstract— The adoption of innovation in the building sector is currently too low for the ambitious sustainability goals that our societies have agreed upon. The concept of smart building, for instance, is being implemented too slowly. One of the main reasons for this is that technologies have to be proven effective and reliable before being introduced at large scale in buildings. Testbeds and demonstrators are seen as a crucial infrastructure to test and demonstrate the impact of solutions in the building sector and hence facilitate their adoption in buildings. The KTH Live-In Lab is a platform of building testbeds designed to this scope. This work describes the Live-In Lab vision, approach, technical features, provides an overview on the multidisciplinary projects that it has enabled and discusses its replicability.

Keywords— smart buildings, testbeds, living labs, sustainable buildings, co-creation lab, collaboration platform.

I. Introduction

Buildings are estimated to account for 30-40% of overall energy use and 40% of CO_2 emissions in developed countries [1,2]. Implementing new technologies and methods accompanied by new business models and regulations is a way to decrease building related resource usage and emissions [3]. However, the current implementation rate of these technologies is too slow to reach national and international resource related targets.

Information and Communication Technologies (ICT) has been shown to enable and determine resource efficiency in the built environment, through advanced controls, energy monitoring and fault detection and promotion of energy-efficient behaviors, [4–9]. Smart buildings possess ambient intelligence and automatic control, which allows them to respond to the behavior of residents and provide them with various facilities. Smart buildings and homes offer potential features that go beyond the capabilities in current buildings, such as improved security, assisted living and e-health capability, augmented entertainment, communication and visualization, improved comfort and indoor air quality and more efficient use of resources. Smart buildings are seen as the forefront of technology in the construction sector and the widespread use of sensors is expected to increase the understanding of the building processes and unlock their resource efficiency potential. Smart buildings are expected to play a crucial role as units in smart sustainable cities, and have been the object of great attention in the literature in recent years. Still, their adoption in the building sector is falling behind the societal expectations, and the introduction of new technologies in the residential and construction industry is currently too slow to meet crucial long-term societal goals of reduced use of resources and emissions.

Novel resource saving technologies carry risks beside their advantages. Once technologies are proven to function then also contextual factors such as business models, agreements and regulations have to be adjusted to reduce and share risks in a rational way [10–15]. Living Labs or testbeds are real-life platforms to investigate not only technology, but also associated risks, user behavior, operation aspects and new skills. A living lab methodology or framework is a way to tackle complex, multi-stakeholder and urgent problems in a co-creative way [16].

The KTH Live-In Lab is a concept that allows research, industry and societal stakeholders to work tightly together in a physical and virtual infrastructure that includes an increasing number of building testbeds. The widespread adoption of innovative technologies facilitates multi-disciplinary collaboration and is expected to foster the adoption of smart buildings [17].

This paper introduces the concept of the Live-In Lab and the methodological approach to manage the innovation and the knowledge transfer to make a significant societal impact, and it draws the first conclusions on the experience developed so far.

The KTH Live-In Lab has been initiated and made possible by a donation of Einar Mattsson-Group, whose support is kindly acknowledged. Donations from Akademiska Hus and Schneider Electric are also kindly acknowledged. The work in this paper has been supported by the Swedish Energy Authority and IQ Samhällsbyggnad, under the E2B2 programme, grant agreement n. 47859-1 (*Cost-and Energy-Efficient Control Systems for Buildings*), by the Swedish Foundation for Stretegic Research-SSF-, under grant agreement n. RIT17-0046 (CLAS - *Cybersäkra lärande reglersystem*), and by Digital Futures, (HiSS - *Humanizing the Sustainable Smart City*).

II. Methodology

A. Management theory and approach

The KTH Live-In Lab is intended as the node for investment and risk management that is needed in the end phase of product/service/process development for large-scale dissemination. Allowing industry, academia and society to collaborate in an open and neutral testbed lowers and redistributes risk, uncertainty and costs in a way that allows for greater impact. The products and services can be evaluated, not only technologically but also socially, economically and environmentally. Technology-specific models can be tested and developed, rules and norms can be tested, questioned and reworked; all to allow for tomorrows form of living to be redefined and improved through an increased innovation rate.

KTH Live-In Lab is based on theory around Strategic Niche Management (SNM) and Multilevel perspective (MLP), mainly as described by Rip, Schot & Geels [18] and Berkers and Geels [19] that is strongly influenced by earlier research related to technological niches [20–23]. Both theories discuss innovation and technology shifts. They argue that players who are actively involved in the innovation process affect, through collaboration, the selection process of new technologies and the future trajectory of research and development. These theories emphasize the importance of demonstration projects, or testbeds, that provide partial shelter for new technological innovations, referred to as technological niches. Products and services can be tested and verified within these protective environments, technological niches, with higher levels of interactions and of knowledge transfer between different players of the market, a key success factor of dynamic clusters.

B. Organization and business model

The KTH Live-In Lab way to tackle complex problems has been to use a co-creation and a multi-stakeholder approach [16,24]. The organization of the Live-in Lab has been rather similar from the start in 2015 until today (2021), but funding conditions have significantly changed. Initially, all work was performed solely by engaged persons who believed in the concept, but it has gradually moved over to funded positions once the financial situation has been consolidated.

The overall management is performed by the Director, who also acts as coordinator between the Executive group (performing technical supervisory duties) and the Steering Board (formally responsible for the Lab' operation and selection of R&D-projects). Supplementary personnel, (Co-Director, Project manager, Technical Director and Research and Education Coordinator) support the Director for specific tasks, providing at the same time the necessary organization flexibility and the specific skills required for the Lab operation.

The research and education activities mainly fall in three types of projects: industrial projects, thesis projects and research projects. Industrial projects are implementation projects for companies in need of near-real or real environments to test working prototypes that are ready for the market. Research projects are larger projects that involve at least one research institution and most often one (or many) industrial company. Applications to the Live-In Lab are managed by the Executive group and decided by the Steering Board; the Lab does not grant financial support, which is applied for to external funding bodies, but the possibility to link research to real case studies increases the success rate of the applications. In 2019, 9 out of 10 applications using KTH Live-In Lab received funding from different agencies.

The business model of KTH Live-In Lab targets the national (Swedish) focus of combining governmental funding, industry co-funding and applied research contracting. Value propositions for industry to engage in KTH Live-In Lab are: 1) test infrastructure, 2) researchers and competence 3) possibility to double the value of already ongoing industry R&D-activities.

The first and second points above are rather intuitive, but the third is actually the key value that ensures the longevity of the KTH Live-In Lab. KTH Live-In Lab acts as a mediator between researchers and industry, creating increased value from already ongoing company R&D-activities. The financial resources planned for these company-internal activities is used to co-finance and strengthen applications in order to receive external governmental funding to cover research activities of mutual interest. In short, KTH Live-In Lab creates value by 1) using industry costs for ongoing internal R&D as co-funding in applications to 2) get access to governmental funding for 3) researchers that will 4) investigate an area of mutual interest, and 5) help to accelerate innovation and reduce climate impact related to the built environment. In order to create these connection, support writing applications, leading co-creation activities, help managing data and results and access testbeds and office space, KTH Live-In Lab charges a yearly fee in relation to the amount of work that the different research projects need. The yearly fee typically ranges from 5000 – 30000 Euro per year.

III. Experimental setup: Building testbeds

The idea behind KTH Live-In Lab is to open up buildings for real-life experiments, conduct research projects, and share validated results with different decision makers in order to accelerate innovation and change. To make this happen, KTH Live-In Lab has three connected functions: 1) collaboration platform, 2) building testbeds and 3) data- and ICT-infrastructure (Datapool). The whole structure, from management to sensor system, is flexible, adapting and growing depending on type of projects, collaborating partners and financial possibilities.

The current buildings testbeds in the Live-In Lab are grouped into three categories: 1) Core Lab, i.e. Testbed KTH, 2) Extended Labs, i.e. Testbed AH (owned and operated by Akademiska Hus, center member) and Testbed EM (owned and operated by Einar Mattsson, center member and founding partner), and 3) External Labs or Trusted buildings (owned by different project partners), see Fig. 1. The Core Lab is the most advanced testbed facility, with a more extended sensor network, a higher degree of interaction with the testbed occupants and the possibility of extensive layout redesign. Extended testbeds are buildings typically equipped with modern but standard equipment, and External lab testbeds are project-specific. Data from all testbeds are stored and shared through the Live-in Lab Datapool.

The Testbed KTH and the Testbed EM are housed in the same building at KTH main campus in Stockholm.

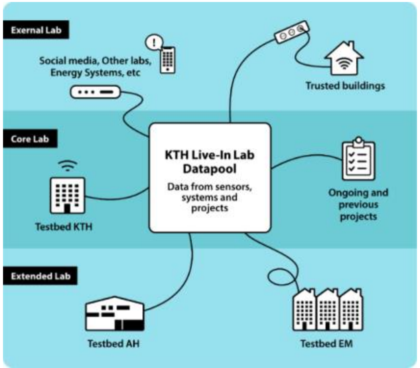

Fig. 1. Live-In Lab building testbed setup and datapool.

A. *Core Lab: Testbed KTH*

The Live-In Lab Testbed KTH in its current configuration comprises of four student rooms with their own bathrooms, a shared kitchen and living room, and an office and technical room, for a total of 300 m^2. Heating to the apartments is provided by ground-source heat pumps and distributed through either the ventilation system, or water-based or electrical floor heating (depending on ongoing studies). Water, ventilation, electricity, and control systems are developed and installed to ensure fast and cheap reconfigurations depending on project type and scope. Electricity is generated locally in the Testbed EM with panels installed on the flat roof; additionally, storage systems, in particular batteries for electricity, can be installed.

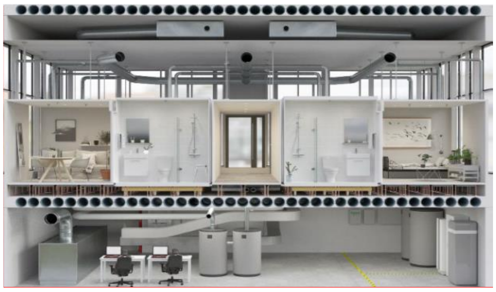

Fig. 2. Testbed KTH, showing underlying operation facilities, and area for building innovation units or apartments.

Advanced sensing capabilities have been deployed to monitor indoor environment parameters -like temperature, humidity and CO_2-, to meter the energy used in the apartments for space heating, domestic hot water production, tap water, as well as the energy delivered from the borehole heat exchangers, the heat recovery and the PV panels. Redundant temperature sensors placed in the walls allow a better assessment of the comfort, Fig. 3. Furthermore, real-time measurements of ventilation airflows and temperatures enable detailed mapping of space heating use. Additional sensors detect windows opening and occupancy used to optimize resource usage without compromising user experience. The adoption of light sensors make it possible to study internal illuminance, maximize the use of daylight and improve the light comfort; acoustic comfort level is assessed via noise level meters. The whole sensor network is conceived with a flexible and modular approach, to allow the installation of extra sensors.

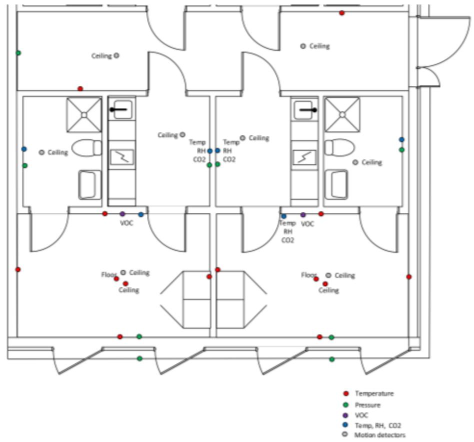

Fig. 3. Layout of the sensor network in two of the four apartments in Testbed KTH, layout 1.0 (2018-2020). The deployed sensor network allows detailed monitoring of the Indoor Environmental Quality (thermal comfort and air quality) in parallel with the mapping of the resource flows.

The Testbed KTH is also freed from building permit, meaning that technologies, geometries and resource flows do not need to follow Swedish building regulations, and can hence function as niche for innovative technology and methods. The testbed is designed with detachable walls to act as a flexible design experimental setup and to quickly accommodate for changes required in research. An example of this is the already performed and the coming redesign of the layout of the indoor environment. To gain a better understanding of how people use the indoor spaces the layout has changed from the Testbed KTH 1.0 to Testbed KTH 2.0, with a further evolution planned for summer 2021. The layout of the Testbed KTH 1.0 featured four independent apartments, each consisting of a living/bedroom, a kitchen, a bathroom and a shared corridor (see Fig. 4). The Testbed 2.0 merged the corridor and the kitchens to create a larger shared space, but still keeping the private rooms and bathrooms. The layout changed the ratio between private and public from 85/15 to 65/35; the earlier relatively unused corridor, accounting for 15% of the total floor area, became part of a vibrant 35% co-living area. This design approach enables research on interaction design and creates a unique venue for interdisciplinary research. The project behind the redesign was named "*Co-living and productive space usage*"; it was a collaboration project consisting of seven industry partners and two universities, concluding that co-living units like shared kitchen and bathrooms can lower their environmental impact up to 50% compared to normal setups [25].

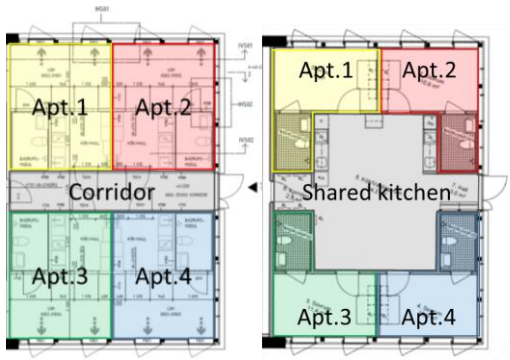

Fig. 4. Layout of the Testbed KTH 1.0 (on the left) and of the Testbed KTH 2.0 (on the right). The intended use of the spaces has been redesigned, with an increased share of common spaces – the shared kitchen and living room.

B. Extended Labs: Testbed EM

The Testbed EM is a set of three residential buildings designed to be positive energy buildings. The Testbed EM features a total of 305 student apartments with an average size of approximately 20 m^2; each apartment includes a living room, a small kitchen and a bathroom. The indoor thermal comfort and air quality are controlled separately in each apartment via dedicated temperature and CO_2 sensors that act on supply and return airflows. In addition, domestic hot water and electricity are measured in all apartments.

Fig. 5. Testbed EM and Testbed KTH in the same picture. Testbed KTH is housed on the entrance and basement floor in one of the three buildings that constitutes Testbed EM.

A set of three 64kW geothermal heat pumps provides heat to the Testbed EM; the heat pumps use 12 boreholes as a heat source. The geothermal installation design has some unconventional features in order to function also as an infrastructure for research. The boreholes have lengths ranging between 100 and 450 meters and are equipped with measurement probes to provide data for the evaluation of the thermal performance of boreholes of different lengths within the same borehole field. A dedicated "research borehole" featuring a length of 100 meters is also ready for different types of heat exchangers, and a coaxial design is currently tested. The concept behind this borehole is to provide borehole researchers with a very flexible system to experiment with innovative ideas, but having the surrounding ground as a fixed parameter. A four year project including 21 industry partners and three universities has recently been finalized, using Testbed EM to analyze major features characterizing the design and operation of for example building signature, energy exchanged with the borehole field and temperature of the secondary fluid in the borehole loop [26].

The buildings feature an efficient thermal envelope with high air tightness and the Termodeck system [27], an example of Thermally Activated Building Systems (TABS) for heat emission. Ventilation air circulates through the building slabs before entering the rooms, preheating or precooling the slabs; this feature allows a more stable and homogeneous temperature distribution in the indoor spaces, adding to the comfort.

The positive energy building design benefits from an efficient heat recovery systems for ventilation and for the wastewater, and 68 waste heat exchangers. The efficiency of the wastewater heat recovery system, in particular, is being actively monitored as part of a collaborative project between industry and research. In addition, renewable energy is generated locally with PV panels installed on the whole roof surface, for a total of 1150 m^2.

C. Extended Labs: Testbed AH

The Testbed AH is a recently built university building used for lecturing; occupancy patterns and interaction with indoor environments are hence significantly different compared to the Testbed KTH and the Testbed EM. The building consists of seven floors, 363 study places, six exercise rooms, and 11 group rooms and break out areas over a total of 3500 m^2.

The building is monitored with ubiquitous ambient sensors, e.g. temperature and CO_2; additional sensors have been embedded in the building envelope to investigate, for instance, temperature and relative humidity distribution within the walls.

Fig. 6. Testbed AH at KTH main campus in Stockholm.

IV. RESULTS

The main goal of the Live-In Lab is to accelerate innovation in the building sector and to make technically and economically feasible smart and sustainable buildings and cities; hence, it is critical that the industry is centrally involved in research of the Live-In Lab. Consequently, the evaluation of the success of the Live-In Lab approach has to be done focusing on two aspects: the capability to attract the interest of the industry and the capability to produce interdisciplinary, high quality research. TABLE I summarizes the main Key Performance Indicators (KPI) for the Live-In Lab.

The Live-In Lab has been functioning as a research project between 2015-2019 and became a research center in 2019, with around 1/3 co-funding from the industry, 1/3 from academia and 1/3 from projects using KTH Live-In Lab. The platform has succeeded in attracting interest from the industry, with 71 industrial partners participating in the center activities and/or in single research projects. All partners support the center with either in-kind contributions or direct funding.

The project areas currently active in the Live-In Lab platform cover most of the core topics not only to overcome barriers to the implementation of smart buildings, summarized in [28], but also to boost the rapid adoption of smart buildings with new economic and technical incentives. Fig. 7 illustrates the main project research areas, i.e. areas with active projects, [29]. Thematic areas include technical ones, like building data integrity and security and sustainable buildings (e.g., projects like "*Smart Building Management systems*", "*Improved borehole technology for Geothermal Heat Pumps development*", "*Ensuring sustainability and equality of water and energy systems during actor-driven disruptive innovation*"). The legislative area deals, for instance, with the proper handling of the data generated in buildings and has resulted in two publications in Swedish related to GDPR and smart buildings, and ethical aspects and smart buildings [30,31]. In the business research area focus is on the development of digital services (e.g., "*Service design for the sustainable behavior modeling: Smart schedule*", [32]). Equally important are social research areas, with co-living topics (*"Co-living & Productive space usage"*), sociology and behavior (*"Occupant pro-environmental choice and behavior"* [33]), and health, for instance with the monitoring of quality of indoor environment (with the project *"Allergen free indoor environment with innovative ventilation strategies"*, resulting in a recent publication [34]).

In 2019, the first year as a center, there were 16 ongoing projects, with 10 newly funded projects [29]. Two thirds of the active project in the Live-In Lab were interdisciplinary university-wide collaboration projects, with several projects spanning among beyond KTH. In 2020 there were a total of 17 research projects ongoing, of which 47% were university-wide collaboration projects.

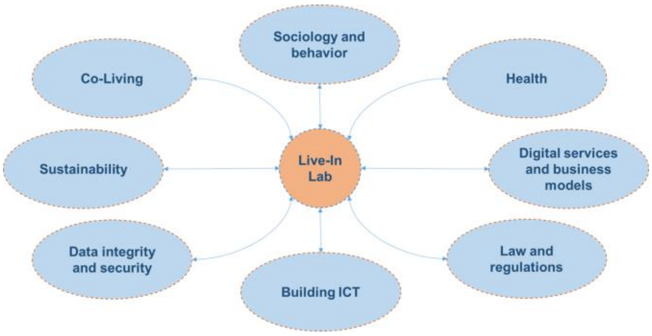

Fig. 7. Thematic area of the projects currently active in the Live-In Lab platform.

From a financial point of view, the platform has collected over 10 MEuro of funding for projects, and 2020 the ongoing projects had a total budget of 4.2 MEuro of which 1.5 MEuro were industry co-funding

In terms of societal impact, the communication efforts promoted by the Live-In Lab governance and community have resulted in 19 public presentations and 8 public seminars directly related to the Live-In Lab vision in the year 2020.

TABLE I. KEY PERFORMANCE INDICATORS FOR THE LIVE-IN LAB

KPI type	**KPI 2020**		
	Table column subhead	***Target***	***Results***
Research	Ongoing projects	10	17
Research	Larger projects	5	8
Research	University wide project collaborations	>50%	47%
Finance	Total funding 2020 [MEuro]	1	4.2
Finance	Total industry cofunding [MSEK]	0.5	1.5
Finance	Companies/organizations associated with Live-In Lab	10	71
Impact	Public presentations	10	19
Impact	Seminars and workshops	6	8

V. DISCUSSION AND CONCLUSIONS

The figures introduced in the section IV illustrate the success so far that the Live-In Lab has encountered both in industrial applications and in the research community. All but one target KPIs – research, finance and impact - have been reached.

Three key value propositions can be identified as basis of the success of the LIL: i) the intrinsic value of the building testbeds and the data generated, ii) the established competence and expertise, which facilitates the production of innovative ideas, and iii) a protected environment, that lowers the competitive barriers, thus promoting the knowledge transfer.

A protected environment, a niche, acts as a proxy both for industrial organization and for research groups to find relevant partners to share and discuss problems; this informal community building has in several cases led to successful project consortia. A prerequisite for this is the mutual trust that an independent organization like the Live-In Lab promotes. This facilitates an initial demonstration of project concepts that are often too innovative for market uptake, but that can provide strong arguments for rapid upscaling once the initial demonstration has proven successful.

In terms of organization development, the Live-In Lab has been initiated on the informal collaboration among several interested and motivated researchers from a variety of research communities, coordinated by the platform promoters. Such an informal setup is lean in terms of organizational burden and requires a limited budget, but it relies on motivated people and an effective leadership. This setup can be decisive in the initial phase of the platform but it requires a more stable and institutionalized organization when the necessary critical mass (financial resources, testbeds) is reached, and to ensure that the platform runs with continuity between initiators and followers, with proper procedures and documentations to operate the structures and to transfer the developed knowledge.

The competitive environment where the Live-In Lab grew has been alleviated by a unique set of factors: the societal interest for the topic and positive reception for technology, the financial support by Einar Mattsson-Group, the availability of research and development funding, a focus of industrial contribution (time/funding etc.) as enabler for further funding and a widespread culture of research in companies. Some factors are country-specific for Sweden, Stockholm in particular, and should not be underestimated for a successful replicability of the concept; however, a combination of different supporting factors are likely to result in a different but equally successful business model.

The experimental setup is by its nature complex. The complexity resides in the organization; different platform stakeholders are in charge of managing parts of the technical tasks. As such, the successful development of technical tasks requires effective communication among the constellation of technical groups, competent and dedicated people and the definition of clear tasks and responsibilities. This is sometimes challenging as research projects are often non-standard and ad-hoc solutions are needed, putting extra demand on project managers that require specific competences. However, the KTH Live-In Lab has chosen a way that is intended to help organizing people and tasks, without interfering with individuals' different preferences and theoretical frameworks, so that in all projects, so far, the specific goals have been met.

The experience so far has shown that the Live-In Lab approach is sustainable from a technical, organizational and financial point of view. The overall idea and most of the theoretical framework and structures are believed to be replicable without having to investigate contextual preconditions. However, some contextual factors such as funding possibilities, project management and research culture, industry-academia collaboration, among others, are believed to be crucial factors to investigate to develop national structures for Living Labs.

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