Value Creation Patterns for Industry-relevant Model-based Cyber-Physical Systems

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Abstract: Recent development in technology brought Cyber-Physical Systems (CPS) to innovate across many industry fields. However, given the heterogeneous nature of the different integrated components from the virtual and physical spaces, creating a CPS requires high expertise in both engineering and the addressed application domain. Hence, a CPS is complex and time-consuming to design, deploy and test. A model-based approach can tackle this problem by enabling conceptual models to control physical objects and fostering the quick creation of Cyber-Physical Systems. The process logic and decision logic are implemented in re-usable graphical models instead of software code, which makes possible to involve domain-experts early in the design of the CPS. Given the relatively young approach, this paper explores the various model-based CPS that are relevant across industry and how they create value, respectively. For the investigation, a case study research strategy was adopted, which included both literature and a workshop targeting several industry experts. Finally, a pattern matching technique was applied to detect value proposition elements across the created cases.

1 INTRODUCTION

The digitalisation and technological advancement are in the top agenda of industries, governments, and society. This is particularly the case for companies associated with production of high-tech products such as cars, aircrafts, medical devices, computers, processors as well as military and space equipment. The vision of higher competitiveness, higher value-added and increased productivity motivates businesses to pursue research and development of highly advanced industrial technology and applications (Vyshnevskyi, 2020).

Recent applications of Cyber-Physical Systems (CPS) shown to be driving force for innovation in various application domains (Acatech, 2011). CPSs are engineered systems that integrate physical part (i.e., IoT devices or robots) with the cyber part (i.e., the digital representation of the physical part) and offer close interaction between the two parts (Tao et al., 2019). The integration between the two parts allow to achieve a higher level of control intelligence, automation, and communication (Acatech, 2011).

However, the development of reliable automated Industrial Cyber-Physical Systems is a challenge for the high-tech industry (Kravets et al., 2020, p. 198).

According to Lee & Seshia (2017), the heterogenous nature of Cyber-Physical Systems is the major challenge to be addressed. Cyber-Physical Systems are harder to model, harder to design, and harder to analyse than homogeneous systems. The key challenge is to conjoin abstractions about an addressed application domain, e.g. a particular core process of a company, with abstractions that have evolved over decades in computer science, such as programs, algorithms and data structures.

Consequently, the creation of Cyber-Physical System artifacts requires high expertise and specialized knowledge in engineering and in the addressed domain. Numerous engineering loops are required between the engineers and the domain experts, which is a time-consuming engineering practice.

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A way to address this problem is through conceptual models. They abstract away from a certain complexity and conceptually represent relevant aspects of a "system under study" for a specific purpose (Benyon, Green, & Bental, 2012). In the Enterprise Modelling discipline, conceptual models serve as basis for discussions, analysis, improvements, and for the support of decision-making (Giachetti, 2011; Hinkelmann, et al., 2016). Considering that, a model-based approach that makes use of conceptual models promises to support the closing of the gap between the engineering and the domain expertise for the quick creation of Cyber Physical Systems.

However, given the early stage of the approach in CPS, the extend of which CPSs are embedded into successful business models is debatable and can vary from case to case. Since the fundamental basis of innovative business models is the value proposition, this research work investigates the value propositions that emerge from industry-relevant model-based Cyber-Physical Systems. The contribution of this paper is, therefore, a list of model-based CPS use cases that are currently relevant in the industry. The list aims to serve as a basis for experiments in development environment such as OMiLAB[3], thus for the continuous prove about the validity of the model-based approach in the creation of CPSs.

The structure of the paper is as follows: in Section 2 the methodology that was applied to conduct this research is outlined. Next, in Section 3 cases about industry-relevant and model-based Cyber-Physical Systems are described and analysed. Then, in Section 4 patterns are identified through the application of the pattern matching technique and finally a conclusion is drawn in Section 5.

2 METHODOLOGY

This section describes the methodology that was adopted to conduct the research. Respectively, the below sub-section elaborates on the adopted research design and data collection.

2.1 Case Study Research Strategy

The creation of value creation patterns for industry-relevant and model-based CPS was carried out by embracing a case study research strategy. As stated in (Yin, 2003), a case study research strategy is an empirical inquiry that investigates the case or cases by addressing the "how" or "why" questions concerning the phenomenon of interest. It allows gaining a rich understanding of the context of the research and is well compatible with explanatory research (Saunders, Lewis, & Thornhill, 2019), thus fitting the objective of this research work.

A rigorous design for the case study comprising of the following five proposed components by Yin (2003) has been followed:

1. *Question.* The question refers to the query that the case should address. In our case, the main research question was the following:
   - What are the value creation patterns of model-based CPS that are currently relevant in the industry?
2. *Proposition.* The proposition highlights the issues that should be examined within the scope of the case study. In our case the proposition refers to the value creation elements that are associated to the industry-relevant model-based CPS.
3. *Units of analysis.* It specifies what should be analyzed elucidating what the case is; it is related to the way the research questions are defined. Unit of analysis is defined as the model-based CPS of the different application domains.
4. *Logic linking the data to the propositions.* It anticipates the possible steps involved in the data analysis (e.g., pattern matching). In our case explanation building and pattern matching were used as techniques for data analysis. Namely, first it is explained how the identified industry-relevant model-based CPS are capturing values and then the pattern matching technique is used to identify the value creation patterns of model-based CPS that are currently relevant in the industry.
5. *Criteria for interpreting the findings.* A case study analysis strategy is to identify and address rival explanations for the findings. Hence, by addressing rivals the strengths of the findings can be interpreted. In our case findings about the value creation of each model-based CPS are consolidated and compared with the theory. The data collection for the respective findings is described in the following sub-section.

2.2 Data Collection

To ensure the quality of the case study investigation, each case is constructed by considering two data

[3] https://www.omilab.org/

sources: literature review and a workshop with industry experts. Namely, a systematic literature review was performed which first considered a number of relevant keywords (e.g., model-based approaches for cyber-physical systems, industry-relevant cyber-physical systems) and then a list of selection criteria, which is presented in Table 1. In result, four industry relevant model-based CPS were identified.

Next, a workshop was conducted to elicit the value creation of each industry-relevant model-based CPS. The workshop consisted of four focus groups, targeting each of the four application domains. The workshop was set to a duration of 30 minutes. In total there were 25 participants who are in their final year of the Master of Science in Business Information Systems of the University of Applied Sciences and Arts Switzerland. Participants were (1) employed in companies across the industry (2) had a mixed background between engineering and domain expertise, (3) had an average age of 30 years old and (4) were free to select the application domain in which they had expertise. The final findings are reported in Section 4.

During the workshop, the participants were asked to provide structured inputs on the value proposition canvas for the presented model-based CPS. Notes were taken during the observation of the brainstorming sessions, to explain the interpretation how CPS use cases can deliver value. Results from the workshops were crossed checked with literature and the final findings are reported in Section 3.

Table 1: Papers Selection Criteria.

	Selection Criteria for Papers
Included	Papers which present a description and visualisation of a conceptual model of a CPS use case
Excluded	Papers which do not describe a conceptual model of a CPS use case
Included	Papers which present a CPS use case for business purpose
Excluded	Papers which present a CPS use case for non-commercial purpose
Included	Papers which present a CPS use case with the aim of socio-economic enhancements
Excluded	Papers which present a CPS use case for military or other non-socio-economic purpose

3 CASES FOR INDUSTRY-RELEVANT MODEL-BASED CPS

This section describes the four cases that were created following the case study strategy.

The first case relates to the robotic assisted surgery, which is presented in Nagyné Elek & Haidegger (2021). The model includes human components like surgerons, assistants and a patient. Furthermore, physical objects are represented in form of robotic assisted surgial equipment, sensors, cameras, lights, surgical instruments and computers.

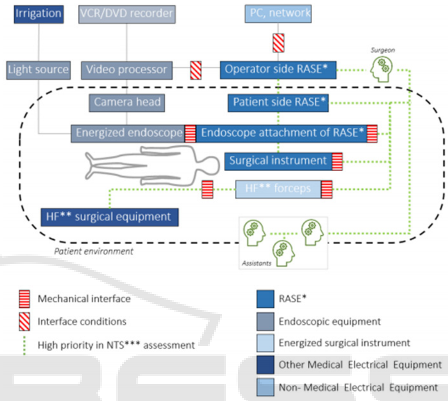

Figure 1: Conceptual Model Robotic Assisted Surgery (Nagyné Elek & Haidegger, 2021, p. 6).

Upon presentation of prior-described CPS use case of robotic assisted surgery, the dedicated focus group was asked to collect inputs through collective brainstorming and discussions. The goal was to brainstorm and structure a value proposition for the customer segment surgeons. Customer jobs were defined as planning, preparing, executing, and documenting surgeries. The focus group started by discussing the pains as administrative work, high concentration required, zero error tolerance and complicated procedures. On the other side gains were described as high-tech materials, highly advanced medical devices, and precision tools. Next, the focus group discussed how robotic-assisted surgery can relieve the prior identified pains. First, it was mentioned that on the cyber part of the system a digital twin of the patient could help the surgeon to plan, model and test certain procedures before execution. Furthermore, a digital assistance in form of a smart workflow which is hosted on a digital platform and represented to the surgeon on monitors, could help the surgeon to remind if process steps were missing. On the physical side of the system, the group discussed that a robotic assisted intervention might achieve a higher level of precision and through that make complicated procedures easier for the surgeons, while reducing the patient risk. In summary, robotic-assisted surgery generates additional value by helping surgeons to increase their performance while decreasing risks.

The findings from the workshop go along with the literature. Lee & Seshia (2017) describe risky procedures like heart surgeries, which often require stopping and restarting the heart. In such procedures robotic assisted surgery might open new opportunities. CPS might be the solution to avoid the artificial heart stop during the surgery. This could be achieved through robotically controlled surgical tools which synchronize automatically with the motion of the heart or a stereoscopic video system which presents the surgeon an illusion of a still heart. However, it is highlighted that the realization of such a surgical system requires extensive modelling of the heart, tools, hardware, and software including a detailed analysis of the models and decisions to ensure highest confidence. Thus, safety mechanisms and fallback behaviors must be programmed to be able to handle malfunctions (Lee & Seshia, 2017, pp. 2-3).

The second case relates to the model-based CPS described by Inkamp et al. (2016). The physical part of the system is represented by the parts, which can be spare parts or raw materials, and the process, which involves human operators, factory, and assembly line workers, and machines, which are integral part of the manufacturing infrastructure. The cyber side of the system is represented by data bases, machine models, planning and controlling systems.

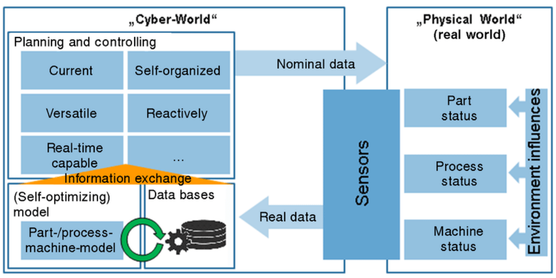

Figure 2: Conceptual Model Cyber-Physical Production System (Inkamp, et al., 2016, p. 326).

A brainstorming with the dedicated focus group on the use case Cyber-Physical Production Systems has been conducted. As such, the customer segment was defined as manufacturing plant managers. The plant managers are confronted with tasks such as overseeing of production, planning and resource allocation as well as taking management decisions. The focus group discussed major pain points around backorders, defects, inventory management as well as complex decisions to be taken. On the other side, the group mentioned that concepts like lean manufacturing, six sigma or just-in-time production represent a gain for plant managers. Furthermore, it was discussed that CPPS can relieve pain points from plant managers in the form of advanced monitoring and regulating systems and ultimately generate additional value by self-optimizing and operating system capabilities. In summary, CPPS generates additional value by helping plant managers to increase productivity and through that managers reach a higher performance while reducing the costs.

The findings from the focus group workshop point into a direction of highly advanced and automated production systems. Literature goes beyond automation and describes Cyber-Physical Production Systems as a combination of highly advanced computer science, information, and communication technologies with manufacturing science (Inkamp, et al., 2016). A practical example of a CPPS is described by Lee & Seshia (2017) as a high-speed printing press for a print-on-demand service. As such, the control motors driving the press which is governed by laws and strategies compensating for paper stretch, temperature, and humidity, whereas the network structure allows rapid shutdowns in case of paper jams to prevent damage of equipment (Lee & Seshia, 2017, pp. 2-3). Thus, artifacts of CPPS are adopted across the manufacturing sector and ideally are also embedded within supply chain systems from other domains, such as transportation and logistics.

The third case focuses on Agricultural Cyber-Physical System, ACPS, which is described by Sharma et al. (2021). The physical part of the system is conceptualized by the warehouse, machines, field, plants and a satelite. The cyber part of the system is conceptualized by the data warehouse, business intelligence applications and a virtual network of interconnected systems.

A brainstorming with a dedicated focus group on the use case ACPS has been conducted. The customer segment has been defined as farmers. Tasks of farmers can be very diverse, however for the purpose of the workshop were defined as managing the farm, planning, cultivating, and monitoring fields. In the

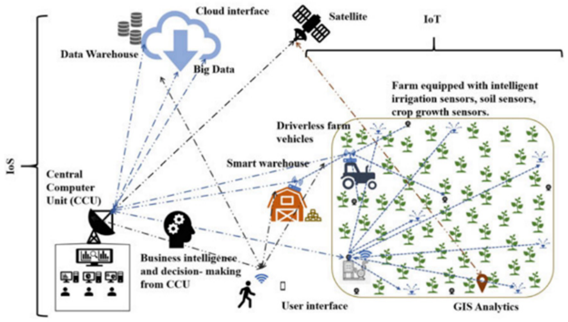

Figure 3: Conceptual Model of ACPS (Sharma, Parhi, & Sishodia, 2021, p. 809).

discussion of the focus group first pain points were described as bad weather conditions or soil erosion, which are difficult for farmers to manage, especially as farmers are facing an ongoing productivity pressure while they must make sure to comply with increasing regulations. On the other hand, if farmers follow the regulations subsidies are provided, which represents a gain. As per discussion of the focus group, ACPS can relieve pains via automation of heavy work in connection with the use of modern technology tools and machines. Furthermore, a gain can be created through the implementation of self-regulating smart systems which adjust according to changing weather conditions to optimize the output. In summary, the hereby presented use case of an ACPS generates value to farmers in form of increased productivity as the performance of existing agricultural processes is enhanced. Also, value is generated in form of customization, as farmers can customize the agricultural production through the modification of the ACPS.

The value proposition described by the focus group points out the importance of data in the agricultural field. This goes along with literature, which describes the concept of precision agriculture.

Precision agriculture is described as an approach in which data is gathered, processed, and analysed and combined with other information to support management decisions to optimize efficiency, productivity, quality, profitability, and sustainability of agricultural production. As such, sophisticated technologies such as robots, drones, temperature and moisture sensors, aerial images and GPS are used. These advanced devices enable precision agriculture that help farms to be more profitable, efficient, safe, and environmentally friendly (Stafford, 2019).

In the fourth case focuses on smart homes and is described by Bakakeu et al. (2017). The physical part of the system is conceptualized by the house. The cyber part of the system is conceptualized by a service platform, which interfaces to a number of external services, such as utilities, pharmacies, doctors, health insurances or supermakets. Aspects like energy management, home automation and health management are self-regulated by the smart house system.

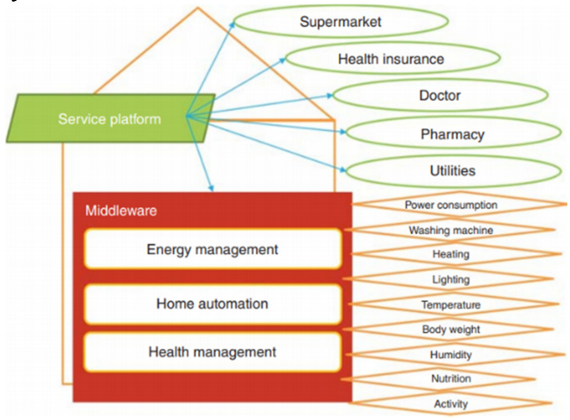

Figure 4: Conceptual Model Smart Home (Bakakeu et al., 2017, p. 629).

A value proposition brainstorming with a dedicated focus group on the use case smart homes has been conducted. The customer segment has been defined as homeowners. Tasks of homeowners include but are not limited to housekeeping, maintenance, or gardening. In the discussion of the focus group first pain points were described as security and privacy. Homeowners invest financial resources and efforts to securing their own home to protect it from burglary. Next, the focus group discussed other pain points, such as housekeeping, maintenance, and high utility costs. Thus, often the described pain points are involved with human efforts or costly services. On the other side, it was discussed that new developments have brought up innovative concepts like cleaning robots or smart kitchen tools, which tend to relieve the pain of housekeeping and maintenance. Also, it was mentioned that owning a house which is located with access to public services like transport, healthcare, education, grocery is described as a big gain. Embedded self-regulating efficiency management systems were described as pain relievers, especially in the context of optimizing the utilities consumption. In summary, the presented use case of a smart home generates value for homeowners in form of convenience, cost reduction and sustainability aspect.

The focus groups value proposition of smart homes goes along with literature, which argues that technology is already part of our social community and will be an integral part of our future homes and buildings supporting an adaptive, intelligent communication in decision making processes. Hence, smart homes or buildings are described as dynamic complex of living beings and intelligent technical devices, which requires a complex interrelationship (Bakakeu, Schäfer, Bauer, Michl, & Franke, 2017). The findings of this section clearly go along with efforts of existing smart home providers, which address comfort, security, and efficiency of utilities as a value proposition (BKW, 2020).

4 VALUE CREATION ELEMENTS PATTERNS

As described by Yin (2003), case study analysis pattern matching logic is one of the most desirable techniques. As this is an explorative case study the patterns relate to how the presented model-based CPS use cases generate value.

Osterwalder & Pigneur (2010) describe value creation as the distinct mix of elements catering a customer segment's needs. Elements listed by Osterwalder & Pigneur include newness, performance, customization, design, price, cost, accessibility, risk reduction, convenience, and usability (Osterwalder & Pigneur, 2010, pp. 22-25). Thus, the following analysis was inspired by the value proposition elements by Osterwalder & Pigneur (2010). However, the challenge of this paper was to analyse the elements of value propositions on the level of use cases rather than products. Elements like design, price, accessibility, and usability are hard to assess as they are strongly product dependent and may vary from case to case. Therefore, on the one hand, these elements were excluded from the analysis. On the other hand, this paper follows an explorative approach and elements which emerged during the data collection, e.g, productivity or sustainability, were included in the analysis.

Table 2 outlines a value creation pattern that is based on the qualitative inputs presented earlier. It can be interpreted that industries with high pressure on productivity, like manufacturing or agriculture can profit from CPS in form of increased productivity. Furthermore, it was found that industries which have a low error tolerance, like healthcare can profit in form of risk reduction. Additionally, CPS also offer opportunities for industries which struggle with high societal pressure towards more sustainability.

Table 2: Value Creation Patterns.

Industry-relevant and model-based CPS cases	Productivity	Performance	Customization	Cost Reduction	Risk Reduction	Convenience	Sustainability
Robotic Assisted Surgery		X			X		
Cyber-Physical Production Systems	X	X		X			
Smart Homes				X		X	X
Agricultural Cyber-Physical Systems	X	X	X				

5 CONCLUSION AND OUTLOOK

This paper explored value proposition of model-based approaches of industrial Cyber-Physical Systems. Upon literature review, application domains of CPS were defined as healthcare, manufacturing, energy, facility management and agriculture. For each application domain one model-based use case was assessed. Dedicated focus groups discussed how value propositions of the presented model-based approaches of CPS use cases can emerge. The findings suggest that CPSs generate value in form of enhanced productivity, performance, customization, cost reduction, risk reduction, convenience, and sustainability.

Before deducting any practical value of the presented findings, it is important to consider rival explanations as per Yin (2003). First, it must be reflected if the observation of the result is a chance of circumstances only. The circumstances presented in this paper are largely dependent on the data collection from a workshop with dedicated focus groups. However, it is argued that based on the logical reasoning of the findings, a replication of a larger empirical study would show similar results. Next, the treats of the validity, such as maturity, instability, or selection must be assessed. The findings presented in this paper are based on a rigorous case study design and the selection criteria has been clearly described.

As a future work, the identified model-based CPS-aware industry use cases can be implemented in OMiLAB infrastructure. Such implementation would serve as a basis to learn more about the employment of a model-based approach for CPSs. Moreover, to assign priority for implementation one possibility would be investigate about to technology readiness level (TRL) of the presented CPSs. Those with the least level could be chosen as first as they would gain more value from the OMiLAB experiment. Finally, the presented value propositions can serve as a basis to continue research about how to embed the presented value propositions into innovative CPS based business models.

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