DESIGN AND EVALUATION OF A "SMART INDIVIDUAL-ROOM HEATING IS" TO IMPROVE COMFORT AND SAVE ENERGY IN RESIDENTIAL BUILDINGS

Prototype

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Abstract

Large amounts of energy are wasted due to unnecessary space heating in residential buildings, i.e. by heating rooms (or whole dwellings) even though residents do not occupy them. Several studies have shown that the major reason for this behaviour is the poor usability and understanding of current heating controls. For that reason, most people also prefer to adapt their thermal comfort by changing clothes or opening windows as their principal action, instead of adjusting the heating. Following the recent development of "smart" thermostats, we address the aforementioned challenges by developing an heating IS with better controls and comprehensive heating feedback to empower residents to adapt heating radiators in their rooms to their needs. In this work, we present the requirement analysis, implementation and field test evaluation of a novel smart individual room heating prototype. The system combines an intuitive user interface, supporting feedback and automation capabilities. We demonstrate that such a new generation of heating controls indeed improves usability and understanding and thereby leads to lower setpoints by 2-3° Celsius on average, which could enable significant energy savings.

Keywords: design science, energy informatics, smart heating

Problem Description

In Germany, space heating is responsible for 73% of the energy consumed by private households (BDEW 2010), which accounts for 19.4 % of the total primary energy consumption (BMWI 2014). The German government aims to reduce this total primary energy consumption by 80% in 2050 (compared to 2008) by using renewable energy resources and energy efficiency measures (BMWI 2015). Besides technical improvements, user behaviour has a substantial impact on residential energy demand for space heating (Haas et al. 1998). In recent years, several IS-based behavioural interventions were developed and evaluated to motivate users to save energy (Allcott & Rogers 2012; Baca-Motes et al. 2012). However, in the case of heating, studies identified the poor usability of typical heating controls as the main obstacle for saving energy (Meier et al. 2012; Peffer et al. 2011; Karjalainen 2009). Therefore, we aim to addresses this problem by an IS with better controls and comprehensible heating information instead of behavioural interventions. Following the IS stream of Energy Informatics (Watson et al. 2010), we applied information systems thinking and skills to design, implement and evaluate a prototype that helps users to save energy and improve comfort.

In Europe, the most prevailing heating controls in residential buildings are central thermostats that directly control the heating and thermostatic radiator valves (TRV) which control the radiators in each room. In principle, the heating controls allow residents to save energy by turning down the heating for a room or even for the entire home when it is not occupied. However, this means that users have to remember to lower setpoints when leaving, and they have to tolerate unpleasant temperatures when coming back home. Moreover, they do not receive any direct feedback about possible savings. In the 70s and 80s, programmable central thermostats were developed to solve some of the aforementioned issues by a configurable schedule. However, several studies showed that users struggle to program the schedule correctly due to the bad usability (Meier et al. 2012; Peffer et al. 2011; Combe et al. 2012). As a consequence, users did not adapt the schedule to their changing daily routines. In the 90s programmable TRVs were developed but they were conceptually similar and lead to the same usability issues. A recent study has also shown that most people actually rarely use the heating controls to improve their comfort (Karjalainen 2009). People preferred to cope with uncomfortable room temperatures by simply changing or opening doors and windows. In a survey with 3096 participants in Finland Karjalainen (2009) found that 60 % of households do not adjust thermostats at all or less than once per month. Moreover, when feeling cold, 52% of the people put on more clothes as their principal action, only 22% adjust the heating. When feeling hot, about 45% of the people claimed to open open a window, 10% to take a walk, 10% to adjust the heating, and 8% to take off some clothes. Thus, people seemingly prefer to adapt to the environment instead of regulating the cause of their thermal discomfort. Karjalainen (2009) conclude that this could be improved by a greater usability of thermostats. Another reason for the poor use of thermostats and TRVs are the general misconceptions about them. The studies by Vastamäki et al. (2005) and Meier et al. (2012) show that many users think of thermostats as an On–Off switch or they assume that it works like a valve. Accordingly, users misleadingly think that they can accelerate heating, by turning it up or even to the maximum. This often leads to overheating of rooms at some point in time, e.g. in case of a TRV the maximum is level "5" which actually heats up the room until a setpoint of 24° - 28° Celsius is reached. Summing up, the poor usability of thermostats and TRVs is a major problem, which leads to comfort issues and a waste of energy.

In recent years, a new generation of "connected" thermostats emerged that provide a much better usability, e.g. by having intuitive user interactions via smartphone, providing more feedback information about the thermostats and remote control from everywhere. In some cases, they are also called "smart" thermostats because they are able to adapt automatically the heating to the occupancy of the home. The most prominent solution on the market is the NEST Thermostat by Nest Labs. It is claimed to have a great user experience and it is able to "learn" automatically the heating schedule based on the user's interactions with the device. The studies by Yang & Newman (2013) and Yang et al. (2014) investigated how users interact with a NEST compared to conventional thermostats. They reported that the usability of the NEST has a positive impact so that it is more engaging to save energy Also, the schedule control is said to be much more fluid and adaptive. However, they also stated that users struggle to understand and control the automatic features like the "learning schedule". Moreover, the interest and engagement of the users decreased over time. As a consequence, the resulting heating control patterns of the NEST were not as efficient as they could be. There are similar "smart" thermostat solutions available on the market, Tado from Germany and Hive/BritishGas from the UK, or Lyric/Honeywell from the US. Examples can also be seen in academia, for example Lu et al. (2010), Gupta et al. (2009), Gao & Whitehouse (2009). All of them replace the central thermostat which controls the heating based on the measured temperature of one room in the building, usually the living room. However, in European homes, replacing the central thermostat by a "smart" thermostat would not solve the usability issues of heating, since the heat emission in each room is still controlled by TRVs with poor usability. Thus, users would still use the TRVs incorrectly or not at all, which results in the already mentioned issues.

Therefore, we decided to close that gap by designing, implementing and evaluating a smart individual room heating prototype following the design science paradigm (Hevner et al. 2004; Gregor & Hevner 2013; Peffers et al. 2007). This work is based on an early prototype (blinded for review) and presents a refinement of the design objectives, a full IS implementation and a field test evaluation.

1 Conceptual Approach and Design Objectives

We intend to develop a smart individual room heating IS that empowers residents to save energy and improve comfort by providing better controls and information to adapt room temperatures. Thus, instead of replacing the central thermostat, the TRVs in each room are replaced with connected TRVs for remote access and control. The user is then equipped with a smartphone app that we designed to overcome the mentioned misconceptions and usability issues of current heating controls.

Solutions of connected TRVs with smartphone- and web-based interfaces are already available. And even though they allow remote control and setting up a schedule, they are rather complex since most of them were designed to control a full smart home even beyond heating. Furthermore, they are not able to automatically adapt the heating to the occupancy of the residents.

Based on the studies of the usage of current heating controls, we developed several design objectives for our solution:

- Simple user interface for individual room heating control: To overcome current usability issues and poor usage of TRVs, we aimed for a simple, appealing, and fun-to-use smartphone user interface. We developed and tested it with five test households in several iterations (blinded for review).
- Feedback about the heating: As already explained, most users think of a TRV as a valve or On-Off switch which leads to improper use of the controls. A major reason for this behaviour could be the poor labelling of TRVs with meaningless levels from 1 to 5 and the lack of any feedback information about how much the room will heat up or cool down. This is particularly problematic in the case of heating, since changes of the room temperature due to a new setpoint are delayed by hours. We think that this can be improved by providing the users a more intuitive control via temperatures and more feedback about current room temperatures and current heating supply, i.e valve opening. To have more insights about the heating behaviour, this information should be also available in retro perspective.
- Easy-to-use manual scheduling: As described, programmable TRVs failed because it was too much effort to program the schedule. This can be solved by an easy-to-use schedule design on the smartphone. Since the NEST schedule design was well received, we implemented it similarly but adapted it for individual room heating.
- Occupancy-based heating capabilities: Users struggled to understand how the auto-schedule by NEST actually works. We believe approaches that use the phone's location to adapt the heating, are easier to understand, since the general concept is already familiar by other applications (apps). Thus, we developed an occupancy-based heating concept based on the work of Gupta et al. (2009), i.e. the room temperature is decreased and increased depending on the resident's distance to their homes. It can be activated for each room and for each resident individually.
- Room climate information: Besides an optimal room temperature, good/bad air quality and humidity can also have an impact on the residents thermal comfort, as reported by the study of Frontczak et al. (2012). Thus, the system should also provide feedback on the current room climate.

2 Description of the Prototype

Based on our conceptual approach, we developed a prototype for the most prevalent individual room heating infrastructures in European homes. The prototype consists of a smartphone app, a backend server and the following devices, which are installed in the dwelling:

- A home controller which is a Raspberry Pi computer with internet access and a 868MHz radio communication to the connected TRVs. It relays the data and control signals between the connected TRVs and the backend server.

- Connected TRVs which replace the traditional TRVs at each radiator. They are commercially available by eQ-3 Homematic (2016).
- Connected room climate sensors by Netatmo (2016) that provide temperature, humidity and air quality (CO_2 concentration) measurement data in 5min resolution via a cloud-based API.

The smartphone user interface is illustrated in Figure 1. The overview screen shows the room information where the user can easily check the status of each room. Moreover, the residents and their state of presence are shown either inside ("at home") or outside ("away") of the indicated circle. The room screen currently shows that in the room labelled "Badezimmer", the room temperature is 21.4°, the setpoint is 18.0°, the schedule mode is active and there is currently no heating supply, which is indicated by the grey flame. This basic information should make it more transparent how the room is and will be heated up or down, respectively. The current comfort setpoint can be changed by moving the heart icon along the circle.

Each room can be either run in "manual" mode, e.g. it just keeps the chosen setpoint, or in "schedule" mode, which controls the heating according to the chosen schedule. Modes can be switched easily by sliding in the center. In addition to that, the automatic occupancy-based heating feature, which we call AutoAway, can be activated for the room and resident. If active, it will overrule the current chosen setpoint by a lower setpoint if the resident's distance to home increases and it will be raised if the resident comes closer to her home again. On the app, this will be indicated by showing "AWAY" instead of the setpoint for the room. Moreover, to help the users to comprehend what the AutoAway is doing in the backround, every decision by the system is shown in the activity screen, e.g. "Thomas has left the home, AutoAway decreases the temperature to 19°". Moreover, the current air quality (450ppm) and humidity (54%) are displayed. The colour indicates whether the current room climate is optimal (green), could be better (yellow) or is critical (red). By clicking the buttons, the users get advice for improving room climate, e.g. to open the window for 15 minutes.

On the schedule overview, all setpoints of a day can be copied or edited. On an additional screen, each setpoint can be shifted vertically for temperature changes and horizontally for time changes. Setpoints can also be deleted or added. This design should allow users to program any kind of schedule without much effort. The history screen shows the changes over time for the room temperature, setpoints, air quality and humidity. For hands-on experience, the reader may download the app (blinded for review) from the iPhone/Android App Store.

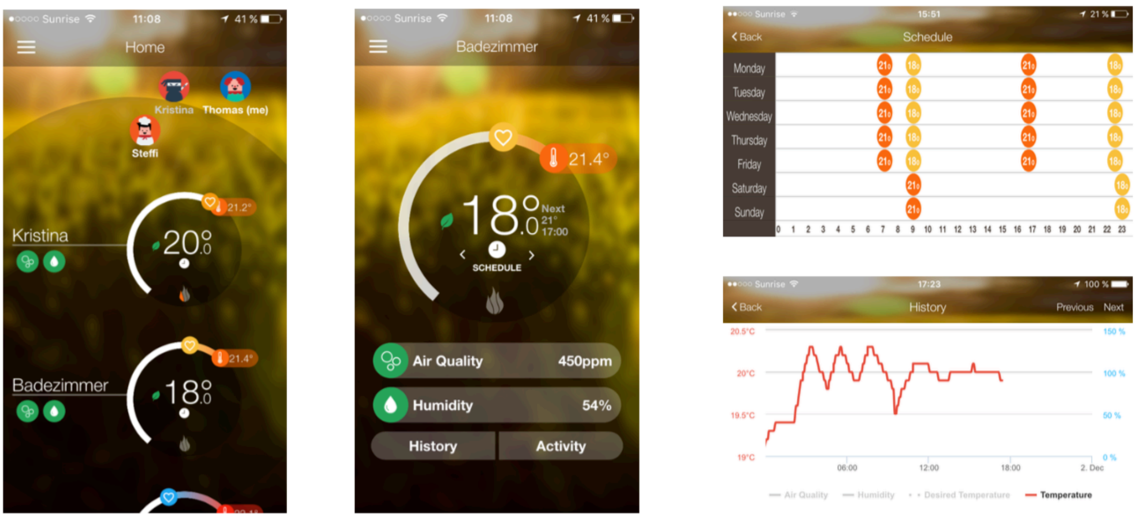

Figure 1. Smartphone App User Interface: Overview Screen, Room Screen, Schedule Overview Screen, History Screen

3 Evaluation

To evaluate the prototype, we conducted a field study with 15 households over 8 weeks in Switzerland. In the following we briefly describe the methodology and present results.

3.1 Field Test Methodology

In order to recruit participants in a confined region around Zurich, we collaborated with a large property management company and advertised our project in an online city portal. Overall, we received about 60 signups. We filtered out 15 suitable participants by checking properties like heating type, building isolation quality, radiator type, smartphone type etc. The selected group of participants contained seven households with a female person as the main user of the application. This is not common for smart home studies (e.g. compare Yang & Newman 2013). About half (n=8) of the households are families with children, 3 couples without children, 2 singles, and 2 are student flat-shares. The majority of residents are between 30 and 40 years old. Most of the flats have 3-4 or 4-5 rooms and are part of a multiple dwelling building. Although the 15 participants are diverse, it is a convenience sample and not representative.

The study can be divided into two phases: pre-use stage and in-use phase. We initially installed connected TRVs, room climate sensors and a home controller in each household, but we did not provide the users with the app since we wanted to determine how people are normally using their TRVs. After 3 weeks, the app was distributed together with a short video tutorial. After 4-5 weeks, the participants were asked about their perception and usage of the connected solution in an interview and by a short survey. The interviews were semi-structured with open questions. They were conducted via telephone and lasted about 10 minutes on average. In the survey respondents were asked to rate several aspects of the solution such as [The app was easy to use], on a 5-point Likert scale with “1” = “strongly disagree” and “5” = “strongly agree”.

During both phases of the study, measurements of temperature, humidity and air quality (in CO_2) were recorded in five minute intervals of all considered rooms by the room climate sensor. We took care to choose an optimal position of the sensor to reduce side effects, like direct solar radiation, direct heating radiation or cold draught of windows, etc.). Manual interactions with the connected TRVs, i.e. manual setpoint changes, were also recorded. App interactions, like programming schedules, checking temperature profiles, setting a new temperature, were also logged by the system.

3.2 Field Test Results

3.2.1 General Perception of the Solution and Perception of Feedback Information

The general perception of the system by the majority of participants was positive. Most participants agreed that the system helps to better control the room temperature (M= 4.53, SD= 0.51). Moreover, they were satisfied with the overall usability: the app was perceived as easy to use (M= 4.47, SD= 0.64), not taking much effort (M= 4.53, SD= 0.64), having a clear interface (M= 4.53, SD= 0.64), not taking much time (M= 4.07, SD= 0.88), being fun (M= 3.39, SD= 0.80) and being interesting (M= 4.07, SD= 0.80). Moreover, the app also seemed to help users: they claimed to better being able to control the temperature of the individual rooms (M= 4.60, SD= 0.74), to adapt the heating when away (M= 4.20, SD= 0.86), to improve comfort (M= 4.33, SD= 0.72), to program a heating schedule (M= 4.27, SD= 1.22) and to learn more about room climate (M= 4.33, SD= 0.98). A few participants also explicitly pointed out that they like the ease-of-use of the system, e.g. “it was simple - it doesn't need much effort - I really liked it” (P2) or “After a bit of playing around, even a 6-year old could use it.” (P4). These results indicate that people are able to understand und use the solution without much effort.

We also evaluated the perception of the feedback information. According to the survey, the solution helps to better understand what the heating is doing (M= 4.27, SD= 1.22). Also, several participants emphasized strongly that the information of the current room temperature and the direct control of the temperature (instead of setting a level 1-5) was a great help for them:

“[I like] that you are made aware of how warm it is at home and that you actually do not need it.” (P1)

“Before [the system was installed] heating was difficult, because you put it on level 5 and then it is not as warm as desired, and instead it is going to heat on somehow. That was great, that you had a temperature [depicted by the IS], because I think, although you can not always know the warmth of a room, it is a better statement: I want the room on 23° than I want the heating on level 3 or 4.” (P3)

“I have to say that all the information, which I could see [on the app], where I could see which temperature is on in in which room, actually helped me to decide: turn the heating up or not.” (P7)

Thus, we can conclude that this information is successful in adjusting the heating to achieve comfortable room temperatures.

3.2.2 Perception and Usage of Schedule and AutoAway Modes

As explained in Section 3, users can choose between “manual” and “schedule” control modes. In addition “AutoAway” can be activated. At the start of the field study, each room was set to manual mode and AutoAway was deactivated. After the study, we calculated the time each mode was active in each room. In Figure 2 (left), the results of the active time, averaged on all rooms, are shown as a barchart. The schedule mode is active about 80% of the time, 70% only schedule mode and 10% schedule mode with AutoAway. In more detail, the active times of each mode per household (P1-P15) are shown in Figure 2 (right). We can see that most participants used the schedule most of the time. Only P1, P5 and P6 never used it. This indicates that users were able to adapt the schedule with the app user interface and preferred it over the manual mode.

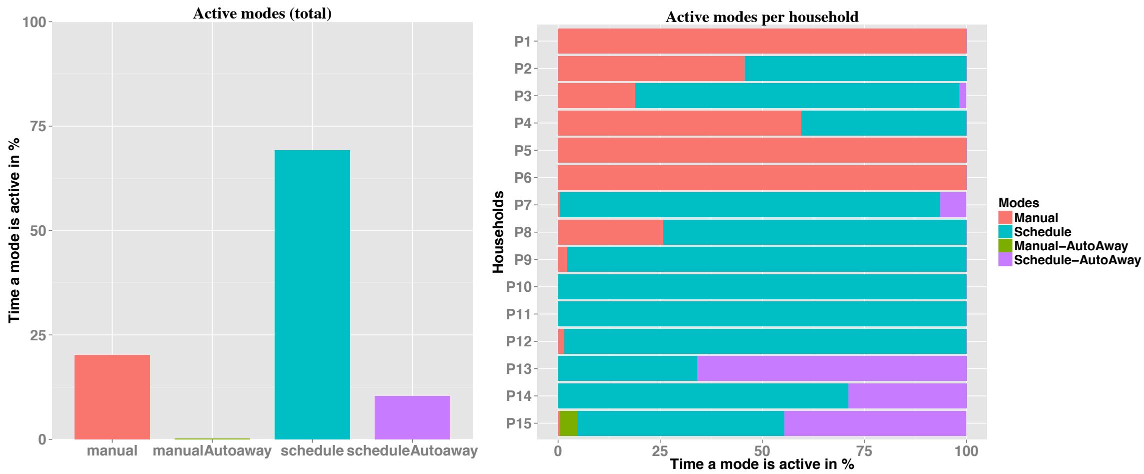

Figure 2. Active time of modes in total (left) and per household (right)

Furthermore, several participants reported their experience with the schedule in the interviews:

“My usage was mainly about the schedule. I programmed my routine for each day, which I adapted if I had some special meetings. Then I reflected it there accordingly. This worked great for me” (P12)

“I liked it. I've set it up and then I did not have to worry about it anymore” (P11)

“It's great that I can adapt the heating of the kids’ room according to the school schedule [...] the schedule mode was the highlight” (P13)

Overall, the schedule is used by the majority of participants and it seems to help users to adapt the heating to their daily routines

However, the active time of the AutoAway was much lower than expected (only 10%). Only three participants (P13, P14, P15) activated it for a considerable amount of time. The others tested it briefly or did not use it at all. There were several reasons: Participant P3 did not like the additional battery drain of the geolocation service. Participant P12 does not want to share his location due to privacy reasons. Besides these concerns, the major problem was that several participants tested the AutoAway, but could not figure out if and how it worked. It was intended that the activity screen should have explain this, however this remained unclear to users. We believe that after activation there was more direct feedback needed and a simple visualization of the general concept necessary, which will be part of future work.

3.2.3 Potential for Saving Energy due to Heating Control via Schedules

Besides certain comfort benefits, using schedules for heating control should enable energy savings. We analysed this saving potential by comparing the average setpoints of certain daytime periods between the in-use stage and the pre-use stage. More precisely, by analysing the participants schedules, it turned out that most of them (N=12) used schedules to have a setback temperature for the night and for certain periods during daytime, e.g. when they were not at home or did not need the room (e.g. bathrooms). Hence, we annotated theses time intervals for each weekday of a schedule as "At-Home", "Night" and "Away", respectively. Then, we calculated for each weekday and time interval the average setpoint. For comparison, we computed also the average setpoint for the corresponding weekday and time interval of the pre-use stage. The boxplots in Figure 3 show the comparison for each time interval. Given a time interval and a stage, a specific boxplot shows the average setpoints of all rooms. In case of the "At-Home" intervals, there is no apparent difference of the setpoints. Thus, people with our IS did not choose lower setpoints when they were at home and wanted a comfortable room temperature. But, in case of the "Away" and "Night" intervals, there was a significant effect of the schedule control on the setpoints: A paired-samples t-test indicated that setpoints of "Night" intervals of 25 rooms were significantly higher for pre-use stage ($M = 20.2$, $SD = 2.16$) than for in-use stage ($M = 17.9$, $SD = 1.53$), $t(25) = 5.07$, $p < .001$. And another paired-samples t-test indicated that setpoints of "Away" intervals of 16 rooms were significantly higher for pre-use stage ($M = 20.4$, $SD = 2.21$) than for in-use stage ($M = 18.3$, $SD = 1.05$), $t(15) = 3.67$, $p < .01$. By comparing the medians, this difference is between 2-3° Celsius. Overall, we can conclude that the use of the schedule leads to lower setpoints for certain time intervals, which might lead to energy savings. However, we cannot provide exact numbers on saved energy since it was not possible to measure the energy consumption of each radiator in our field test setting.

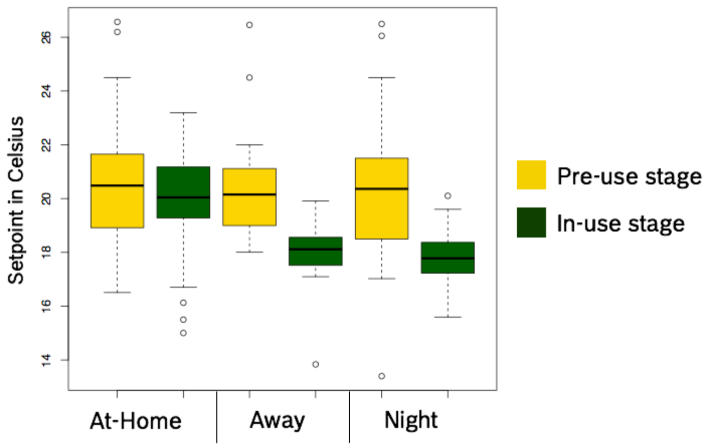

Figure 3. Average setpoints between pre-use and in-use stage.

4 Conclusion and Contribution

This work presents a novel smart individual room heating prototype that was designed to empower users to save energy and improve their comfort by solving well-known usability and understanding problems of current heating controls. In general, the prototype's user interface provides good usability and helped users to accomplish heating related tasks without much effort. The feedback information of the current room temperature and also control by temperature was very well received by several participants. The most used heating control mode was the "schedule" which users set up for their individual rooms without tedious effort as in the case of programmable TRVs. Moreover, they chose significantly lower setpoints by 2-3° Celsius for the night and when away, which may lead to significant energy savings without sacrificing comfort. The AutoAway feature was hardly used since most people did not grasp its function despite detailed explanations and feedback on the Activity Screen.

Summing up, we developed an easy-to-use, feedback-enhanced, and "intelligent" heating IS to enable people to actually use and adapt their radiators to their needs. To the best of our knowledge, we conducted the first field test evaluation of such a smart individual room heating IS. Although the number of field test participants is limited, we provide evidence that a new generation of heating IS might lead to significant setpoint reductions. Furthermore, it turned out that the main enabler for the setpoint reductions was the rather simple but easy-to-use manual scheduling option. In contrast to common expectations but in line with other studies (Yang et al. 2014), the "intelligent" and more sophisticated AutoAway options have still not much impact on user's heating patterns. Thus, we conclude that the main benefits of new heating IS are driven by usability rather than new "smart" control concepts.

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