Sustainability in the built environment using embedded technology

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Innovation of sustainable products and solutions in the built environment using embedded technology in Constructions, is from various earlier investigations shown to increase the value both by reducing emissions of green-house gasses from buildings and by optimising the comfort of living condition for the end-user. Based on a project on User-driven Innovation and Embedded Technology in Construction, this paper presents different potential products and solutions for sustainability. This covers a variety of areas such as recycling, energy efficiency, as well as a new concept of sustainable products designated Open Built Source products (OBS), by applying two principle: compatibility and reuse of building products with embedded technology. The project is carried out by DI and SBi and involves 30 firms namely building materials manufacturers and IT developer companies. The methods used in the User-driven Innovation will be presented, with focus on user engagement, interest and acceptance of the ideas arising from the process. This will be exemplified by a developed pilot project involving embedded technology in a building material. Sustainability is categorised in the three dimensions environmental, social and economic sustainability. In this paper a fourth sustainability field will be introduced; The adoption of sustainability. User adoption of sustainable solution is not only achieved by developing the solutions, the user also needs to adopt the solution, before it may be implemented in practise. Several barriers need to be taken into consideration, such as usability, functionality and value for the user, technology fear, cultural and social backgrounds, when developing sustainable solutions. The paper presents a new approach in dealing with User-driven innovation as a mean for developing sustainable solutions. The methodology will be analysed, exemplified by innovated products and show how sustainable solutions may be implemented much more efficiently, by applying this new approach.

KEYWORDS: Userdriven innovation, embedded technology, sustainability, energy efficiency, recycling.

INTRODUCTION

Sustainable developments are often achieved through technological discoveries, but they need to be able to be carried out as business in a value creating way at the same time to be a commercial success. The main focus in this paper is to show how firms may use collaborative innovation methods and user-driven innovation in the early-stage of innovation to realize high-technology sustainable products with a high degree of user adoption. The technical angles may be many, but in this paper technology advances of embedded technologies in building materials, developed in the project 'User-driven Innovation and Embedded Technology in Construction' (BIIB) ¹, will be used as example. The main barrier is the

¹ The project, Brugerdreven Innovation og Indlejret Teknologi i Byggeriet, BIIB, is carried out by the Confederation of Danish Industry, Building Materials and IT, 28 firms from the organisation and the Danish Building Research Institute. The project is financed by support from Governmental funds on User-Driven Innovation.
adoption of the end-users, hence, if end-users do not accept developments, they will not be realized.

In the endeavour to create sustainable solutions taking into account i.a. the barrier presented by adoption, the project 'User-driven Innovation and Embedded Technology in Construction' was established, which involved firms manufacturing building materials and IT developer companies. The main purpose was to bring the developers from the companies together with the end-users and lead-users, and to create an innovation climate, which would generate realizable sustainable solutions by using collaborative innovation and taking into account the drivers and barriers of the users. The project was divided into four segments. In each segment the focus was on different users in the built environment, i.e. segment one deals with building process, segment two with facility management, both in regard to continuous operation and maintenance, the third and fourth segments focused on the user of the finished house, i.e. end-user, in rental and private residences respectively.

This paper presents a new approach combining collaborative innovation with user-driven innovation, analysed from the point of adoption of the end-user. As a basis, the approach will be developed using principles from recognised methods of technology acceptance e.g. the TRA (Theory of Reasoned Action) and TAM (Technology Acceptance Model) models, keeping the focus on the effect of the interaction between the users and developers in the development of sustainable solution.

Sustainable solutions are characterised by being either environmentally, economically or socially improving solutions. In the process of innovating sustainable solutions, there are several barriers to be taken into account, if the solutions are to meet the users’ needs, be accepted and realized. Examples are privacy and lack of experience of the new technology. Therefore it is important to create the right surroundings for creating the collaborative innovation climate for the users, which will give the realizable solutions. For this purpose a theoretical approach to deal with these items will first be presented in the paper, followed by presentation of the methods used. Next some examples of sustainable solutions developed in this project will be presented and discussed in the context of the new approach.

It will be shown that given the right condition and surroundings, and with the rightly chosen users, collaborative innovation combined with user-driven innovation is a useful approach for developing sustainable solutions.

THEORETICAL APPROACH

Apart from classical innovation such as innovation driven by entrepreneurship or innovation driven by strategic technological innovation, the innovation process may exclusively focus on the customers need or more precisely on what the costumer might need without yet knowing it. This type of innovation is called user-driven innovation. One might say that user-driven innovation is as old as the market economy itself. This is true since companies generally focus on the customer. However, this is merely a normal routine rather than involving the user directly in the innovation process. The expression 'user-driven innovation' was originally introduced by von Hippel (Hippel, 1986) from MIT. He also defined the lead-users as those whose present strong needs will become general in a marketplace months or years in the future. Identifying the lead-users is important, for understanding the end-user’s adoption of new products. In the effort to innovate new sustainable solutions, user-driven innovation may be useful, also being aware of the importance of identifying the relevant users.
Sustainable Solutions with Embedded Technology

Sustainable developments are the future innovation fundament for maintaining economic growth in the world, without compromising the environment or our life quality. There are three main dimensions in sustainable developments. The first dimension is to control the environmental challenges as a consequence of the increasing amount of chemicals, materials/substances and waste, which will affect our health, environment and nature. The second one is to optimise economic benefits for example by controlling the use of the limited energy resources, which will at the same time diminish the discharge of CO2 concentration. And finally the third dimension is to maintain or improve our living standard both socially, but also our degree of comfort and life quality. The three dimensions are normally referred to as the environmental, the economic and the social dimensions.

The solution is to develop technical solutions, which improve at least one of the three dimensions compared with existing solutions, without compromising the other dimensions e.g. achieving environmental benefits without reducing economic or social standard. Since buildings is the centre of many human activities, i.e. working, educating, sleeping etc. it is a relevant area to look at, when innovating new solutions. Embedded technology is a technology, that embeds various sorts of technology from sensors to more advanced information technology into building materials. For example a sensor, that can measure moisture content. The sensor is built into a gypsum board. The sensor register moisture data and the data may be collected through a connected data logger to a computer. When the moisture content reaches a certain critical value, the computer may be used as a pre-warning before severe damage may occur in the building construction, and from that point save the building owner the unreasonably high costs of repair. Instead the building owner is able to stop the development of damage in due time. More advanced IT technology like RFID (Radio Frequency Identification chip) is a wireless identification system, which consist of RFID-tags with unique identification numbers, which may be built into a building material. Using RFID-reader the product can be identified and from a database like for example integrated in a BIM model (Building Information Model) information can be obtained about the production date and place, information about replacing or repairing the building material, logistic management and much more. Also supplementary information technology devices may be used like a PDA (Personal Digital Assistant) both for scanning and operation.

To achieve adoption of the advanced technological solutions, it is rewarding to take into consideration the barriers of the end user in the early-stage innovation.

Adoption of Sustainable Solutions

Adoption of new technology developments depends on various factors. Personal factors e.g. social background, willingness to use, privacy and level of technology fear. Further it depends on technology characteristics such as relative advantage, meaning the extent to which the solution offers improvements over existing solutions, compatibility, meaning its consistency with social practices and norms among its users, complexity, meaning its ease of using or ease of learning to use. More detailed reading is given in (Dillon, 2001). In this Paper we will assume that the most important personal factors when dealing with high sustainable advanced technology solutions are:

- Cultural and social background
- Privacy
- Technology fear
and the corresponding most influencing technical characteristics are:

- Relative advantage
- Compatibility

 Compatibility means that the solutions are consistent with social practice and norms among the users. These factors have been considered in the project when using user-driven innovation with the end-users, with the aim to develop the most likely solutions to be realized.

**Technology Acceptance Model**

In the field of information technology the widely used and proven Technology Acceptance Model (TAM) was developed by Fred Davis (Davis, 1989). The model is an extension of the Theory of Reasoned Action TRA, (Ajzen, 1980), mainly replacing several attitude measures such as consumer attitude or consumer behaviour like e.g. when privacy issues may limit the users acceptance of new technology. Two technology acceptance measures are perceived ease of use and perceived usefulness, where ‘ease of use’ is defined as the degree to which the user believes that the new development may be used effortlessly and ‘usefulness’ defined by the user believing there is an advantage or benefit when using the new development. Several methods have been developed on the basis of TAM. Venkatesh et al. gives an overview of various models of technology acceptance models and compares the models by means of a unified model entitled ‘The Unified Theory of Acceptance and Use of Technology’ (UTAUT), see (Venkatesh et al., 2003).

It has not been the main intention to adopt the technological acceptance models directly in this project since these models are normally used in measuring the acceptance parameters, where users are exposed to ready-made solutions. Nevertheless it has been the aim to increase the likelihood of reaching realizable solutions by taking these parameters into consideration in the early-stage innovation, i.e. we assume that we will achieve an even higher degree of success, when combining the basic principles of user-driven innovation with the parameters influencing the technological acceptance models.

We therefore assumed that adoption of sustainable solutions was highly dependent on the level of user acceptance from the perspective of a user-driven innovation, i.e. keeping the users aware of barriers and usefulness from their own point of view, when developing the ideas for solutions. It was expected that increasing adoption would achieve the highest rate of realizable solutions, i.e. if they the user barriers are small and the user had a high level of perceived usefulness at the same time in the early-stage innovation, we would expect to achieve high realizable solutions, as illustrated in figure 1.
Figur 1. Principle of user driven innovation model for the new approach.

TAM defines behavioural intention as a measure of the strength of one’s intention to perform a specific behaviour, i.e. it may indicate willingness to use a new solution. In early-stage innovation this is assumed to be approximately correspondent to the user awareness of his own barriers on the possible solution. Perceived usefulness is in the context of user driven innovation considered as the users own perception of the value if the solution, e.g. increased relative advantage.

An open solution is defined as a solution that is not obvious to continue developing. However since the barriers are small, it should be kept open as a possible solution for further investigation, i.e. involving user-driven innovation in later stages like further marked investigation or even pilot testing. Expensive solutions may similarly be kept open, but need more investigation of the necessary investments since the marked may be limited due to the amount of barriers.

The complete approach to developing sustainable advanced technology solutions involves focus on the adoption parameters presented above, controlled through well prepared facilitation, including the user-driven innovation methods, see next section. The intention to use this approach is to enhance the guarantee of success, before the solution is accomplished and it is finally implemented in the market. This new approach illustrated in Figure 1 developed in this project is named the ‘Technical Adoption with User-driven Innovation Model’, abbreviated the TAU-model.

METHODS USED FOR USER DRIVEN INNOVATION

User-driven innovation is increasingly used in research and development. The main idea is to differ from traditional linear innovation starting at the manufacturer and ending at the end-user, by shifting the focus directly to the end-user and thereby get improved innovation. In Denmark two programmes for user-driven innovation were recently established. A research programme for Strategic Research (Forsknings- og Innovationsstyrelsen, 2006) and an Innovation Programme for User-driven innovation (EBST, 2011), the latter being the one in which this project was established.
The project was divided into four segments, see Table 1. In each segment two main meetings were held with the relevant users. Firstly a **Focus Meeting (FM)**, with the main purpose of identifying possible needs for the end-user, which it might be possible to satisfy by innovating new solutions using embedded technology. The FM was followed up by a **Dialogue Meeting (DM)** with the main purpose of making collaborative innovation, with the developers, end-users and advanced-users - including lead-users. At the FM it was also important to identify the main barriers for using potential solutions, mainly with regard to the end-user. Several methods for achieving these goals were used, e.g. interviews, assigning the user with predefined assignments like taking photos of relevant items that might be improved, and thus establish a picture of relevant needs or problems and barriers. The methods used are described in detail in (Storgaard et al, 2011).

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<tr>
<th>Project meetings</th>
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<td>Segments</td>
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The first FM was established at a building site. Various stakeholders from contracting businesses represented the end-user. Subjects like logistics, assembling methods and many more were considered. Similarly the second FM concerning facility management of housing, i.e. continuous operation and maintenance, was held at a large apartment building. Stakeholders from the housing administration, the caretaker and operating and maintaining firms represented the end-users. The third FM was held inside the apartments of the end-user. Similar the fourth focus meeting was carried through at the residence of the end-user, i.e. town house, villa or summer house.

At the third and fourth FM typically four to five end-users were chosen. To get some variation of the needs and barriers, the end-users were chosen based on different criteria, e.g. age, social background, occupation etc. At the first and second focus meetings the variation of end-user was characterised by their role in the building phase examined, e.g. carpenter and building owner respectively in the facility-management phase.

The resulting scenarios from the FM were used to establish the surroundings at the second meeting – the **Dialogue Meeting**. At the DM all the users, technological experts and developers from the firms and an extended group of stakeholders, were brought together and involved in different settings, with the main purpose of brainstorming and creating ideas i.e. early-stage innovation. Two main methods were used: ‘Scenarios’ and ‘Design Games’, see (Brandt, 2004).

A scenario is a story describing a future scene introducing a social context, needs and introducing solutions were embedded technologies are implemented in building materials. The scenarios were developed on the basis of the input from the FM.

In each segment several scenarios were developed. The participants at the DM were divided into groups across the type of participants, each with the objectives to validate one scenario,
with special focus on whether the solutions presented were realistic both from an economic and a technical angle. All the scenarios will be published in (Nielsen, 2011).

The Design Games were designed for the main purpose to facilitate a collaborative brainstorming over new ideas for solutions with embedded technology. A game board was prepared for each DM. Again participants were divided into new groups and brought into a context controlled both by the facilitators and the game board with complementing game cards with questions or other types of challenges that escalated the brainstorm process.

In the Design Game, several stage gates are passed in order to access the relevant information in the brainstorming process e.g. firstly a building material is chosen, then possible future functions and/or properties for the actual building material are proposed, and then relevant embedded technology is decided and so on. Typically the upcoming ideas in the process were written down on post it's, and placed on the game board, to make the process flow, not interrupted by time consuming writing manoeuvres, and making the ideas common knowledge both in the group – and later – between all participants. The game board is then designed from the information generated. Both in the Scenarios and in the Design Games it was influential for the social and collaborative processes, that the processes were thoroughly facilitated and that the facilitation was well prepared.

RESULTS

In this section three developed sustainable solutions in the BIIB project will be presented, as examples. Each of them covers the three dimensions of sustainability in the built environment. Actually it might be more correct to denote the solutions: Concepts. This is because, the solutions involve embedded technologies and building materials and in some cases information technology as a whole concept.

The first solution to be presented was developed in DMII, i.e. facility management. The users were grouped around a table with a game board. The users were led through a process, and confronted with a series of questions to be decided on in the group. Firstly they should consider which building materials could be used for embedded technology in general. Secondly they should consider what type of user and needs/problems could be relevant to find solutions for. And then to bring through a solution, describe it and test it against the users need, acceptance, usability, through the developers and the technological experts assessment of how to produce the technical solution, and through the extended stakeholders assessment of functional value. This process continued until a solution was proposed including considerations of how the solution would be realized. Costs of maintenance and operations of a building had a very high focus, seen in relation to the total lifetime of building. Sustainable solution are therefore of importance when considering the energy efficiency of the building. Several solutions were developed in this area. As an example it was proposed to make windows with transparent glass, denoted the intelligent window, which could vary the amount of incoming solar radiation. When the building is overheated the glass can diminish the income of sun light, instead of installing cooling systems, and conversely solar heat can be used to warm up the residence, when beneficial. Furthermore a lot of research in this area also considers saving energy in the developments of Smart Windows, which use electrochromic devices, suspended particle devices, micro-blinds or liquid crystal devices built into the window glazing, See also (Grandqvist, 2008). It is well known that solution that exploits the sun are very cost beneficial, especially in regard to the passive-house building design.
The second solution comprises two closely related solutions developed in DMVI, i.e. the private residence. The starting point in the Design Game was to guide the users to define a combination of embedded technology and building materials. One of the three dimensions in sustainability is the social dimension. A sustainable solution was developed, focusing on health in the effort of achieving higher living standard in general. One of the solutions was to embed sensors measuring the moisture content and temperature to evaluate the Relative Humidity (RF) i.e. the climate in the rooms in the house. The benefits of the idea were to ensure healthy climate in the rooms, and prevent eventual growth of mould fungus and similar problems. The embedded technology was implemented by creating intelligent doors controlled by a Building Information Model (BIM-model\(^2\)). The concept was named ‘The sensor door’.

In regards to sustainable solutions the third solution to be presented covered basically all three sustainable dimensions. The solution was named Open Building Source (OBS) by the users. The idea behind the solution was to create a standard with harmonised requirements covering the interfaces in the built environment, e.g. the connections between different building materials. The standard should make sure that developments of different building materials were always standardised, in regard to how they would be connected with each other on site, independently of what company or institution developed the solution. This could lead to a standard which could provide the space for independent developments, from which the definition ‘Open Building Source’ followed. The standard should cover both requirements for technical connections e.g. reinforced shear connections in concrete structures, bolted steel connection etc. But also electrical and plumbing connections i.e. cables, wires, pipes etc. must be covered. Complications often arise in the interfaces, when connecting different building materials. Having the standard defining a common base would ensure compatibility with other building materials as they are developed. Furthermore such a standard would encourage the use of sustainable solutions, if it considers connections which may be easy to dismantle and reinstall. In other words it may be a basis for reusing and recycling building materials in general.

A solution was proposed that uses embedded technology by incorporating a sensor in the product which register the life history of the product, e.g. condition, temperature and moisture influence etc. The information may be useful when following the product from cradle to grave – or even be used to recreate part of the product if necessary. Additionally the product may be connected to a BIM model, so that it would be easy to obtain the necessary data when the product need to be demolished and reused in some other form, and in this sense the product may even be followed from cradle to cradle.

**ANALYSIS OF APPROACH AND DISCUSSION**

During the process of developing the solutions several phases were undertaken with the users, both end-users and users from the industry, e.g. brainstorming sessions where the user

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\(^2\) Building Information Modelling (BIM) is the process of generating and managing building data during its life cycle (Lee et al, 2006). Typically it uses three-dimensional, real-time, dynamic building modelling software to increase productivity in building design and construction. The process produces the Building Information Model (also abbreviated BIM), which encompasses building geometry, spatial relationships, geographic information, and quantities and properties of building components.
intuitively came up with needs and solutions involving building materials and embedded technology. In some phases the focus was put on barriers and the usefulness of the solutions by the facilitators, with the main purpose to validate the proposed solutions. The users were indirectly forced to select the best solution, facilitated for instance by using surroundings involving competition. On the contrary this led to several other solutions being given a lower priority. As an example it was proposed to embed sensors to measure the *history* of the climate, i.e. moisture etc., in the apartments. The users preferred privacy in their whereabouts, and preferred sensors to discover only just in time damage, not to reveal their daily routines. In contrast to the privacy issue, it was proposed to install cameras to increase security, and surprisingly enough this solution was not rejected for reasons of privacy, but purely from the lack of *relative advantage*, since the users felt it would have the exact opposite effect, i.e. lots of cameras leave residences with a ‘fake’ feeling of in-security.

From these examples, it was clear that it was important to identify barriers as well as the solutions at the early-stage innovation, since it will determine the adoption level of the solution, see Figure 2.

Figur 2. Early stage developed solution introduced in the TAU-model.

Together with several solutions it was proposed to install info-screens for various purposes locally in the apartments, e.g. for reporting activities of common interest, for showing any monitoring of the apartment, news about residence regulative etc. In regard to some of the solutions, the users were very keen on making the system easy to use. In some cases this was clearly technology fear, but in some cases it was more ambiguous. In other cases it was a lack of relative advantage, which ruled out the proposals. In the first case the solution would be rejected with regard to the approach shown in figure 1, due to barriers and lack of relative advantage. While in the other case the solution should be classified as an *open solution*, to be more thoroughly studied. This could for example be implemented by using user-driven innovation in a future pilot test. Several models were discussed, among others, an idea of slowly introducing the info screen with ease of use solutions, and test other solutions one by one. Agreement was achieved on that the economic benefits to use such a procedure was obvious.

Some other ideas involved highly advanced technological solutions, i.e. partly manually controlled heating systems in the house. The social background played a significant role in these types of solutions, mainly due to technology fear. In DM VI, this was not an issue. On the contrary, to some degree, the more complicated technological advanced the solutions were even more interesting for the users. This may nevertheless in some cases not relate
solely to social background, since many of the users involved in this last DM were classified as lead-users. It was generally confirmed in the project that barriers influenced the decision process on the chosen solutions.

After each DM an evaluation was carried through, i.a. the facilitation level was evaluated on the various methods used. One common picture was observed, that when facilitation was well prepared and the process thoroughly controlled by prescheduled plans, the most stringent solutions were obtained. As an example the motivation among the participants was clearly increased with a high level of facilitation and consequently more and better ideas arose. Therefore the facilitation procedures were improved through the DM during the project, by means of preparation and thoroughness at the meetings.

At the end of the DM IV the developers from the industry were put together in a match making process, where the selected solutions, i.e. the solutions presented in the section: ‘Results’, were evaluated discussed and action for the next step was considered. The first solution: ‘the intelligent window’, led to intense discussion of costs compared with the market possibilities. The solution was classified as expensive solution and the stakeholders decided to continue with collaborative investigations, with some reservations of the possibility of continuing the development to final implementation. It may be argued whether a solution, which may have high socio-economic value can be realizable if individual developers solely are to implement the innovation process. The intelligent window is a good example of such a solution, which may fail to be realized, even though it is highly valued. It is not possible to generalise, but it could be argued that expensive solutions in some cases need to be innovated through PPI models\[3\] or other type of corporate innovation systems.

When developing sustainable solutions the relative advantage may not be directly clear in all solutions. On the one hand we may have solutions that are profitable from a socio-economical point of view, but will not be realized due to the lack of adoption by the end-user. Surprisingly it was observed in the project that the phenomenon of talking about sustainable solution in itself added some value for the end-user, i.e. if the adoption is focus of the developments also this effect is positively included in the early-stage innovation process. The second solution with the social dimension was a good example of this phenomenon, since lots of users we not pre aware of the social dimension in sustainability, which intrigued them to rate the experience solutions, e.g. ‘the sensor door’, on relatively higher ranking, when discovering this third dimension, social sustainability. The solution was classified as realizable solution in the context of the new approach.

The third solution focused on the compatibility of standardised solutions. So they can be built in or replaced with no further considerations, i.e. the principle of plug and play in the built environment, see (Marechal:2010). Furthermore the success of this solution is highly dependant on the compatibility, meaning its consistency with social practice and norms among the users, since the adoption by the users of the system is evident, i.e. are the users willingness sufficient to support the investments for the developments of the system. Therefore the OBS idea also should be classified as an expensive solution. This solution is highly dependent on the behavioral intention of the end-user and could be interesting to investigate in the near future with a technology acceptance model like UTAUT: ‘The Unified Theory of Acceptance and Use of Technology’, see (Venkatesh et al., 2003).

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CONCLUSIONS

It was shown that given the right condition and surroundings, and with the rightly chosen users, collaborative innovation with a strong focus on the adoption combined with user-driven innovation is a useful approach for developing sustainable solutions.

It was shown that an even higher degree of success could be achieved, when combining the basic principles of user-driven innovation with the parameters influencing the Technological Acceptance Models.

And finally it may be concluded that the most influencing parameter of the success level of the new approach is the level of facilitation, both in regarding preparation and thoroughly facilitating each of the processes of user-driven innovation.

The complete approach presented: ‘the TAU – model’, for developing sustainable advanced technology solutions involves focus on the adoption parameters presented in the model, controlled through well prepared facilitation, including the user-driven innovation methods applied. The approach is not solely limited to sustainable solutions, but can also be employed on other advanced technology developments in general.

Furthermore several early-stage innovated sustainable advanced technology solutions have been the outcome of this project. Whether these solutions may be realized throughout the innovation process is far too early to estimate. It would therefore be of interest to follow these ideas in the near future. It is further recommendable to carry out regular tests with Technology Acceptance Models, e.g. UTAUT, on ready-made solutions, and reflect back to the experiences from this project, to draw more precise conclusions and further validate the early-stage innovation approach used in this project.

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