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The Role of Digital Twins in Collaborative Cyber-Physical Systems

Artem A. Nazarenko and Luis M. Camarinha-Matos

Faculty of Sciences and Technology & UNINOVA-CTS and Socolnet,
Nova University of Lisbon
2829-516 Monte Caparica, Portugal
a.nazarenko@campus.fct.unl.pt, cam@uninova.pt

Abstract. The growing smartification of devices and systems, combining physical and virtual parts, offers a great potential to improve the daily life of people through the establishment of context-rich environments. Cyber-Physical Systems (CPS), embedding collaborative features, can be considered as one of the key enablers of such environments, providing support for life quality improvement. Besides the general aim of the conventional CPS, further aspects related to co-existence and collaboration among different heterogeneous and autonomous components within a system, are in the scope of Collaborative CPS. These systems allow looking at the technical and organisational challenges from the perspective of interconnected and jointly acting entities. Such entities can be the physical devices or their virtual representations, which are called Digital Twins (DT), understood as digital replicas of physical assets. However, a DT provides more than just a digital simulation of the physical device or process, including reasoning and prediction mechanisms. This work is devoted to the discussion of how Digital Twins can be used in the design, development, and functioning of Collaborative CPS. As such, a design approach is suggested and illustrated with a smart home scenario.

Keywords: Collaborative Cyber-physical Systems, Digital Twins, Smart Home.

1 Introduction

Smart interconnected systems, which can easily adapt to changing conditions, are playing an important role in modern manufacturing as well as in other domains, such as smart buildings, healthcare, etc. This led to emergence of the ongoing digital transformation processes, encompassing various concepts such as Cyber-Physical Systems, Internet of Things, Data Mining, Cloud Computing and Digital Twins. Some of these concepts are tightly interrelated, as for instance Cyber-Physical Systems and Digital Twins. Both concepts are bridging physical entities and processes, and virtual artefacts. More specifically, the Digital Twin is a term that, in a simplified way, can be described as digital replica or an avatar of the physical entity/system, being one of the key enabling technologies for Cyber-Physical systems, as well as for Collaborative CPS (CCPS) [1].

Further smartification of modern digital systems and to higher extent the Collaborative CPS, combining virtual and physical elements, has created the need for adequate design approaches, which have to provide a reliable methodology for developers, whereas integrating several relevant approaches in the clear way. A framework that can, on one hand, integrate available achievements in the form of generic models and on the other hand bridge those models with the real case scenarios is a promising research direction. However, to be able to provide proper methods and an associated framework several difficulties have to be addressed, namely: (i) models, used during the design process, need to be generic enough to be applied to various use-cases, (ii) clear definitions of the concepts used in the approach need to be given and explained, (iii) design steps also need to be generic in order to cover various application areas and use cases, and (iv) the order of design steps need to be clearly identified.

Besides the technological and design challenges, the goal of improving life quality has a significant impact on the aimed systems. Although there is a lack of a proper definition and metrics for the “life quality”, in [41] several approaches for assessing the impact on life quality improvement are given. For instance, one of the approaches is the “theory of needs” taking into consideration how the users’ needs are satisfied by the system. This approach should be reflected in design frameworks through the users’ requirements or desirable functionality to satisfy formulated needs.

Often existing research works directed towards the design of complex CPS are focused on some partial aspects of the design methodology, as for instance the models for some concrete use cases as smart home and social services [2], or focused on particular issues related to information model building [3], without giving a general picture and indentifying the steps for designing a complex Collaborative CPS. In order to offer some guidance for CCPS design, a proposal for a Design Framework for CCPS covering various aspects including the role of DTs is presented and illustrated.

The remaining of the paper is structured as follows:

- Relation of the presented topic and in particular the CCPS and DTs for the life improvement with the focus on smart home;
- Related literature mostly focused on the concept of DT itself, as well as its significance for the CCPS;
- Introduction of a Design Framework aimed at giving the general understanding and guidance for design of CCPS;
- Example scenario representing the application of the proposed Design Framework;
- Conclusions and direction of further work.

2 Relation to Life Improvement

Smart Home and Smart City are two important application areas, where CPS and DT can have significant contributions to life quality improvement. One example can be the road traffic and parking issues, informing the drivers about available parking opportunities or providing information on-fly about the traffic in various city parts to

avoid traffic jams or even consider the usage of public transport instead of a personal vehicle. In the case of the Smart Home, the spectrum of issues that can be supported by the CPS is large. For instance, improving the energy and resources consumption, if the inhabitants of the house forget to turn off the light or water tap, this can be done automatically, heating can be reduced if no one is in the room, etc. By acting collaboratively Smart Homes can improve the energy efficiency even more. For instance, if solar panels are installed and during the day the load drops, the excess of energy can be distributed among other participants of a collaborative community or for the public purpose considering local needs. Moreover, resorting to DT provides the necessary basis for simulating and predicting various aspects from resources usage and needs to human behaviour, detecting the patterns of human habits. Another example is the use of systems to monitor and assist people with special needs to help them living independently [4].

In summary, the integration of physical and virtual spaces can significantly support people in daily activities, from business routine to health care and elderly care. This implies integration of different data flows coming from different sources and building predictive models. In its turn DT can significantly contribute to service evolution, when a service can be updated based on historical data and current status of the physical device or system.

3 Related Literature

Modern Cyber-Physical Systems can be considered as complex systems of systems, incorporating heterogeneous, distributed and collaborating components [1]. These components have a physical part and a cyber part that can be modelled as a digital twin. In this section the evolution path of the DTs is presented along with possible benefits they have for the CPS and in particular for CCPS. An earlier reference to a DT-similar concept goes back to 2003, when the concept of “Digital Thread” was proposed [5]. A Digital Thread at that time was a set of 3D models to represent a physical product for facilitating collaborative engineering. In 2005 the term “Digital Representation” for Product Lifecycle Management was introduced [6]. This concept was closer to the current understanding of DT. However, the term “Digital Twin” started to have a widespread use later in 2010 [7, 8]. A more comprehensive definition of DT, including some intelligent functionality for product life prediction analysis or decision making, was stated in [9]. In a next development stage, DT is also considered to represent the human being within a manufacturing process, whereas emulating the human employee’s behaviour [10]. This aspect was also extended with the creation of DT to represent human organs [11]. In [8] the DT concept was refined to include integration levels and further concepts of Digital Model and Digital Shadow were introduced. To visualise the evolution of DT notion, Fig. 1 presents a brief timeline perspective.

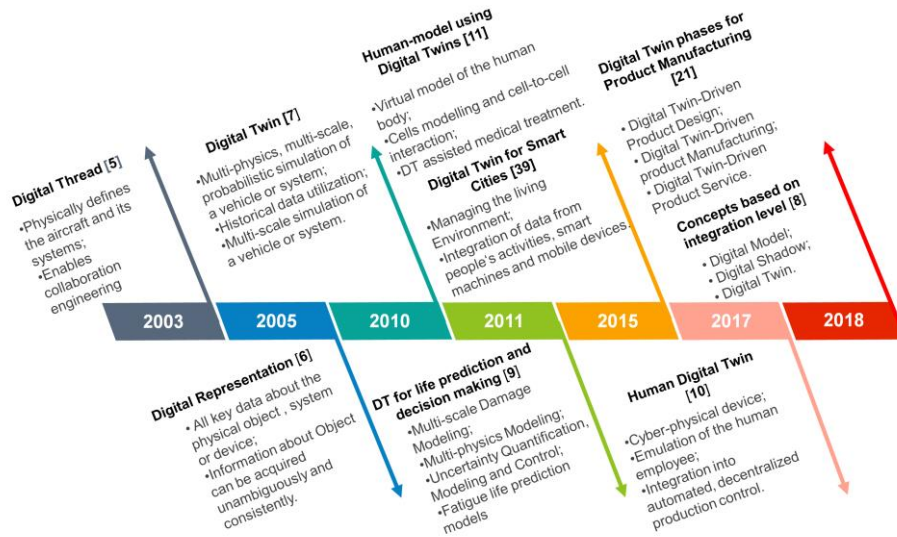


Fig. 1. Some important stages of the DT notion development.

Therefore, there is a need for a definition which, on one hand, is generic enough to be used in various application areas and at the same time extending the various existing partial views of the DT concept. In order to refine the notion of DT and include its different dimensions, [12] introduces 4 levels of virtual representation of an artefact in a virtual space, namely: (i) Pre-Digital Twin – virtual prototype created before its physical twin, (ii) Digital Twin – which is a virtual model of a physical artefact used for exploring the system behaviour in a controlled system environment, (iii) Adaptive Digital Twin – according to which the DT is able to extract the priorities and preferences of the users in various contexts, and (iv) Intelligent Digital Twin – providing not only internal adaptive capabilities, but also considering other entities and subsystems coexisting in the environment, as well as the environmental factors. Moreover, a DT can be considered in terms of scale, thus it can represent a single unit/component/artefact or a complex system or even a system of systems. In [13] authors consider the DT as based on a five-dimensional, three-layered model. Where layers identify the scale of the DT: (i) Unit level (single DT), (ii) System Level (integration of several single DT), and (iii) System of Systems level (cross system interconnection and collaboration). And the dimensions reflect the nature of the DT in conjunction with a service-oriented approach, namely: (i) physical entities, (ii) virtual models, (iii) connections, (iv) fusion data (combination of data from entities, models, etc), and (v) services (functions encapsulation).

An important purpose of a Digital Twin is to capture the behaviour of the physical component or system that it represents [14]. One example is described in [15], where the behaviour of a system is simulated through different modules. These modules

follow the Functional Mock-Up Units (FMI) standard that allows building a single model of a system through adding and combining the models of system components. The modular way of adding new simulation modules is particularly important when considering complex Digital Twins. A Digital Twin includes, according to [16], a “comprehensive physical and functional description of a component, product or system”, possessing the relevant information used during the whole lifecycle of the product/system/component. However, it is very difficult to include all the relevant aspects about the product, as they largely depend on a lot of factors involving interaction with other systems and characteristics of the environment. Thus, the modular approach might enable adding the missing models in consideration with the current status of the system, product or component. Another challenge regarding the simulation process of complex systems is to generate models at the level of components and integrate them for simulation at the system level [17]. This might be even more challenging if the modelled system collaborates with other complex systems or components, as it will require some additional methods to deal with collaborative factors.

The digital twin concept can be considered from different perspectives: (i) digital replica of a device, system or system component, (ii) support for the products during their lifecycles, and (iii) digital representation of human or human organs. Considering the first perspective, a DT can be established based on the information retrieved from the Cyber-Physical System [18], as it possesses data about itself and its components. This information is used to build models of the system and its components or even the buildings where the system is deployed [3]. According to [19], a Digital Twin is, first of all, a “real-time reflection of a physical device being permanently synchronised with a real-world asset”; secondly a “complete integration with physical device assuming the access to real-time data flows”, as well as historical data, and finally allowing verification and analysis of measured and predicted values. Moreover, according to [20], a DT is responsible for condition monitoring, control and real-time simulation. Thus, the notion of the DT evolved from just a digital replica of a physical artefact to a more sophisticated definition including simulation, data analysis, and prediction techniques, interaction with the artefact, user experience consideration, etc.

Another perspective of DT refers to the lifecycle of smart products, from the design and manufacturing to the recycling phases. In this regard the concept of Digital Twin Driven Product Design (DTPD) has appeared [21]. DTPD can be seen as an intelligent support tool for designers, delivering the “information, recommendations and assessments throughout a product design process” [21]. In [22] the authors propose to divide the whole product design process assisted by the DT into several steps:

- Conceptual design – a stage, when the concept and functionalities of the product are defined. It also includes the analysis of users’ feedback and data about product utilization which are delivered by the DT.
- Detailed design – a stage during which the development of the product prototype is accomplished, which also includes the simulation tests. Data can be gathered during the lifecycle of the previous product’s version through the DT, whereas DT can evolve together with the product.

- Virtual verification that is the process of predictive analysis of the product utilization (environment influence, faults, etc.) and manufacturing, before the product is physically produced.

Another paper devoted to Twin-driven Manufacturing states three levels or scales for the manufacturing data aggregation [23], namely: (i) Physical, (ii) Cyber and (iii) Social. Physical data are gathered directly from devices; on the cyber level they are analysed and knowledge is extracted; and on Social level the human-factor is considered. The topic of improving the process of recycling the manufactured products using DT is raised in [24], where four main actors (physical layer) with appropriate product lifecycle stages (cyber layer) are identified as follows: (i) Producer/Distributor – Product Design, (ii) End User – Product Status, (iii) Collector – Logistic and Exam Results, and (iv) Recycler – Recovered Material or Component.

Digital Twins can be also used for human behaviour modelling or modelling of functioning of human organs in order to detect diseases or deviations from the normal behaviour. An example can be the Digital Twin of the human heart. Some research activities are directed towards analysis of cardio diagrams with further classification to detect disorders [25]. This type of Digital Twins can be described as passive, as they only monitor the heart conditions and reason over the gathered data, helping the diagnostics process by doctors. However, there is another type of Digital Twins which can act actively, for instance, being able to regulate the heart rate through the pacemaker, combining both sensing and reasoning parts with actuation [26]. The vision of the future development of Digital Twin in the area of healthcare expressed by Siemens Healthineers is that the whole human body can be represented into a Digital Twin. This might allow early detection of diseases and application of preventive measures. Moreover, this can be used for athletes in order to optimise their training processes. Another example of the application of the DT for human behaviour modelling can be found in industry considering anthropometric data for calculation if the task can be performed by the human-worker or needs to be performed by a robot [27].

Most of the mentioned works are focusing on technical issues of building the DT and mostly ignoring the question if the DTs can be considered as smart entities, which are interconnected and collaborate. Let's assume that fully operable DTs can be applied to all technical systems, buildings or even humans. Then there is a need to define new architectural and methodological principles for developing such environment where they are able to operate. Thus, as every DT is assigned to a real-world object which can change the environment, the possibility of simulating or modelling the outcome is a crucial advantage of the DT. For instance, if the DT can discover other DTs which can provide the necessary functionality to fulfil some need and assess how efficient could be the process of collaboration, it can turn the DT into a more complex entity going far beyond the controlling capabilities. In this regard, some major collaborative challenges are mentioned in [28], namely: (i) Information sharing (internal and external data), (ii) Data ownership, and (iii) Over-dependency (one component or entity is too dependent on another). In this work we aim at contributing to representing the DT from a collaborative point of view with respect to different aggregation and hierarchical layers.

4 Design Approach

As Collaborative CPS are complex systems containing smart/intelligent and autonomous components, thereby their design is a non-trivial task. This requires new approaches for the design process to give developers a clear understanding of the whole workflow. Some research works in the area even go further while combining systems' design with product's design, following the V-model approach [29]. The issues of modular CCPS design appear in the scope of some research groups such as in [30]. However, most of the authors agree, to some extent, on similar design steps [29, 30, 31], namely: (i) requirements clarification, (ii) selection of technical tools and approaches, (iii) structuring the developed system, and (iv) technical implementation.

For our research, the design science research methodology presented in [32] was chosen. This approach combines the behaviour-science and design-science paradigms and comprises three pillars: Environment, Information System Research, and Knowledge Base, with appropriate relations among these pillars. In our work the Application domain is equivalent to the Environment, as it defines the problem space, the CCPS Design pillar corresponds to the IS Research, containing the Development and Evaluation phases, and finally the Knowledge Base accumulates foundations and methodologies along with reference models, methods, frameworks, instruments, etc. One of the advantages of the adopted design method compared to some others [29, 30, 31] is, that it considers the Knowledge Base for accumulating the knowledge generated during the design process, but also allows importing and reusing some key technical models and approaches to support the workflow in the CCPS Design. Another work [33] considers reusing knowledge generated during the design process, dividing generated knowledge in two key categories – system models and verification methods, but the presented design framework does not reflect in detail input parameters from the application area. A second advantage of adopted method is that it supports iterative design, which is also the case of some other methods [31], [29] in which, however, iterative design is only considered between System Design and Expert Design blocks.

Digital Twin can be considered as a key component of the CCPS. On the stage of Pre-Digital Twin the concept is used in order to test various aspects of the designed system. During the development stage, physical artefacts which are implemented within the system are having the digital replicas which allow controlling the physical assets. Adaptive and intelligent DTs can supply the necessary data on how to improve digital models in the knowledge base, as well as better adjust the entities developed within the CCPS design pillar to user requirements identified in the Application Domain, as well as ensure the evolution of the developed system.

The framework based on the adopted design method described above is represented in Fig. 2.

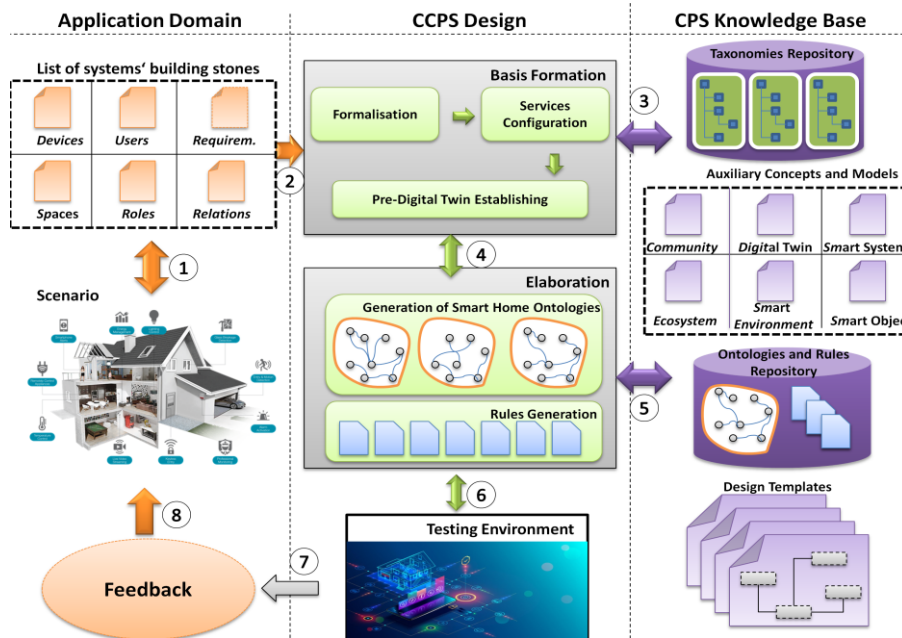


Fig. 2. CCPS design framework inspired by the Design Science Research method.

The proposed framework includes three pillars:

- Application Domain;
- CCPS Design;
- Knowledge Base.

The Application Domain contains some basic building blocks for the CCPS Design workflow, among which are lists of: roles, devices, spaces, users, requirements and relations. These are extracted from the problem stated within the scenario (1). The Application Domain is also receiving feedback from CCPS Design workflow (8) to adjust deliverables with the defined requirements and problem stated within scenario (7). It is important to mention that there are no clearly defined services or detailed descriptions of devices, but only a set input parameters and components at this stage/in this pillar.

The next stage – CCPS Design, is the core part of the framework. It contains three blocks:

- Basis Formation, which is intended to formalise the building blocks retrieved from the Application Domain (2), whereas loading the models and taxonomies from the Knowledge Base (3), as well as keeping the models and taxonomies up-to-date. A taxonomy, in this case, serves the goal of classification of items or components exported or loaded from the Application Domain. Subsequently the capillary

services to satisfy the needs and requirements received from the Application Domain, are configured. The final step is formation of DT prototypes or Pre-Digital Twins frames – virtual prototypes to be launched in the *Testing Environment* to validate the design process outcome;

- Elaboration, which aims to generate ontologies based on taxonomies delivered by Basis Formation block (4) and generate the rules for appropriate functioning of the system. Rules specify the conditions of how the components collaborate with each other. CCPS Rules and ontologies might be exported to the Knowledge Base to be reused in the future (5). An example of rule can be, for instance, a rule regulating the order of tasks executed in regard to daily electricity consumption. At this stage new collaborative forms and complex collaborative services can be formed. Testing Environment is, in fact, a test bench for the system models, generated during the CCPS Design workflow. Thus, Testing Environment is launched at the run-time, whereas previous stages CCPS Design pillar are implemented at design-time. The entities, which are executed inside the Testing Environment, are the Pre-Digital Twins aimed at testing and validating designed system in a virtual environment to fix the problems and adjust all components and services (6), before building the system's physical part.

The Knowledge Base pillar accumulates the base knowledge that can be used during the design process and provides technical tools and models. Examples of the Knowledge Base can be found in the literature [34], where it is used to support digital twins and containing domain ontology and its associated rules. In the current work this pillar is used to support the design of the whole Collaborative CPS including the DTs. The main idea is to provide to the designer some ready-to-use building blocks, which can be used to build the system's core elements. Moreover, its content can evolve as a result of the processes happening within the CCPS design pillar. Key constituents of the Knowledge Base include:

- Rules and ontologies: The rules can be considered from several viewpoints: as internal rules for the Smart Components and global rules which are applied to the environment where the entities are deployed [35].
- Design Templates repository: which encapsulates the Model of a Problem and Solution Model. The Model of a Problem [36] is composed of some templates allowing determining the basic elements of the Design Space as input for the Solution Model. For instance, when the designer plans to develop a system in some application area, by choosing a template in the Problem Model she/he will get access to the templates of core components. In its turn the Solution Model provides information about topologies, relations, successful examples of smart objects coalitions, hierarchical interrelations of components, etc.
- Concepts' Models Repository contains important formalized models of key concepts related to CCPS, such as Smart Environment, Cyber-Physical Ecosystem, Smart Object, Digital Twin, Users' Community, etc. It also contains Templates, which are used to provide information about the virtual and physical entities, such as: state, quality of service, etc, allowing high-level abstractions.

5 Example Scenario and Implementation

In this section we present a model of a DT in the context of other concepts that were previously identified and discussed in [1] (Fig. 3), and a small illustrative scenario implementing the proposed model. This model is divided into three layers: Ecosystem, Organisational, and Entities layers. The Ecosystem Layer is the highest abstraction layer which integrates the cyber-physical and social aspects. The Ecosystem itself can be composed of, or in other words, possess other Ecosystems. The Organisational Layer groups technical components as well as humans into the organisational units, namely through the concepts of Smart Environment and Smart Community. At the same time, Smart Environment and Smart Community can be composed, including subordinate constituents. The Entities Layer contains the single entities represented through DTs and/or Human DTs.

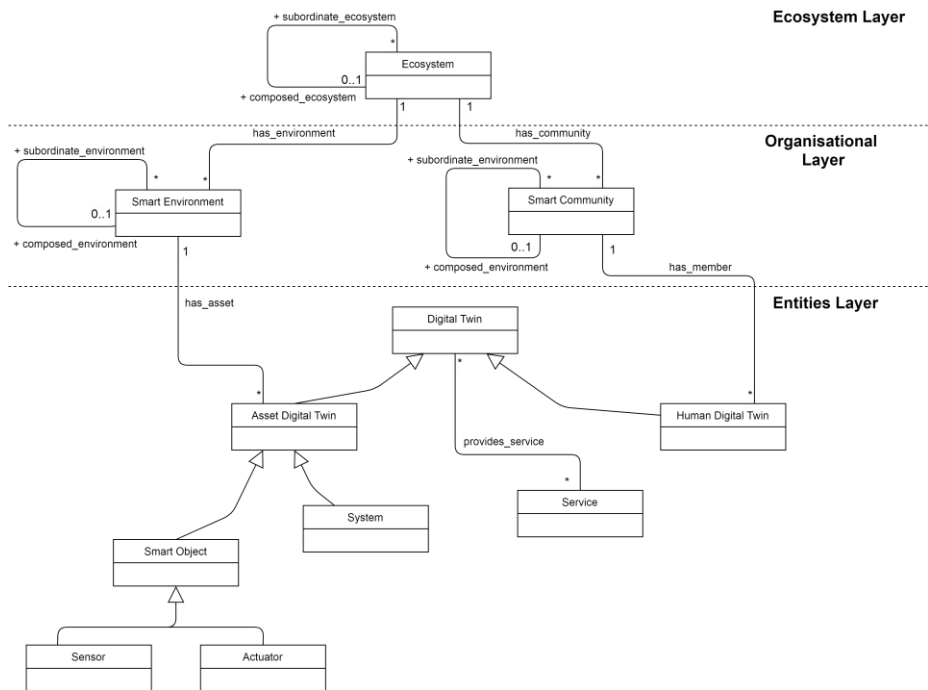


Fig. 3 – Model of Digital Twin with interrelated concepts

Besides the core concepts identified in [1], as for instance Ecosystem, Smart Environment and Smart Community, or the concept of Digital Twin which was discussed in section 3, some other elements require specification. As a DT has a dual

nature, i.e. representing the physical and virtual entities, it includes the model of the represented asset. The model should reflect the attributes of the physical entity, as for instance a sensor (e.g. identifying the measurement units, data type and other relevant data) in order to reproduce the physical asset as a virtual replica. An asset can, on its turn, be a Smart Object, e.g. sensors and actuators, or a (complex) System. On the other hand, the Human DT is representing the Human members of the Smart Community. Separation of DTs into Asset DT and Human DT is needed to consider the dual nature of Human DT. From one side, the Human DT can be considered as part of the system or system asset, but from the other side the human-user is involved in social, administrative and organisational tasks. For instance, a user can own various physical artefacts possessing corresponding role and regulate (introduce new, change existing) the access policy for the other users. The social part is also of big importance, an illustrative example could be the emotional state of the human [40] and how this specific topic can be addressed by digital twins. Thus, the Human DT is the combination of both: (i) being virtual replica of all smart things deployed in or used by the human (e.g. smart bracelets, wearables, pacemaker, etc), and (ii) covering other tasks, such as administrative or social, which are not directly related to replication of physical assets.

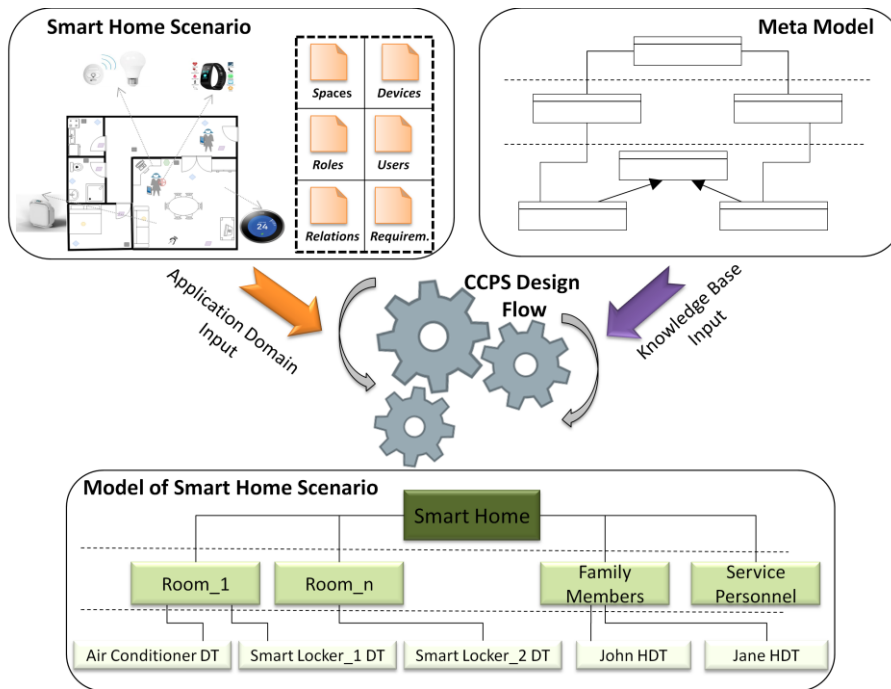


Fig. 4. Illustration of the design process.

For a test case scenario, the Smart Home domain was chosen. A Smart Home can be represented as an Ecosystem (Fig. 4), whereas each room inside a home is an environment encapsulating various devices providing services within this unit. Some services can be provided by several collaboratively acting systems. Thus, a temporary coalition of digital twins can be formed, similar to the one described in [37], thus reflecting the notion of collaborative CPS. Moreover, combining various Asset DTs and Human DTs into the temporary coalitions can improve the variety of tasks that can be solved, whereas improving the context awareness of the system.

Smart Communities are organised based on belonging to a certain group as for instance, “Family Members” and “Service Personnel”. In the proposed illustrative scenario, there are 2 family members, John and Jane belonging to the “Family Members” community. Both are represented through their Human DTs, which can also provide some services, such as “Personal Health Condition Service”. The process of generating the Scenario Model based on the input from the Knowledge Base (Meta Model) and Smart Home Scenario requirements is illustrated in Figure 4.

The Smart Home Scenario part of the design process identifies the number of users, their demands, requirements, responsibilities and groups they belong to with corresponding roles, which in conjunction with Access Policies determine the access to the services of the Smart Home. The Meta Model coming from the Knowledge Base supports the formalisation of the systems’ components, whereas giving the understanding of how those components are interrelated. In the given example, the Smart Home is divided into logical partitions that, in this case, are the same as rooms.

Various services are intended to be deployed within the Environments depending on the needs. For instance, one room can contain services which are not available in the other rooms, or the kitchen requires different level of security assurance than an ordinary room and thus security services can be different inside the kitchen and inside other rooms. In terms of implementation, a prototype of this framework is being developed in Prolog, extended with a library of predicates representing a frame engine. After the framework is finalised, validation procedure is foreseen. The validation procedure is split in two phases: validation through applying the framework to a set of representative scenarios retrieving feedback from the professional community. During the first phase it is planned to apply the framework to several use-cases or scenarios checking the framework’s usability. Whereas the second phase implies collection of the feedback from the conferences and workshops along with usefulness assessment gathered from a focus group of system designers.

6 Further Work and Discussion

The proposed design framework aims at supporting provision for systems’ designers. There are various goals which are in the scope of this particular research: one is to give the designer a clear set of steps for developing a complex CCPS and on the other hand to reduce the time for the designing process through enabling of a set of ready-to-use building blocks, such as taxonomies, concept models and templates. Moreover, this article discusses various types of the DTs depending on the abstraction level or the systems’ design phase and their application in CCPS. The application area is

defined in the Smart Home domain targeting the life improvement aspects. As the life improvement is a very broad term including a lot of notions and ideas, the “theory of needs” is considered in the design framework.

For the next stages we will progress towards completing the implementation of the framework that follows the methodology described in this work. As such, the next stages include the development of: (i) the templates of the models used in the knowledge base to support the development, (ii) developing the set of functions guiding the designing process, and finally (iii) elaborating a set of scenarios (some are already partially mentioned in the current work) for validating the framework. One of the aspects which are only slightly covered within this work is the issue of DT utilization for the system’s evolution, along with DTs being used during all stages of the system’s lifecycle. However, it is partially covered, as the framework assumes the constant update of the Knowledge Base with knowledge acquired during all design phases. Another challenge is the transition from the Pre-DT, being used during the design phase for the testing purposes, and DT that will be assigned to the real-world item or artefact.

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