A Digital Twin to Enhance Energy Consumption Awareness in a Smart Home

Barbara Rita Barricelli, Luca Cotti, Daniela Fogli, Davide Guizzardi, Matteo Pigoli
Department of Information Engineering, University of Brescia
Brescia, Italy
{barbara.barricelli,daniela.fogli,davide.guizzardi}@unibs.it

ABSTRACT

This paper explores the development of a Digital Twin (DT) of a smart home, which allows end users to monitor the state of appliances and their energy consumption. The DT will also make it possible to simulate different 'what-if' scenarios related to the automations defined by the end users through End-User Development. Simulations will allow users to evaluate in advance the effects of appliance activation in terms of energy consumption and, after their analysis, to approve the deployment of automations in the domestic environment or modify them as suggested by the DT.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in interaction design**.

KEYWORDS

Smart home, Digital twin, End-user development, Automation

ACM Reference Format:
Barbara Rita Barricelli, Luca Cotti, Daniela Fogli, Davide Guizzardi, Matteo Pigoli. 2024. A Digital Twin to Enhance Energy Consumption Awareness in a Smart Home. In *International Conference on Advanced Visual Interfaces 2024 (AVI 2024), June 03–07, 2024, Arenzano, Genoa, Italy*. ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/3656650.3656708

1 INTRODUCTION

A smart home is an Internet of Things (IoT) ecosystem [7] encompassing smart appliances, sensors, and software applications, which operate synergistically, to ensure the smart home behavior desired by its inhabitants. An IoT ecosystem can be usually controlled remotely, and suitable applications can be used to create automations - i.e. sequences of actions triggered by an event - for tailoring the behavior of the IoT ecosystem. An IoT ecosystem is also a source of data that can be fed to Artificial Intelligence (AI) algorithms and big data analytics to optimize system behavior, help creating effective and efficient automations, and enhance inhabitants' awareness of the energy they consume. This bidirectional interaction between a physical world (the IoT ecosystem) and a virtual world (data and algorithms) paves the way for the design and development of a Digital Twin (DT)[3, 16, 17]. DTs of smart homes are meant to play a dual role: providing real-time information about the functioning of the connected devices [1] and simulating possible usage scenarios to understand their potential and weaknesses [8].

Giving home inhabitants the possibility of creating automations through End-User Development (EUD) [4, 19, 21] techniques, such as Trigger-Action Programming (TAP) [23] carried out through graphical user interfaces [9, 11, 13, 15], voice interaction [10, 12, 14, 18], augmented reality [20, 22] or multi-modal interaction with smart speakers [2, 6], may contribute to engage them in a more adequate control and use of the IoT ecosystem.

Combining EUD with the DT of a smart home thus opens new ways for personalizing a smart home behavior to achieve building sustainability, by lowering energy consumption and optimizing appliances usage. In literature, there is a lack of approaches to EUD for smart homes that foresee an evaluation, in terms of energy consumption, of automations created by the end users before their actual deployment. We would like to fill this gap through the design and development of a DT that allows users to reflect on automation consumptions and on possible conflicts with other automations (created by the same user or by other users), and to receive warnings and recommendations about more effective, efficient, and sustainable automations. This paper delineates the main features of this DT and explains how it will contribute to enhance home inhabitants' awareness of their energy footprint.

2 A DIGITAL TWIN OF A SMART HOME

The DT proposed in this work presents a dashboard for monitoring and controlling the different appliances available in the smart home and their consumption during a day, week, or month. The DT is able to forecast and show energy consumption in a future period on the basis of collected consumption data. In particular, in the DT's first screen (see Figure 1), each inhabitant can see the house plan where each appliance is represented by an icon positioned in the room where it is installed. Icon's colors reflect the status of the devices: green when they are on, grey if they are off, and orange for disconnected devices. On the same screen, the users can see the current indoor temperature and the instantaneous energy consumption. When a user would like to create a new automation to manage their appliances, the DT allows the user to simulate what would happen in case of its activation, by returning different types of feedback associated with different scenarios:

- *Conflict that determines overcoming the energy meter load capacity*: in this case the automation can not be executed as-is because it includes an appliance activation that will bring energy consumption of all active automations over the admitted load capacity for the energy meter (in Italy it is commonly set to 3kWH for domestic use). The DT may suggest how the automation could be modified, for example,

AVI 2024, June 03–07, 2024, Arenzano, Genoa, Italy

ACM ISBN 979-8-4007-1764-2/24/06
https://doi.org/10.1145/3656650.3656708

Figure 1: The interface of the DT visualized on a smartphone.

its activation could be postponed after an appliance involved in another automation has completed its operation;

- *Conflict due to operation mode inconsistency*: this case occurs whenever the automation under creation includes the activation of an appliance in a given operation mode (e.g., for a washing machine, a short sports cycle), but there is another automation scheduled on the same appliance with a different operation mode in an overlapping time slot. The DT may present the user with different options: the deletion of one of the two conflicting automations or the modification of one of them;
- *No conflict, but a suggestion to be more sustainable*: in this case, even if the automation can be executed without generating conflicts with other automations, the DT may suggest reducing energy consumption costs, avoiding cases of non-sustainable appliance activation.

3 EVALUATION OF AUTOMATIONS

To provide the user with a simulation of what would happen if a particular automation is executed, the DT must have some knowledge about the possible operation modes of each appliance, their duration, and their energy requirements. Hence, Machine Learning techniques were applied to power consumption datasets[1,2]. The procedure involved extracting sequences of power consumption values corresponding to the same operation mode and subsequently grouping and classifying them using clustering techniques. The result is a table that specifies for each operation mode, identified with an ID, its estimated consumption, and overall duration. Then, a data structure is needed to model the state of each appliance at any time. This is a matrix (herewith called *state matrix*) where each row corresponds to a minute of the day, and each column corresponds to an appliance of the smart home. The value of each cell is the ID of the operation mode in which the appliance is set at that minute. Consequently, the dimensionality of the matrix is $1440 \times n$, where n is the number of appliances. In Figure 2, an example of a state matrix for a smart home with 15 appliances is shown.

The state matrix makes it straightforward to simulate the addition of a new automation and check if any previously mentioned scenarios occur. The process starts by creating a copy of the current state matrix and by updating it with the new appliance states of

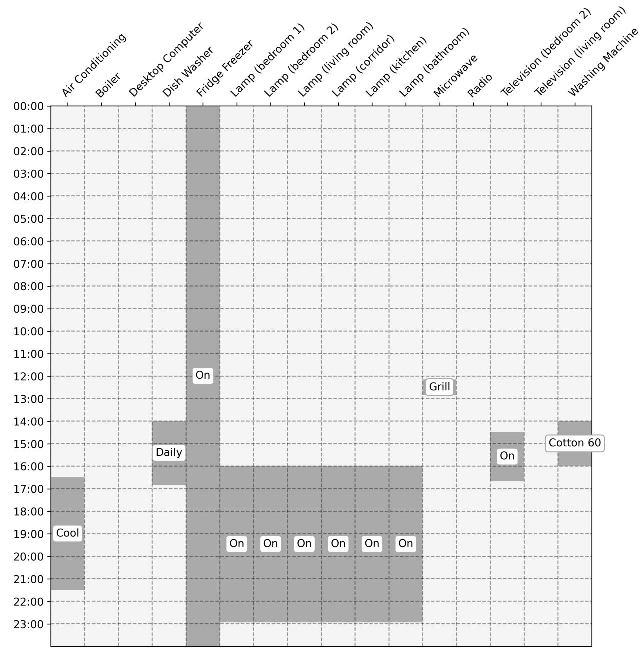

Figure 2: Example of a state matrix.

the automation under creation. Then comes the evaluation of conflicts: excessive energy loads are checked by calculating the total consumption for every row of the new state matrix and comparing it with the maximum limit; an operation mode inconsistency is detected when a cell containing an operation mode different from “off” or “suspended” in the original matrix is overridden by a different value in the new one. After conflict evaluation, the DT looks for the best activation time slot for the automation using a brute force approach that estimates the energy cost of starting the automation at every minute of the day. If a better activation time is found, the system suggests it to the user along with the monetary saving associated with executing the automation at that specific time instead of the one set during the creation.

4 CONCLUSION

This work is only the first step of a long journey. We are planning to integrate the DT with features for automation creation by different users and manage conflicts arising in shared environments as discussed in [5]. Conflicts between automations and direct appliance activations will be considered as well. The DT deployment and experimentation in real domestic environments will be finally carried out.

ACKNOWLEDGMENTS

This work has been supported by the Italian MUR PRIN 2022 PNRR Project P2022YR9B7, End-User Development of Automations for Explainable Green Smart Homes, funded by European Union - NextGenerationEU.

[1] GREEND - https://www.andreatonello.com/greend-energy-metering-data-set/
[2] UK-DALE - https://jack-kelly.com/data/

REFERENCES

[1] Alireza Asvadi, Andrei Mitriakov, Christophe Lohr, and Panagiotis Papadakis. 2022. Digital Twin Driven Smart Home: A Feasibility Study. In *Participative Urban Health and Healthy Aging in the Age of AI*, Hamdi Aloulou, Bessam Abdulrazak, Antoine de Marassé-Enouf, and Mounir Mokhtari (Eds.). Springer International Publishing, Cham, 18–29.

[2] Barbara Rita Barricelli, Alessandro Bondioli, Daniela Fogli, Letizia Iemmolo, and Angela Locoro. 2023. Creating Routines for IoT Ecosystems through Conversation with Smart Speakers. *International Journal of Human–Computer Interaction* 2023 (2023), 1–19. https://doi.org/10.1080/10447318.2023.2247845

[3] Barbara Rita Barricelli, Elena Casiraghi, and Daniela Fogli. 2019. A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. *IEEE Access* 7 (2019), 167653–167671. https://doi.org/10.1109/ACCESS.2019.2953499

[4] Barbara Rita Barricelli, Fabio Cassano, Daniela Fogli, and Antonio Piccinno. 2019. End-user development, end-user programming and end-user software engineering: A systematic mapping study. *Journal of Systems and Software* 149 (2019), 101–137. https://doi.org/10.1016/j.jss.2018.11.041

[5] Barbara Rita Barricelli and Daniela Fogli. 2023. Routine Creation in Multi-User Contexts: Improving the Quality of Life through Conflict Resolution. In *Joint Proceedings of the Workshops, Work in Progress Demos and Doctoral Consortium at the IS-EUD 2023 co-located with the 9th International Symposium on End-User Development (IS-EUD 2023), Cagliari, Italy, June 6-8, 2023 (CEUR Workshop Proceedings, Vol. 3408)*, Andrea Bellucci, Luigi De Russis, Paloma Díaz, Anders I. Mørch, Daniela Fogli, and Fabio Paternò (Eds.). CEUR-WS.org, Aachen, Germany, 8 pages. https://ceur-ws.org/Vol-3408/short-s2-01.pdf

[6] Barbara Rita Barricelli, Daniela Fogli, Letizia Iemmolo, and Angela Locoro. 2022. A Multi-Modal Approach to Creating Routines for Smart Speakers. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces* (Frascati, Rome, Italy) *(AVI 2022)*. Association for Computing Machinery, New York, NY, USA, Article 37, 5 pages. https://doi.org/10.1145/3531073.3531168

[7] Barbara Rita Barricelli and Stefano Valtolina. 2015. Designing for End-User Development in the Internet of Things. In *End-User Development*, Paloma Díaz, Volkmar Pipek, Carmelo Ardito, Carlos Jensen, Ignacio Aedo, and Alexander Boden (Eds.). Springer International Publishing, Cham, 9–24. https://doi.org/10.1007/978-3-319-18425-8_2

[8] Damien Bouchabou, Juliette Grosset, Sao Mai Nguyen, Christophe Lohr, and Xavier Puig. 2023. A Smart Home Digital Twin to Support the Recognition of Activities of Daily Living. *Sensors* 23, 17 (2023), 27 pages. https://doi.org/10.3390/s23177586

[9] Danilo Caivano, Daniela Fogli, Rosa Lanzilotti, Antonio Piccinno, and Fabio Cassano. 2018. Supporting end users to control their smart home: design implications from a literature review and an empirical investigation. *Journal of Systems and Software* 144 (2018), 295–313. https://doi.org/10.1016/j.jss.2018.06.035

[10] Fulvio Corno, Luigi De Russis, and Alberto Monge Roffarello. 2021. From Users' Intentions to IF-THEN Rules in the Internet of Things. *ACM Trans. Inf. Syst.* 39, 4, Article 53 (aug 2021), 33 pages. https://doi.org/10.1145/3447264

[11] Joëlle Coutaz and James L. Crowley. 2016. A First-Person Experience with End-User Development for Smart Homes. *IEEE Pervasive Computing* 15, 2 (2016), 26–39. https://doi.org/10.1109/MPRV.2016.24

[12] Luigi De Russis, Alberto Monge Roffarello, and Carlo Borsarelli. 2021. Towards Vocally-Composed Personalization Rules in the IoT. In *EMPATHY: 2nd International Workshop on Empowering People in Dealing with Internet of Things Ecosystems* (Bari, Italy). CEUR Workshop Proceedings, Aachen, Germany, 1–5.

[13] Daniela Fogli, Matteo Peroni, and Claudia Stefini. 2017. ImAtHome: Making trigger-action programming easy and fun. *Journal of Visual Languages & Computing* 42 (2017), 60–75. https://doi.org/10.1016/j.jvlc.2017.08.003

[14] Simone Gallo and Fabio Paterno. 2022. A Conversational Agent for Creating Flexible Daily Automation. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces* (Frascati, Rome, Italy) *(AVI 2022)*. Association for Computing Machinery, New York, NY, USA, Article 38, 8 pages. https://doi.org/10.1145/3531073.3531090

[15] Giuseppe Ghiani, Marco Manca, Fabio Paternò, and Carmen Santoro. 2017. Personalization of Context-Dependent Applications Through Trigger-Action Rules. *ACM Trans. Comput.-Hum. Interact.* 24, 2 (2017), 33 pages. https://doi.org/10.1145/3057861

[16] Michael Grieves. 2015. *Digital Twin: Manufacturing Excellence Through Virtual Factory Replication.* Technical Report. Florida Institute of Technology, Melbourne.

[17] Michael Grieves and John Vickers. 2017. *Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems.* Springer International Publishing, Cham, 85–113. https://doi.org/10.1007/978-3-319-38756-7_4

[18] André Sousa Lago, João Pedro Dias, and Hugo Sereno Ferreira. 2021. Managing non-trivial internet-of-things systems with conversational assistants: A prototype and a feasibility experiment. *Journal of Computational Science* 51 (2021), 1–12. https://doi.org/10.1016/j.jocs.2021.101324

[19] Henry Lieberman, Fabio Paternò, and Volker Wulf. 2006. *End User Development (Human-Computer Interaction Series).* Springer-Verlag, Berlin, Heidelberg.

[20] Andrea Mattioli and Fabio Paternò. 2023. A Mobile Augmented Reality App for Creating, Controlling, Recommending Automations in Smart Homes. *Proc. ACM Hum.-Comput. Interact.* 7, MHCI, Article 195 (sep 2023), 22 pages. https://doi.org/10.1145/3604242

[21] Fabio Paternò and Volker Wulf (Eds.). 2017. *New Perspectives in End-User Development.* Springer, Cham. https://doi.org/10.1007/978-3-319-60291-2

[22] Fabio Paternò Raffaele Ariano, Marco Manca and Carmen Santoro. 2023. Smartphone-based augmented reality for end-user creation of home automations. *Behaviour & Information Technology* 42, 1 (2023), 124–140. https://doi.org/10.1080/0144929X.2021.2017482

[23] Blase Ur, Elyse McManus, Melwyn Pak Yong Ho, and Michael L. Littman. 2014. Practical Trigger-Action Programming in the Smart Home. In *Proc. of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. ACM, New York, NY, USA, 803–812. https://doi.org/10.1145/2556288.2557420