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Inter-Domain Requirements and their Future Realisability: The ARAMiS Cyber-Physical Systems Scenario

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***Abstract*—Systems whose functionality and services span over multiple, interconnected application domains have become known as cyber-physical system (CPS) and currently receive much attention in research and practice. So far, CPS still come with a variety of development-process-related and technical challenges. These challenges include the interaction between the different domain-specific systems and possible conflicts between their requirements, as well as the choice of appropriate modelling concepts.**

This paper makes two main contributions: First, we show how such an inter-domain development-process can be structured, beginning with a a model-based requirements engineering approach. In order to illustrate the concepts, this paper provides a continuous example scenario, developed within a group of the respective domain experts, that outlines the future of mobility using technologies currently under development in the ARAMiS project. The intention is to allow for an analysis of interaction and possible interference between domain-specific scenarios as well as the analysis of the relation between derived domain-specific scenarios and the global, cross-domain scenario. Second, we provide an analysis of the realisability of the scenario steps according to a set of quality criteria and estimate the respective time horizon, derived from interviews with experts from different domains.

The described scenario allows the reification of goals and requirements of CPS for the mobility domain. Moreover, it makes apparent the need for connecting CPS of different domains. Our validation research provides an accompanying resource for future analysis of the interaction between domains and the relation between their requirements as well as teaching requirements engineering in the domain of CPS.

I. Introduction

ADVANCED features in the mobility domains of automotive, avionics and railway require high-performance computing technologies for complex processing or increased networking, as current technologies used in control devices run up against their performance limit. Future control units will have to perform a greater number of more elaborate functions simultaneously.

One class of such systems with the challenge of integrating different system types are cyber-physical systems (CPS). CPS are integrations of computation and physical processes. Lee [6] defines CPS' as embedded computers and networks that monitor and control physical processes, usually with feedback loops where physical processes affect computations and vice versa. The functionality provided by CPS enables us to realize complex business processes, or complex logistic services as in world-wide travelling.

a) Problem: Today there are typically no or only few shared domain-spanning development artefacts. As a result, domain-spanning RE artefacts are not or only in few cases documented. This results in system functionality which may be adequate for the individual domains, yet cross-domain topics of interests and analyses of interaction and mutual interference between multiple domains are neglected. Furthermore, as domain-specific requirements are located in each individual domain, there is no possibility to link requirements between different domains or associate a common rationale on the CPS level.

b) Contribution: Our comprehensive CPS scenario spans over the relevant mobility domains (automotive, railway, avionics) such that cross-domain topics of interest permit the analysis of interaction and mutual interference possibly arising between domain-specific scenarios as well as the analysis of the interplay of each domain-specific scenario with the global, cross-domain scenario. Furthermore, we provide an analysis of the realisability of the scenario steps according to a set of quality criteria and estimate the respective time horizon.

II. Background & Related Work

A. Systems of Systems (SoS) & Cyber-Physical Systems

The software engineering community has developed methodologies to cope with the engineering process of large systems. The term **S**ystem **o**f **S**ystems (SoS) was introduced to characterize such large systems. Shenhar[10] defines SoS as "a large widespread collection or network of systems functioning together to achieve a common purpose". SoS thus stand out because of their composed nature, their large scale, their decentralized control mechanism, their evolving environments, and their large number of stakeholders.

One class of systems of systems with the additional challenge of integrating different system types are cyber-physical systems (CPS). CPS are integrations of computation and physical processes. Lee [6] defines CPS' as embedded computers and networks that monitor and control physical processes, usually with feedback loops where physical processes affect computations and vice versa. This leads to complex functionality that spans a variety of application domains. A helpful overview with a body of knowledge and links to further reading is provided on http://cyberphysicalsystems.org/.

From a more technical point of view, [3] characterises a CPS as system with embedded systems, which may directly record physical data using sensors and affect physical processes, evaluate and save recorded data, is connected with one another and in global networks via digital communication facilities and uses globally available data and services.

Vincentelli et al. [9] and Gezgin et al. [4] discuss the challenges of designing CPS and propose to use contract-based design. Dillon et al. [2] present a case study that presents a framework to link a CPS to the web of things. Lin et al. [7] offer a case study on intelligent water distribution by the integrated simulation of CPS. Huang et al. [5] perform a case study on CPS for real-time hybrid structural testing.

All of these works focus on design and/or implementation instead of requirements and do not provide a case study that reflects and describes the complexity of a large CPS. This is the gap the paper at hand intends to fill.

B. *The ARAMiS project*

The German academy of technical sciences (acatech) has recently completed a study on the perspectives in CPS research, development, and application [3]. This study serves as scientific basis for the publicly funded research project ARAMiS: Automotive, Railway, and Avionics in Multicore Systems (see http://www.projekt-aramis.de/). The main goal of ARAMIS is to provide for the technological basis for improving safety, efficiency, and comfort in the mobility domains of automotive, railway, and avionics by using multicore technology. The insights gained in the project build the indispensable foundation for the successful integration of embedded systems to cyber-physical systems. The structure and decomposition of the ARAMiS systems of systems, the CPS', is depicted in Fig. 1.

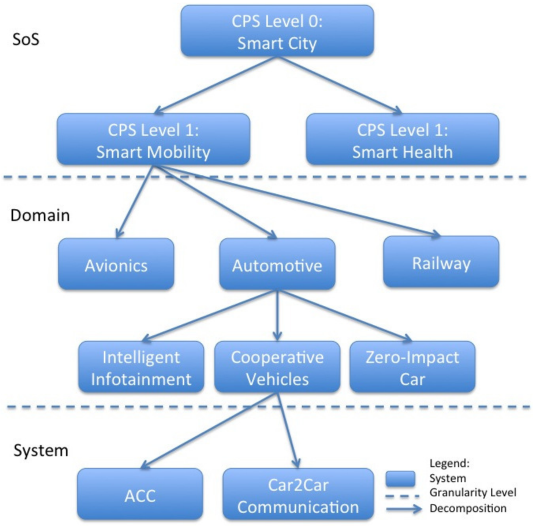

Fig. 1. The ARAMiS structuring and decomposition of SoS

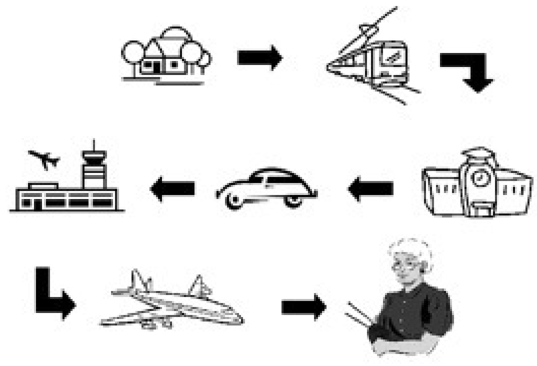

Fig. 2. Overview of the journey

III. The ARAMiS CPS Case Study

A. *Methodical Approach*

The CPS scenario was developed in a combination of top-down and bottom-up approaches in the following phases: We sketched the scenario in a creative workshop and described the initial storyline (top-down). Then the scenario was reviewed in various workshops with domain experts and the storyline was extended with domain-specific contents (bottom-up). In the next phase, the scenario was specified according to the project-wide reference artefact model [8]. In another series of workshops, an assessment scheme was defined to evaluate the realizability of the individual scenario steps and the assessment was performed by a group of domain experts. Finally, concrete requirements were derived from the scenario steps and the assessment results to provide a rationale and an explicit relation to the domain-specific case studies.

B. *Scenario Description*

The scenario's starting situation is as follows: Ms Rosemarie Weber plans to spend the next Christmas break with her two children at her mother's, Ms Pauline Mayer. The Weber family lives in Munich, Ms Mayer lives in Sandvika near Oslo. Ms Weber's intention is to pick up her children from school and from there to travel directly to her mother.

Ms Weber enters departure time as well as from and to locations, a maximum cost amount for the entire route as well as passengers' names in the Travel Management Service (TMS) of her smart device. The mobile device is connected to various providers and to Ms Weber's private cloud, and makes suggestions for the trip. In the following, the individual steps of the envisioned scenario are described.

1) Leaving Home: Ms Weber accepts the TMS's suggestion with the proviso that the car be hybrid and capable of autonomous driving. The TMS issues a ticket for Ms Weber's ride in the urban railway, a car reservation according to her preferences, and three flight tickets from Munich to Oslo; name and age of the passengers as well as Ms Weber's possibly further preferences are stored in the cloud.

2) Local transportation (from home to school): Shortly before departure Ms Weber gets a notice on her handheld device about the current status of the local transportation train. As the train is delayed, she takes the opportunity to call and have a little chat with her mother. Afterwards she leaves her home; as she and her children will be away longer, the home is automatically locked, energy saving mechanisms of all devices are enabled, lights are switched off and the home security is activated. Finally she reaches her train on time.

3) At School: Due to the cancellation of the day's last lesson, Ms Weber's children are allowed to go earlier to their day-care centre nearby. This occurred once Ms Weber already set off to school, and she is informed via her smart device of the new location where to pick up her children. At the day-care centre, the children join their respective project teams, organized to collaboratively do their homework. The younger child's group is not yet done with the homework by the time Ms Weber arrives at the day-care centre. Spontaneously, the group members decide to stay a little longer and complete their task. Given that Ms Weber and her children have a plane to catch, the homework group resolves to keep in touch with the leaving child by means of the videoconferencing support put at disposal by the infrastructure.

4) Car-Sharing (from school to airport): For the route connecting the school with the airport the TMS booked an e-mobility car of a car-sharing provider. Ms Weber picks up her dedicated car in front of the school. The car has her driver profile already preloaded, so that the seat and entertainment system is automatically adjusted to her preferences. In addition, the discussion of her child's homework group is streamed to the in-vehicle infotainment (IVI) system and distributed to the corresponding rear-seat screen. As Ms Weber and the two children enter the car, the navigation system starts and suggests the most efficient route to the airport. The IVI offers Ms Weber to book the "premium lane" on the autobahn, which includes a guaranteed arrival time at the airport as an option. The car leaves the parking slot automatically and integrates itself in the traffic flow. The traffic lights are taken into account in two ways. On one hand, there is a coarse-grained traffic dynamics reduction that is triggered by the (smart city) backend in communication with all connected cars. On the other hand, there is direct communication between traffic lights and cars that provides fine-tuning with more precise local information, including an analysis of movements in front of the car. During the drive on the autobahn, the car is being automatically alerted by car-to-car communication about an approaching rescue vehicle on the "premium lane". The car informs Ms Weber, immediately changes lanes, and reduces its speed. In this car-to-car communication, the rescue coordination center informs the rescue vehicle about the accident location to ensure quick appearance with the most up-to-date traffic information.

Back on the "premium lane" the car's speed is controlled by the supervisory TMS. The TMS detects unconnected cars and monitors them using cameras. The performance of unconnected cars is taken into particular consideration during traffic control and planning. Suddenly the car in front brakes, but the collision can be avoided as the optimum evasive maneuver is initiated by the TMS and applied to all connected cars. Unconnected cars are considered accordingly in the scenario; see Figure 3. Thereby, the emergency brake application is calculated within the vehicle and the information is forwarded to the backend. By Car-to-X communication, the braking maneuver is also broadcasted to other vehicles in the direct neighbourhood. This information about braking maneuvers is collected in the backend, to issue a general warning to the traffic section in case the traffic is prone to producing a traffic jam or an accident.

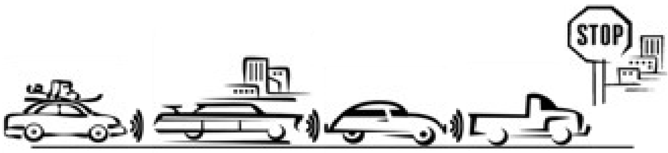

Fig. 3. Avoidance of collision

Close to the airport an Unmanned Aerial Vehicle (UAV) registers heavy rain at position "A (48.456303,12.148819)" with wind direction SE. This information is sent to the TMS, which communicates the upcoming weather situation to every intelligent Road-Side Unit (RSU) within a suitable radius. These RSUs collate the information received with the data they locally sense (wind, rain). The TMS analyses if there is a risk of aquaplaning, in which case a number of actions are taken: unconnected cars are warned using traffic signs, cars equipped with advanced navigation systems are informed in real-time through the system, cars with car-to-x (C2X) close-range communication capabilities receive the warning through nearby RSUs (802.11p) and adapt to the slippery road, and autonomous driving convoys lower speed automatically. Ms Weber arrives at the airport; the car stops and parks in front of the departure entrance according to the flight details, which are sent to the car through the TMS and frequently updated. Ms Weber and her children get out of the car, and label and dispatch their luggage using the automatic check-in counter at the entrance. The car drives autonomously to the parking deck for e-mobility cars of the respective car-sharing provider.

5) Flight (Munich towards Oslo): At the gate, the flight is announced and Ms Weber and her children embark the plane and take their reserved seats. After the boarding is completed, the aircraft takes off in the direction of Oslo.

When the plane has reached a certain height and changes to cruise flight mode, the passengers are allowed to use their personal electronic devices to connect to the wireless passenger network on-board. After reading the digital version of the on-board magazine and ordering drinks and duty free perfumes, Ms Weber starts to watch a TV series and the younger child connects to the school working group via a video conference tool using his tablet device and re-joins the video session that was already joined in the car to the airport; the security of the data exchanged is guaranteed. After twenty minutes into the flight, Ms Weber is informed on her personal smart device that someone rang the bell at her home. She tabs on the notification on the screen and the video and audio signal from her home's door camera is transmitted to her smart device. She informs the calling neighbour that they will be in Norway for the next few days and wishes him a nice holiday season. Meanwhile the pilot notices a warning on the weather RADAR and is informed by air traffic control that there was a major incident on an oil platform with a huge fire and catastrophic leaking into the North Sea. To ensure the safety of the passengers, the flight is dynamically re-routed by SESAR, but can still reach Oslo with the available fuel. The system organizes the new flight routes of all the planes in the airspace and schedules them to safely reach their airports. To warn the passengers of the expected turbulences, the pilot switches on the seatbelt signs in the passenger service unit and makes afterwards an announcement to all cabin loudspeakers in order to inform the passengers of the redirection. Ms Weber's TMS is informed of the redirection and the plane's estimated arrival time in Oslo. Right after the customer service system prompts her if she would like to notify anybody of the incident, Ms Weber receives a call from her mother, Ms Mayer. The old lady has a headache and would prefer not to drive to the airport to pick them up. So instead of using the customer service system, Ms Weber uses the TMS to change her final destination to Sandvika and the system automatically chooses the next available train to Sandvika and reserves seats in the family wagon in order to ensure that Ms Weber and her children are able to reach their final destination.

6) Railway (Oslo to Sandvika): Once Ms Weber and her children occupy their train seats, she discretely discusses via chat with her mother about Christmas presents for the children. The children notice an attendant talking to a senior passenger. The man's pacemaker detected an irregularity in his heart rhythm; therefore, the Telemedicine System (TS) automatically intervenes: It notifies the train personnel as well as the man's cardiologist. The attendant is guided through the immediate actions to be taken by his smart device. An ambulance with the adequate equipment and remedies is sent to the next train stop, which is to be reached within 20 minutes. The man's health is thus properly nursed.

Ms Weber and her children finally arrive at their destination, where the grandmother cheerfully welcomes them.

C. Model of the Scenario

The scenario was modelled according to the ARAMiS artefact model [8] in the tool Enterprise Architect, which is used project-wide for requirements and system modelling. For this purpose, we developed a profile that provides the modeling elements for the defined content items, such that all requirements documents across the project follow the same template structure and use the same elements.

Figures 4 and 5 depict two exemplary illustrations from the model, namely excerpts of the usage model and the functional hierarchy. There are 23 use cases in Figure 4 which describe the journey in detail and about the same number of overall system user functions in Figure 5 which represent the system-sided realization of these use cases. The use cases were also the basis for the realisability assessment in Section III-D. The models were realized in collaboration among the partners from the various domains and detailed further on the respective domain-specific system levels. Further details of the model can be found in [1].

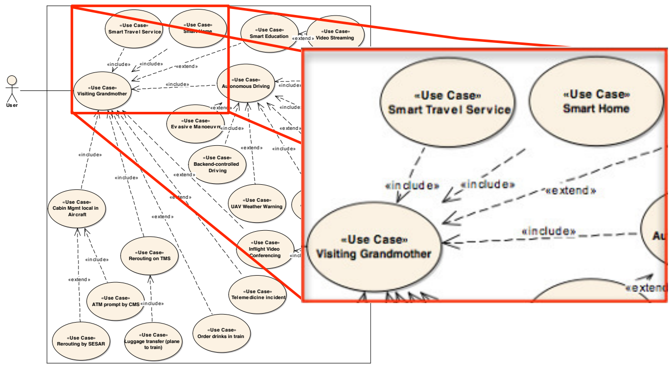

Fig. 4. Use Case Model of the CPS Scenario

D. Technology Realisability Assessments

When describing a future scenario like the CPS scenario, the probably most interesting aspect to assess is the time horizon of the technical realisability of the different parts of the scenario. We performed such an assessment in a number of workshops and in iterations with domain experts. An overview of the results is depicted in Fig. 6 and 7. The domain experts agreed on a list of quality characteristics, for example infrastructure criteria and quality of service criteria, that were relevant to be assessed for judging the realisability of the CPS scenario. We distinguished 3 time horizons (colour-coded in the figures): available today (green), realisable within 5 years (orange), and realisable within 20 years (red). The assessment was performed for all 23 scenario steps in the top row of each table, and for each of the 14 quality characteristics in the first column of the tables. The rationale for each estimation is provided in additional documentation [1]. The time horizon resulting from the justification is coded by colour in the figures for an easy overview of the results. For example, the transmission of a driver profile to a rental car (2nd step "Driver Profil" in the table) and its necessary backend communication (car2backed) is already technically available. This may be implemented in rental cars within the next 5 years (resulting in colour orange), but to actually implement the service, a common data format for driver profiles would have to be standardised among the car manufacturers, which will presumably take considerably longer and is therefore estimated with 10-20 years (resulting in colour red).

IV. Conclusion & Future Work

This paper presented the ARAMiS cyber-physical systems sceanrio, including the methodical approach for developing the scenario, a storyline description, illustrative excerpts from

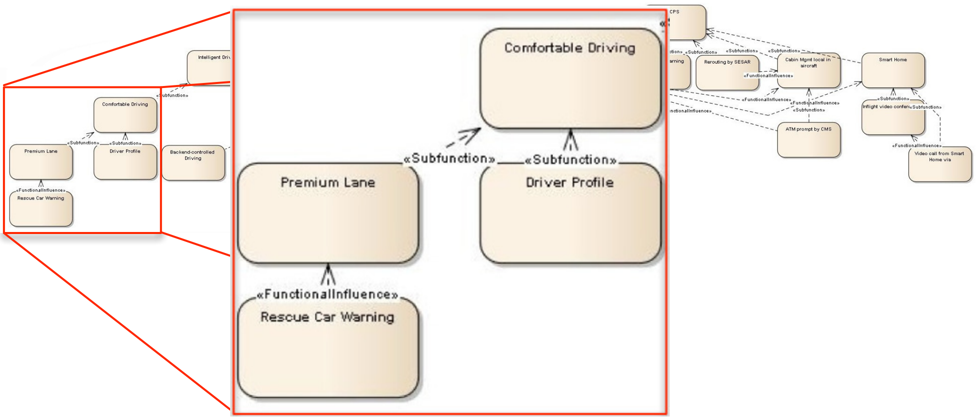

Fig. 5. Functional Hierarchy of the CPS Scenario

Criteria for Realisability		E-mobility										
available today / realisable within 5 years / realisable within 20 years / assumed to be possible		Booking	Driver Profile	Video streaming	Navi-gation	Premium Lane	Autono mous Driving	Backend-controlled Driving	Rescue Car Warning	Evasive Manoeuvre	UAV Weather Warning	Autonomous Car Check-in
Infrastructure	Connectivity											
	Interoperability											
	Portability											
	Performance											
Quality of Service	Security						n.a.			n.a.		n.a.
	Automation											
	Safety		n.a.	n.a.		n.a.						
Reliability												
Availability												
Scalability												
Robustness												
Efficiency												
Adaptivity												
Certifiability												

Fig. 6. Overview of the realisability assessment

Criteria for Realisability					Flight								
		Smart Travel Service	Smart Home	Smart Education	Cabin Mgmt local in aircraft	Inflight video conferencing	Video call from Smart Home	Rerouting by SESAR	ATM prompt by CMS	Rerouting on TMS	Luggage transfer (plane to train)	Order drinks in train	Tele-medicine incident
Infrastructure	Connectivity												
	Interoperability												
	Portability	n.a.			n.a.								
	Performance												
Quality of Service	Security												
	Automation												
	Safety	n.a.											
Reliability													
Availability													
Scalability					n.a.								
Robustness													
Efficiency													
Adaptivity													
Certifiability													

Fig. 7. Overview of the realisability assessment (cont.)

the requirements models, and an overview of the conducted technology assessment. It provides the rationale and the basis for the domain-specific developments in ARAMiS. For the research community, it offers a first available CPS case study of a fictitious system based on real facts targeted for the mobility domain. Therefore, it might serve as input for further research and as a resource for teaching, especially as it might be considered more on the Systems of Systems level, which is a good starting point to educate about CPS. Furthermore, as our paper also provides a preliminary assumption on the scenario parts' technical feasibility in the future, it provides the adequate basis to then go into details with further design-oriented case studies in the respective application domains.

Future Work: The next step is the explicit linking from the domain-specific scenario models back to the overall CPS scenario model in the project-spanning Enterprise Architect repository to allow forward and backward tracing and to provide the traceability for explicit rationale for every requirement in the domain-specific scenarios. The targeted outcome of the project is to provide a showcase that starts with the system of systems scenario at hand and details down to two or three specific use cases in the repsective mobility domains including the demonstrators that show the realization of the prototyped technologies.

Apart from the traceability analysis, we plan evaluation of the quality of the complete model repository to assess the advantages and drawbacks of a cross-domain reference model.

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