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Document Version
Final published version

Published in:
Human Work Interaction - HWID2012

Publication date:
2012

Citation for published version (APA):
Ulslev Pedersen, R., & Clemmensen, T. (2012). A Design Science Approach to Interactive Greenhouse Climate Control using Lego Mindstorms for Sensor-Intensive Prototyping. In T. Clemmensen, J. Abdelnour-Nocera, A. Mark Pejtersen, A. Lopes, D. Katre, P. Campos, & R. Ørngreen (Eds.), *Human Work Interaction - HWID2012: Pre-conference Proceedings of the 3rd TP 13.6 HWID Working conference* (pp. 66-76). Copenhagen Business School, CBS.

A Design Science Approach to Interactive Greenhouse Climate Control using Lego Mindstorms for Sensor-Intensive Prototyping

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Abstract.
In this paper we present a case study of early prototyping work performed within a Danish advanced technology project. We specifically investigate the problems and issues related to throw-away prototypes in sensor-intensive systems. An important criterion is to record and perhaps later reproduce the identified contributions of the throw-away prototypes, and to this end we use the educational version of Lego Mindstorms NXT. To achieve methodological rigor we have used the Design Science Framework by Hevner et. al. It allows us to focus on the prototyping effort (called the design cycle) without letting go of either the relevance or rigor related to the project. We relate the case study to a Human Work Interaction Design (HWID) framework for the use of interactive, sensor-intensive prototypes to develop interactive greenhouse climate management systems. By applying guidelines suggested in design science to the case studied, we identify a number of interactive prototypes that successively address core issues in this particular setting. Finally, the problems and issues pertaining to this setting is presented and identified. The main contribution of this paper is that it, by pointing out problems and issues related throw-away prototyping with sensor-intensive systems, extends the design cycle of the original design science framework. This is determined to be a necessary step in order to address the inherent multi-disciplinarily of sensor-intensive HWID systems.

Keywords: Sensor prototypes, design science, HWID, embedded systems

1 INTRODUCTION

In this paper, we describe the application of the design science framework [3] for the use of interactive, sensor-intensive prototypes to develop greenhouse climate management systems. Consequently, this study emphasizes possible problems and issues when applying design science to indoor greenhouse climate management performance through the utilization of sensor network technology.

We identify the need for specific design science framework to address the complexities of HWID sensor-intensive systems and we provide a case study, as our contribution, as a way to test this framework.

In order to contribute to the body of knowledge on environmentally sustainable HCI [22] and environmental informatics [1], we propose in this paper to approach HWID as a kind of design science. This HWID-as-design-science-approach then forms a representation of a design space a new work system that can be used as a point of reference for further relevant work. Our research questions are:

1. What new utility does the interactive climate management system provide?
2. What kind of sensor-intensive prototypes demonstrates that utility?

We use these questions for guidance in our case study into interactive greenhouse climate management and control, while keeping track of the problems and issues we encounter during the execution of the five prototyping rounds.

2 BACKGROUND

As the importance of eco-sustainable growth becomes increasingly important, the human-computer interaction and micro information systems research communities must address environmental sustainability challenges. This paper has been inspired by recent developments in design science research as described by Hevner, March, Park and Ram [3]. Design science research (DSR) is an approach for evaluating novel artifacts. Therefore, it is different from traditional research that mainly directs attention toward observation and analysis. A DSR project creates an artifact that is then assessed with regard to its contribution to rigor and to relevance. The researchers use scholarly literature to form theories regarding the DSR artifact that is created. The ultimate test is the proposed relevance for use with practitioners.

In line with common DSR principles, we want to design our artifact but doing in a way that optimizes end-user relevance and subsequent published contributions to the academic knowledgebase. A part of this is to be able to reproduce prototypes and user-oriented evaluations of them. We propose to use what we call “throw-away” sensor-intensive, interactive prototypes. We suggest that reproducibility in throw-away sensor-intensive prototypes can be achieved by using re-buildable Lego NXT prototypes with instructions in terms of video clips showing how to build the prototypes.

There are examples of DSR within neuroscience [2] and in sustainability research, such as Watson et al.’s environmental framework [1] using the design science guidelines provided by Hevner et al. in their seminal MIS Quarterly article, “Design Science in Information Systems Research” [3]. In this paper, we focuses on the Design Cycle of the three cycles belonging to the DSR framework. Thus a deliberate limitation of this case study is that we do not consider the rigor and relevance cycles. This may be better addressed in future work.

DSR has been proposed to test the proposition that incorporating user modeling and usability modeling in software requirement specifications improves design [4], and more generally, Human Computer Interaction has been suggested as a design science discipline [5].

2.1 Sensor Intensive Work Systems

The embedded and sensor context for this paper is greenhouse monitoring systems and management of same. Research in this area focuses on sensor-intensive systems [6]. On an even wider scale, OECD [7] presents sensor technology as a fundamental enabler for addressing global challenges with regard to global warming.

We conducted this particular evaluation using a design science framework [8-10] that shows how it is possible to incorporate the notion of sensor-intensive systems into existing frameworks. Our focus here is on rigorous design, as listed by the 5th Design Science guideline published by Hevner et al. Our artifact-driven approach in is addressed in the first DSR guideline: Design as an artifact. The *instantiation* is a demonstration of the usefulness of the generate/evaluate method.

We recognize the importance of other disciplines; two such examples are decision support systems [11] and embedded networked systems [12]. Design science, as discussed in IS [13], guides the design of the artifact and the constructs, models, methods, and instantiations that sum up this meta-artifact.

At that point, the demands and needs for our prototypes are mostly related to size, form, and function for the designed artifacts. The design theory nexus is able to cope with multiple requirements [14]. It forms a method for a multidisciplinary approach to design science studies within HWID systems of this complex nature. We monitor the prototyping efforts and then discuss the possible need for this more elaborate design science method called the *design science nexus.*

In relation to design science, HCI has, for long, been conceived of by some researchers as a design science [16]. The iterative cycle of generate and evaluate designs of design science is at the core of HCI's user-centered design [4, 5]. However, the importance of combining embedded sensor-intensive systems with consideration of users' interactions with such systems has appeared more recently [17]. Within the climate control community (not in the HCI community), Van Straten et al. [18] proposed that the interactive use of sensor-intensive information about crop growth would allow greenhouse control strategies to become more optimal in an economic sense. Both long-term and short-term dynamics of the crop and greenhouse and external weather conditions could be considered in such interactive control strategies. However, a major challenge in the development of interactive control strategies is the lack of reliable crop development models for the wide variety of crops encountered in real settings and the consequential need for a sensible allocation of tasks for the human grower and automatic control systems. One proposed solution is a two-systems approach, an interactive sensor-intensive control system for day-to-day climate control, and another more decision- support-like system to consider the long-term effects of climate management on crop production [18]. Within such a grower-oriented framework, the grower interacts with the system by setting constraints on temperature, humidity, and other evapo-transpiration variables over a period of interest. The grower is supported by a model-based simulation system that predicts how these settings influence energy consumption, photosynthesis, and condensation [18].

In the HCI community, related work has been done by Pearce et al. [19, 20], who studied interactive gardening. They wanted to use what they called "everyday simulations" to allow non-specialists to experiment with and in an interactive way learn optimal strategies for watering gardens. In order to develop such a tool, they noticed "…the absence of design processes specifically tailored to this type of project…" [20], and suggested areas to consider in terms of developing a design process for such a tool. Among the identified challenges were how to allow HCI designers to develop a necessary level of understanding of the horticultural domain and in particular how to do this within a reasonable time period. The solutions included letting the domain specialists automate a large number of decisions and allowing the end-user to only gradually take part in the decision making as he or she becomes more knowledgeable. Secondly, the HCI designers tried to embody material constraints in the design, as suggested by work domain analysis [21]. In the end, they designed a software tool called SmartGardenWatering, which works as decision support for gardeners when defining watering schedules and use. In a study of 20 gardeners using the tool, the researchers identified issues of trust and confidence in the underlying horticultural models and their interactive use. They concluded that the outcome of the interaction with the software should not challenge "idiosyncrasies in existing practice" [19, p. 224] and that gardeners wanted models with higher granularity than those provided by the tested system.

More generally, the whole idea of designing interactive systems for sustainable environments and global climate management has been outlined by leading HCI researchers. Dourish [22] took the opportunity to explain how ICTs can be used to promote environmental sustainability on the part of IT users, but also warned that current HCI research is not sensitive enough in reference to the political and cultural contexts of environmental practice. The idea has also found support in the IS community, where researchers have proposed that information system design can be a catalyst for environmental sustainability as an expression of value-sensitive design [23]. Thus, the role of IS design in developing interactive systems for sustainable environment is being pressed in both IS and HCI communities. So far, most of this work has been on a grand scale of proposals, but the first steps toward meeting the new challenge in the creation of interactive systems, environmental sustainability, have been taken, e.g., [24]. However, rather than focusing on the grand global climate management challenges, in this paper, we report from the perspective of a micro-climate control (greenhouse and plants) research project [25].

METHOD

We introduced design science in the background section. From this framework, we extracted the generate/evaluate activity [3]. The reason for doing so was the need for a clear way of capturing the problems and issues related to throwaway prototyping.

The separation of generate and evaluate activities is useful because it allows us to assume clear roles in each sequential prototyping effort. Moreover, we do not necessarily assume the same roles across all sequential prototyping efforts. This is later demonstrated to be an important driver of complexity. In the very beginning, the HCI researcher may create throw-away prototypes using paper or clay. Later in the process, it could be that the HCI researcher is now in the evaluation role, while the other researcher generates electronic prototypes using Lego Mindstorms NXT. What separates these two activities is that each prototype is evaluated and the feedback is used in subsequent prototypes. The HCI evaluation activity covers both an activity where the HCI researcher is acting as an end user and, later, the HCI researcher will act as part of the design group which is sitting in the generate/evaluate new box.

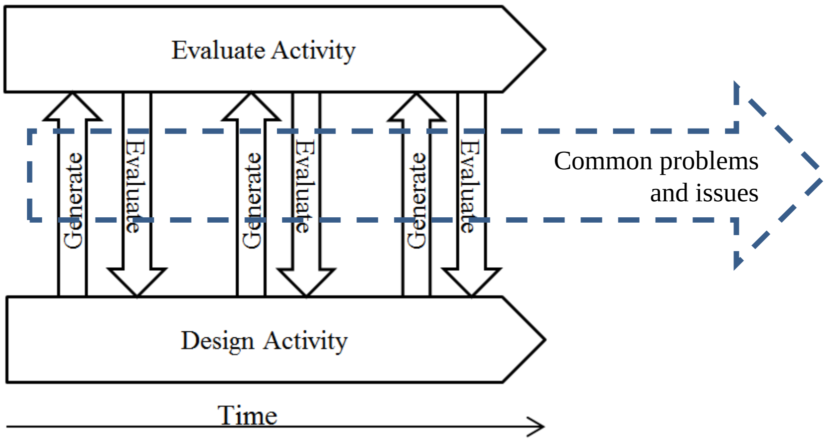

Fig. 1. Design activity and evaluate activity connected by generate and evaluate processes

In Figure 1, we describe how evaluate and generate activities are the two processes in which we intervene by recording the problems and issues we encounter for each prototype we create. That is the subject of the following section. Each of the generate processes outputs a prototype which is then evaluated. This process is repeated, and the prototype is matured over time.

3 CASE STUDY WITH THROW-AWAY PROTOTYPES IN SENSOR-INTENSIVE HWID SYSTEMS

For each of the prototypes we note down the problems we encounter for later discussion.

3.1 Prototype 1 – proof of concept

The first prototype was a ”proof of concept” prototype. It was a simple text-output prototype that served to show that it was meaningful and technically possible to make an interactive sensor-intensive prototype to conduct climate management. The prototype was evaluated by internal discussion in the research group using a generate/evaluate tool with the aim of conducting a rigorous evaluation. We decided to go on with the LEGO due to its ability to connect to the minds of many people with little technical knowledge and its flexibility in programming capacity, both of which had previously been demonstrated [8, 9].

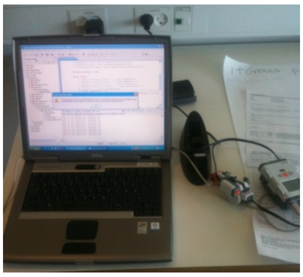

Fig. 2. IT Grows prototype 1 – demonstrating sensor-based climate management prototyping with Lego Mindstorms

Fig. 3. Lego Mindstorms NXT as the platform for prototyping

Lego Mindstorms NXT is the unit that we used to model the sensors and the actuators (motors). The unit has four input sensors, which are in the standard kit: touch (shown in Figure 3), light, sound, and a distance sensor.

Problems encountered: The most predominant problem in this first phase is the individual differences between the researchers which created the prototype. It was not clear if a researcher was speaking/thinking as an engineer, physiologist, or something totally different.

Table 1. Generation of prototypes and their evaluation in growers' work domains and interaction design evaluation

TIME	Work domain and task evaluation	Generation of prototypes	Interaction design evaluation
↑	Field test in greenhouse	**prototype 6 -** Decision support part of system	Cognitive walkthrough by students of HCI
	Review by expert in sensor information	**prototype 5 –** Light sensitive resistor	
		prototype 4 - Sketches of model greenhouse simulation	Evaluation of sketches by greenhouse consultant
	Group discussion with greenhouse grower consultant	**prototype 3 -** Simulated plant table	
	Presentation of LEGO greenhouse climate management for industry	**prototype 2 -** Model of greenhouse	
	Within project team, evaluation of sensor data collection by generate/ evaluate tool	**prototype 1** - LEGO Mindstorm unit	Within project team, evaluation of interaction design by generate/evaluate tool

3.2 Prototypes 2 to 6

We have worked through five more prototypes: Prototype 2 through Prototype 6, and noted the following problems/issues:

- **Prototype 2 -** Model of greenhouse
  - **Problem:** The model turned out to be too complex for the need of the end user, which was a company involved in the project. It was stripped of its sensors and control systems.
- **Prototype 3 -** Simulated plant table
  - **Problem:** There was differences between what the domain expert thought was possible and what could actually be done with the Lego Mindstorms NXT kit
- **Prototype 4 -** Sketches of model greenhouse simulation
  - **Problem:** We lacked some clarity because of the static nature of sketches. A dynamic prototype would have been of better use.
- **Prototype 5 –** Light sensitive resistor
  - **Problem:** We were not clear here in relation to which aspect of the design that was addressed. It was mainly the computer related

aspect, and not the interaction part, but that was not clear until af-afterwards.

- **Prototype 6 -** Decision support part of system
  - **Problem:** A significant change of focus occurred here, and it is not completely evident how this fits with the first prototypes. A need for "some other way" is now quite clear to the researchers.

Each prototype represented a different design task. Prototype 2 was made to demonstrate that the prototype was easy to disassemble and reassemble in new contexts and that it would allow different users and other stakeholder groups to interact with the prototype. The third prototype was aimed at generating relevant functions that would allow greenhouse growers to interact with real sensor data. The fourth prototype was made in order to interact with a greenhouse grower consultant. Prototype 5 was developed with the purpose of simulating the more realistic scenario of managing several sensors from several greenhouses. Prototype 6 was a high fidelity prototype of a part of the to-be-designed climate management system, with a so-called the "side-bar" which gave decision support to the grower based on model simulations of the climate. The results of the cognitive walkthrough were sent to the developers, who stated that some results – that is, some design suggestions in reference to consistency, level of detail, and scalability of graphs were particularly useful in the further development of the system.

4 DISCUSSION

We have described selected parts of a development flow of a sensor-intensive prototype within a DSR generate-evaluate process (Figure 1). For each of the prototypes we identified a problem. Table 1 provides an overview.

The use of LEGO Mindstorm as a sensor-intensive prototyping tool is, we believe, the first attempt to make "throw-away" sensor-intensive prototypes that are easy to assemble, disassemble, move, and re-assemble. In that way, we were able to reproduce the different LEGO Mindstorm sensor-intensive prototypes. Hence the evaluation results can potentially be repeated and easily reproduced by other researchers.

The "throw-away" nature of the prototypes, that is, the easy reproducibility of the sensor-intensive prototypes, may, among other considerations, provide a solution to the problem raised in related HCI research: How to allow HCI designers to develop a necessary level of understanding to design relatively simple user interfaces for complex work domains [27], such as the horticultural domain, and, in particular, how to do this within a reasonable time period [20].

Climate management and climate control overlap in our proposed combination of micro-IS and HCI approaches to greenhouse climate. Thus, we accommodated the proposals [18] to allow growers to use a two-system approach.

In operational climate management, the actions taken by the one(s) using the systems are dependent upon timely readings of temperature, humidity, light intensity, etc. Lego Mindstorms provides these readings and, thus, it provides the dynamic picture which is a requirement of such systems. Furthermore, Lego Mindstorms can control the greenhouse prototypes with its motors. We have used the motors to simulate the opening and closing of curtains.

4.1 RESEARCH CONTRIBUTION

We have demonstrated the usefulness of using a design science research framework approach to capture and identify problems when conducting HWID with throw-away prototypes. A special valuable property of our approach is that we are being explicit about the roles that are assumed by each type of generate/evaluate activity throughout the process. This allows for the creation of a lightweight log book of how a project develops over time and the possibility of going back in time to restart the design at a given point.

The design science research framework has provided us with an established research knowledge base from which we have focused on the generation of prototypes and the subsequent evaluation of same. We have noted who conducted the creation and evaluation at each point in time.

Sensor-intensive prototyping involves electric engineering and computer science in addition to HCI and end user involvement. From the set of noted problems we have identified an important aspect of the throw-away prototyping effort. This can possibly be further researched using the Design Science Nexus by Heje & Baskerville [14].

5 CONCLUSION

The first research question, what new utility the interactive climate management system provides, could not answered in full by the research reported here. However, the LEGO Mindstorm prototypes identified the utility of the to-be-designed climate management system in terms of providing possibilities for allowing growers to participate in the dynamic location of sensors out in the greenhouse. This was a unique finding related only to the use of LEGO Mindstorm prototypes in the case. The second research question, what kind of sensor-intensive prototypes demonstrates that utility, was answered by identifying the possible problems and issues when using sensor-intensive throw-away prototypes in the design cycle. Thus the application of a design science framework for combining micro information systems with human-computer interaction approaches adds structure to the design process. Furthermore, we have been able to point out a multidimensional DSR framework that can be used in subsequent research.

By adhering to a lightweight process that concentrated on the generate/evaluate process, we were able to undertake a series of prototyping efforts over a period of 18 months and keep track of the progress. The relevance of the “interactive, sensor-intensive prototyping” approach has been confirmed by the exhibition of one prototype at a large agriculture exhibition. The rigor has been described in terms of design science, micro information systems, and the ability to reproduce sensor-intensive prototypes.

6 ACKNOWLEDGMENTS

This research was supported by a grant from the Danish Advanced Technology Foundation to the 'itGrows' project.

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