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Visual Analytics for Cyber-physical Systems Development: Blending Design Thinking and Systems Thinking

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Abstract

Cyber-physical systems (CPS) are integrations of computational and physical processes. They represent a new generation of systems that interact with humans and expand the capabilities of the physical world through computation, communication, and control. At the same time, actions and interventions associated with this complex systems can have highly unpredictable and unintended consequences. Furthermore, today's practices of CPS design and implementation are not able to support the level of complexity required to detect these consequences.

One methodology to approach this complex problem space is systems thinking (ST). Systems thinking emerges as both a worldview and a process in the sense that it informs one's understanding regarding a system and can be used as a problem-solving approach. Systems thinking is an abstraction-oriented analysis approach, specifically designed for heterogeneous complex systems.

At the same time, another methodology, design thinking (DT), has enjoyed significantly increased visibility and importance over the last decade. Design thinking is a creative problem-solving approach, which puts human to the center and focuses first on the needs and experiences of the user.

This paper aims to illustrate the possibility to use design thinking and systems thinking methodologies together to better deal with the complexity related problems during CPS design and implementation. The study proposes visual analytics as an integrative tool between these two methodologies, by (1) analyzing and understanding CPS development process through systems thinking, and (2) innovating and transforming the process through design thinking. To this end, an example use case is described and the application of the blended methodology explained step by step in relation to the use case. Visual analytics and data visualization are discussed in several steps and the possible benefits highlighted.

Keywords: design thinking, systems thinking, data analytics, cyber-physical systems

1 Introduction

The integration of embedded computing systems—physical systems where the computer is completely encapsulated by the device it controls—with networked computing has led to the emergence of a new generation of engineered systems, namely, cyber-physical systems (Möller, 2016). The concept represents the integration of computation, networking and physical processes where CPS range from small to large scale systems (Cengarle et al., 2013). Some example CPS can be listed as smart cities, integrated transport systems, medical devices, production lines, automotive systems, avionics systems, and robotics.

Although the CPS concept is relatively new—introduced in 2006—the organizations, design and production systems and processes are not much different than the environments we used to have a decade ago. We are still using same approaches that we created and developed years ago to overcome the challenges that this new era is bringing. National Academies of Sciences Engineering and Medicine (2016) states the following:

> *"today's practice of CPS system design and implementation is often ad hoc, ... and unable to support the level of complexity, scalability, security, safety, interoperability, and flexible design and operation that will be required to meet future needs".*

In other words, today's practices of CPS design and implementation are not able to support the level of complexity that is required (Törngren & Sellgren, 2018). Moreover, the state of the art research suggests that, with existing systems, we are already stretching the limits with which cost-efficient and trustworthy systems can be developed (Platforms4CPS, 2017).

This study proposes one possible solution to change these practices towards better development environments. For that purpose, we first summarize the challenges in CPS development and then suggest a blended approach to overcome these challenges through an example case study. Before going in deep and explaining the case study, the next subsection summarizes the work done by Törngren and Sellgren (2018) that investigated the challenges related to the nature of the complexity of CPS.

1.1 Challenges in CPS Development

Complexity has been considered by a number of authors, from various perspectives. Sheard and Mostashari (2011) synthesized many of these ideas and categorized the complexity into three categories—structural, dynamic and socio-political.

- **Structural complexity:** mainly considers the ways system elements can be combined. In other words, it is related to the potential for the system to adapt to external needs.
- **Dynamic complexity:** considers the complexity of the system when it is in use and performing a particular task. It occurs over a range of timescales. The ways in which systems interact in the short term are directly related to system behavior; the longer term effects of using systems in an environment is related to system evolution.
- **Socio-political complexity:** considers the effect of individuals or groups of people on complexity.

Törngren and Sellgren (2018) state that future CPS is likely to be characterized by unprecedented complexity. In their study, "systems" refers to CPS itself and also to systems including the humans with which it interacts, the operational context, as well as the collaborative information processing systems that have been used for developing the CPS, related stakeholders and other considerations such as standards and legislation. According to the authors, frequently discussed facets of complexity include heterogeneity (Derler, Lee, & Vincentelli, 2012; Horváth, Rusák, & Li, 2017), size-related facets (Shannon, 1948), uncertainty and change (ESD Symposium Committee, 2003; Sheard, 2015), dynamics or structure related complexity (Horváth et al., 2017; Sheard, 2015), incidental vs. essential complexity (Lee, 2009), and unintended and accidental behavior (Qian & Gero, 1996). They also identified limitations related to collaborative information processing systems—i.e. by human developers supported by computer-aided engineering systems and available information and knowledge. These limitations are listed below:

- Human memory capacity
- Bounded rationality and biases
- Communication barriers
- Information capturing abilities of humans
- Information management
- Interoperability barriers

Törngren and Sellgren (2018) review the various facets, defined the limitations and listed some consequences of complexity such as difficulty to understand, difficult to predict and trade-off, emergence, project overruns (cost and time), not meeting requirements and lack of resources and competencies. This study concluded by highlighting the bridging measures that also correspond to limitations in current methodologies:

- **Software as an enabler***:* Software has a critical impact on end system properties and current development methodologies are falling behind for large-scale systems.
- **Interfaces and interrelations management:** These are everywhere—across systems, components, data, models, tools, and people—and future methodologies need to address cost-effective approaches.
- **Design and architecting:** New methods are needed that can deal with CPS complexity facets, including uncertainty and trade-offs.
- **Processes and organizations for CPS:** These need to be able to explicitly address integration among the diverse aspects and parts of a CPS.
- **Computer-aided engineering systems as assistants supporting humans:** Better support systems are needed for dealing with future CPS. Visualization and augmented reality, traceability and change management, automated analysis and improved support for large-scale concurrent engineering are some example areas with strong potential.
- **Education and life-long learning:** Engineers increasingly need to be able to work efficiently in teams and require a broader understanding than what is provided by a traditional disciplinary education. Considering the speed of technology evolution, there is also a need to promote and develop approaches to life-long learning (Törngren et al., 2015).

This paper aims to review two promising approaches—systems thinking and design thinking—for the purpose of integrating them to overcome challenges related to the development of CPS. To this end, the paper continues with describing the case study in Section 2. The state-of-the-art on systems thinking and design thinking approaches and the idea of integrating them is explained in Section 3. The blended approach through visual analytics is described further in Section 4. Later, in Section 5 the blended approach is applied to the case study. Section 6 discusses the findings of the research, and finally, Section 7 concludes the study.

2 Case Study

This use case is designed to exemplify the usage of the blended approach during development to work on issues related to the CPS' complexity. The next subsection summarizes the use case and the implementation of a dashboard for visual analytics through the blended approach.

2.1 Case Description

an integrated transport system (ITS) is a general term for the combined application of communication technologies, control and information processing for transport systems. ITS covers all modes of transportation—including public transport—and all elements of the transportation system, such as the vehicle, infrastructure, and the driver. ITS allows a series of new unconventional solutions to improve the safety of the traffic and to satisfy transport requirements using new technologies for information processing, communications, control, and electronics around the world (Sanaei & Rostami, 2014). ITS involves a wide range of applications including guidance, control, and information systems. Moreover, ITS aims to improve network flow and safety, reduce environmental impact and introduce new market opportunities. ITS applications can be divided into two main groups: intelligent infrastructure and intelligent vehicles (Sanaei & Rostami, 2014).

This case study is designed to show the complexity of an example ITS that deals with both intelligent infrastructure and intelligent vehicles, and includes several stakeholders with varying concerns about the whole system. In this example case, we will concretely focus on a self-driving taxi fleet project. The project includes stakeholders who come from different background groups such as engineers, system developers, integration experts, designers, planners, business experts, policymakers and system users. The fleet of self-driving cars as a fleet is seen as a future of urban transport and the project could eventually change the transport systems. This kind of ITS projects embraces a broad range of information technologies such as satellite and communications-based information, control and digital technologies. However, even though integrating these technologies offers new possibilities for solving the seemingly intractable problems of congestion, traffic accidents, inefficient logistics, and the environmental impact of surface transportation; considering the various stakeholder's concerns is difficult. Moreover, like many ITS projects, the fleet of self-driving taxis will change the way to access mobility, the idea of car ownership and it will bring opportunities and challenges that we did not encounter before.

With this paper we illustrate how visual analytics and tools from ST and DT approaches can be used together to help ITS development for better, connected, collaborative and automated transport systems while considering viewpoints of different stakeholders and promoting innovation as a strategy.

3 Background and State of the Art

In this section, systems thinking and design thinking approaches are summarized briefly by detailing the processes they consider and the tools used during realization.

3.1 Systems Thinking (ST)

After being proposed by Ludwig Von Bertalanffy (1968) as part of systems theory, ST has been accepted, developed further and applied to different systems. Richmond (1994), a well-known leader in the field of systems thinking, is credited with coining the term "systems thinking" (Arnold & Wade, 2015). His view on the importance of ST in dealing with the complexity states that "interdependency demands systems thinking. Without it, the evolutionary trajectory that we've been following since we emerged from the primordial soup will become less viable", and is supported by many researchers (e.g. Meadows, 2008; Plate, 2010; Senge, 2006)

After considering different definitions from the literature, Arnold, and Wade (2015) expound ST as:

> *"Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects."*

ST is an approach that asks how various elements within a system influence one another, rather than reacting to individual problems that arise. ST inquiries about relationships to other activities within the system, look for patterns over time and seeks root causes.

Pourdehnad, Wexler & Wilson, 2011 reflect that ST replaces reductionism (the belief that everything can be reduced to individual parts) with expansionism (the belief that a system is always a sub-system of some larger system),and analysis (gaining knowledge of the system by understanding its parts) with synthesis (explaining its role in the larger system of which it is a part)).

Several researchers mention the benefits of systems thinking in particular to CPS development. For instance, Jacobson & Lawson (2016) published a book on developing a "Systems Engineering Essence" and exemplify several use cases. This study suggests new systems and software engineering methods to deal with future CPS.

3.1.1 Systems Thinking Process

The main systems thinking model that is used to understand global issues related to systems is the iceberg model (see Figure 1), which typically includes four basic levels (Northwest Earth Institute, 2016):

- **Events:** Represent the manifest components and actions observable to us.
- **Patterns:** Behavioral patterns or trends over time.
- **Underlying structures:** Describe how the parts are interrelated to influence the patterns.
- **Mental models:** Support everything else in the system through a set of beliefs, values, and assumptions which shape stakeholders' perceptions.

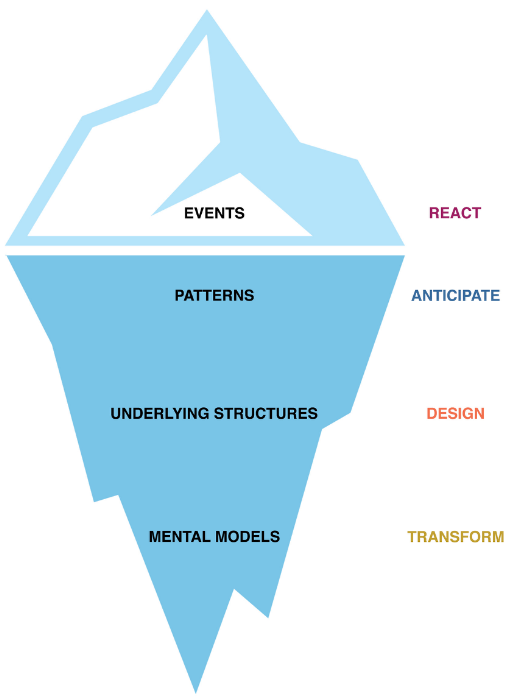

Figure 1. Systems thinking process – iceberg model.

The process starts with selecting a recent event related to the systems that are urgent, important or interesting. The systems thinker is required to write what is observable about the event at the top of the blank iceberg. The important question at this stage is "what just happened?". Then, the systems thinker focuses on repeated events and tries to notice patterns by asking the question "what trends have there been over time?". Underlying systems can be identified by asking "what has influenced the patterns" and "what are the relationships between the parts". Finally, the mental models try to get answers for "what assumptions, beliefs, and values do people hold about the system?" and "what beliefs keep the system in place". It can also be useful to move up and down between these levels and improve the model throughout the process (Northwest Earth Institute, 2016).

3.1.2 Systems Thinking Tools to Tackle the Challanges

Kim (1994) categorizes systems thinking tools into four groups: brainstorming, dynamic thinking, structural thinking, and computer-based. Although each of the tools is designed to stand alone, they also build upon one another and can be used in combination to achieve deeper insight into the dynamic behavior of the system.

3.2 Design Thinking (DT)

Design thinking, in summary, can be defined as "a human-centered approach to innovation that draws from the designer's toolkit to integrate the needs of people, the possibilities of technology, and the requirements for business success" (Brown, 2009). DT emphasizes observation, collaboration, fast learning, visualization of ideas, rapid concept prototyping, and concurrent business analysis, which ultimately influences innovation and business strategy (Lockwood, 2010).

DT primarily concentrates on the needs and experiences of the user (instead of hypothetical system requirements) as a source of inspiration and insight. The objective of DT is to involve different stakeholders in an integrative process, which can be applied to product, service, or even business design. It is a tool to imagine future states and to bring products, services, and experiences to market (Lockwood, 2010).

Cross and Nathenson (1981) stated that designers have specific abilities to

> *"produce novel unexpected solutions, tolerate uncertainty, work with incomplete information, apply imagination and forethought to practical problems and use drawings and other modeling media as means of problem-solving".*

Later, Lockwood (2010) explained that design thinking

> *"is not a substitute for the art and craft of designing, but rather a methodology for innovation and enablement".*

Design thinking combined with decision science results in an infusion of empathy with engineering. This not only ensures a practical and creative resolution of problems but puts the user at the center of applications and at the starting point to develop new products and solutions.

Design thinkers have proven to be more innovative because the design mindset is not problem-focused, it's solution focused and action-oriented towards creating a preferred future. Thus how they think is a subject of interest in many different domains.

3.2.1 Design Thinking Process

The DT process first defines the problem and then implements the solutions according to the user's needs. The five steps of the DT process are (Plattner, 2013):

- **Empathize:** The empathize phase is the work you do to understand people, within the context of the design challenge.
- **Define:** The define mode of the design process is all about bringing clarity and focus to the problem space.
- **Ideate:** Ideate is the mode of the design process in which design thinker concentrates on idea generation.
- **Prototype:** The prototype mode is the iterative generation of artifacts intended to answer questions that help get closer to the final solution.
- **Test:** The test mode is when a design thinker solicits feedback from the users about the prototypes that have been created and offers another opportunity to gain empathy for the people the design thinker is designing for.

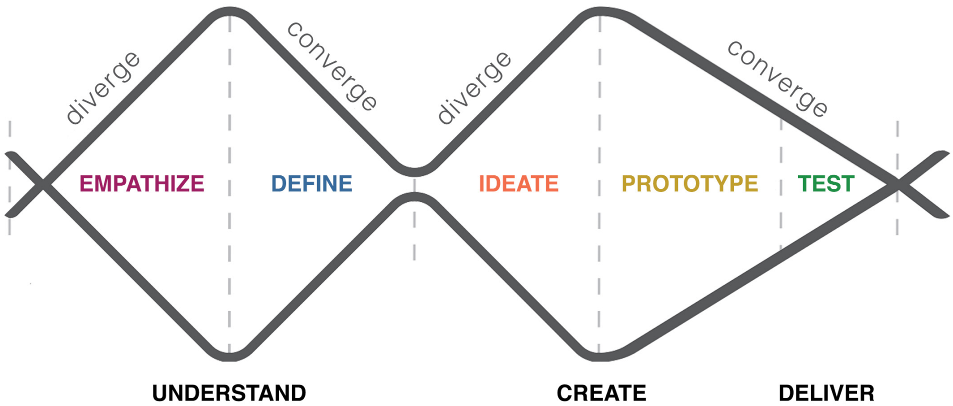

Figure 2. Design thinking processes.

During the DT process, design thinkers are expected to be open-minded, creative and innovative especially during the empathize and ideate stages. Figure 2 illustrates the design thinker's diverge-converge patterns. During the DT process, iteration is fundamental to produce a good design, by cycling through the whole process multiple times but also within each step. It is generally a good idea to create multiple prototypes or try variations of brainstorming topics with multiple stakeholders (Plattner, 2013).

3.2.2 Design Thinking Tools to Tackle the Challenges

IDEO (2014) developed a design kit that supports the use of different methods within projects. IDEO categorized these tools according to the design thinking processes. The three main categories are the inspiration, ideation, and implementation. For instance, tools that one can use for inspiration can be listed as an interview, define your audience, conversation starters, immersion and so on. At the same time for the ideation phase, one can use tools such as share inspiring stories, top five, brainstorm, storyboard, role-playing and so on. Finally, the implementation phase can be done by using tools like live prototype, roadmap, pilot, define success and so on.

3.3 Blended Approach

The complex challenges related to CPS development cannot be solved by one approach, one method or methodology due to the multidimensionality and interlinking relationships between the components of the system. As we mentioned in earlier sections, the need to have an understanding of the overall complexity makes the systems thinking approach logical to start with. However, innovative, abductive transformation can only be possible through the design thinking approach. This study promotes visual analytics as a useful tool to blend the two.

Integrating ST and DT has been suggested earlier by Coughlan and Ponto (2011) as part of Systems Thinking in Action Conference. They proposed a four-phase, twelve-step process that is presented in the study of Pourdehnad et al. (2011) as:

- **Define the Challenge:**
    1. Tell the story
    2. Sketch trends
    3. Name variables
    4. Set system boundaries
- **Ground Understanding:**
    5. Share personal experiences
    6. Explore analogous situations
    7. Identify themes
- **Identify Places to Intervene:**
    8. Make the system visible
    9. Determine leverage points
- **Move Insights to Action:**
    10. Brainstorm many solutions
    11. Prototype promising solutions
    12. Experiment to test solutions

4 Blending Approaches Through Visual Analytics

The use of graphic representations of information is not a new method. In fact, Friendly (2006) began his discussion of the history of data visualizations by looking at pre-17th-century early maps and diagrams. The term, visualization, on the other hand started to be used in 1987 (McCormick, 1987). Visualization is the process of transforming information into a visual form, enabling users to observe the information. The resulting visual display enables the scientist or engineer to perceive visually features (Gershon, Eick, & Card, 1998). In this study, we promote the usage of visual analytics and visualizations to help the stakeholders to understand the system needs of CPS in cooperation with a blended approach.

The work proposed by Coughlan and Ponto (2011) mixes different parts of the ST and DT processes and shows a practical step by step approach to merge them. Figure 3 illustrates each step and related approach(es) with suitable tools for realization. Most of the steps are not easy to categorize as a result of one approach. Identifying themes, making the system visible, brainstorming different solutions, prototyping and experimenting are the steps that one can easily do with either ST or DT tools. In the next section, we will go through these steps and point out which tools are suitable to use and how data visualizations and visual analytics can help to blend ST and DT in each step. However, before going in deep and applying this blended methodology to the case study, the purpose of visual analytics must be explained.

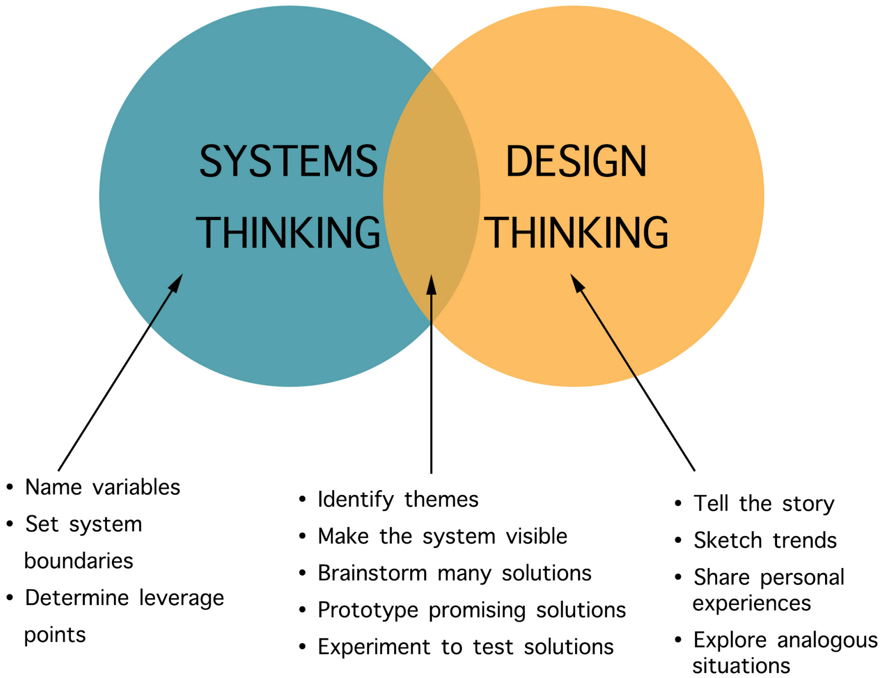

Figure 3. Steps from the study of Coughlan and Ponto (2011) and approaches with suitable tools.

Visual analytics is not only an effective tool to visualize the data beautifully—it also offers an environment for the user to be playful with the data and improves both engagement and understanding of the data set (Gürdür, 2016). Visual analytics supports systems thinking to make sense of complex systems interactions and interrelations, enabling rapid modeling of the systems of interest for systems engineering design and analysis processes. At the same time, during the development of the visual analytics platform, stakeholders have an opportunity to discuss the complex issues of CPS development and can use different DT tools to define and ideate the needs. The stakeholders are thus not only external sources of output, they are also the designers of the solution.

5 Application of the Blended Approach

Before applying the blended methodology one should consider a few points that are important to use in either ST or DT approach. For instance, different stakeholders should be identified; the material, collaboration techniques, and coaches to support the application of the methodology should be ready. DT has several tools to help organizations prepare their teams—establishing team norms, identifying thinking preferences, preparing a team manifesto and so on. For the sake of brevity, in this paper, we go through the 12 steps to integrate the ST and DT approaches but do not cover the earlier processes related to the preparation of the stakeholders or material for applying the blended methodology. While we will go through the steps, we will point out the limitations from the work of Törngren and Sellgren (2018) (See Section 1.1); how blended approach could deal with these limitations; and when visual analytics could use in complementary with the blended approach to support these steps.

The first four steps of the blended methodology concern the definition of the challenge:

- **Tell the story:** The first step is an integral part of DT—storytelling. Storytelling is an essential human activity for sharing experiences, explaining values and deciding on solutions. It plays a key role in enabling change by connecting the meaning to information, creating connections between stakeholders, shifting people's thinking by understanding, expressing empathy and emotion, and making abstract concepts real and tangible. This step is generally missed when we try to solve systems related problems. However, it is an important starting point to ensure innovative and relevant problem-solving activity. One limitation related to the complexity of CPS is the communication barriers among people/team. Starting with telling and listening to the story is a fundamental step towards better communication. For the self-driving taxi case, we suggest allocating time for this activity and give space and time to different stakeholders to listen to each other's stories, needs, and even emotions. Including the users of the transport systems, such as drivers or taxi users, is a vital part of this particular step. When one tries to approach problems such as ITS, it is almost inevitable that different perspectives will be overlooked. Without including the different stories of all stakeholders and empathizing with each other, we cannot find innovative solutions.

- **Sketch trends:** The second step requires stakeholders to sketch trends. In this step, information visualizations are great tools to show the trends, make insights visible to all stakeholders and to start conversations. By this way limitations such as bounded rationality and biases could become less problematic. Several stakeholders have enough data to create information visualizations about the future fleet of self-driving taxis. Municipalities, transport agencies, vehicle manufacturers, taxi companies, users and so on have different perspectives and get affected by different trends in ITS. Visualizing these trends and discussing them together is an effective way to find common ground. This common ground is the only tool we have against the bounded rationality and biases.
- **Name variables:** The third step is about naming the variables. Giving the right name to variables on diagrams and charts is common practice, especially in ST. Even though it seems an easy activity, going through this exercise as a team can bring several fruitful discussions that team members can consider—and make better decisions together as a result. The activity is not only about giving a name to a variable but creating a common language. This language is an important tool which could help stakeholders to communicate without borders. When stakeholders define variables for the autonomous taxi fleet they will consider keywords that some of them never heard about, they will describe these keywords and share the meanings with each other. This activity towards a common language could become a way to overcome limitations related to communications barriers.
- **Set system boundaries:** The fourth step is a vital part of the ST approach—setting system boundaries. One of the challenging aspects of systems is knowing where the boundary lines are that separate the system from its environment, and it often depends on the different points of view (Johnson, 2018). With regard to this specific self-driving taxies case, considering what each stakeholder can provide for an ITS can only be reached by setting the boundaries of the system. In this complex CPS example, one can choose the boundaries of the systems according to the stakeholders. One reason to do this activity is also to identify the need to overcome the limitation due to the interoperability barriers. If the stakeholders know the system and their role in this big system and have the opportunity to discuss the whole system without communication barriers, then we can deal with interoperability barriers.

Then, the methodology focuses on grounding the understanding with the next three steps:

- **Share personal experiences:** The fifth step is also related to the storytelling with a focus on sharing personal experiences on the topic. After setting the boundaries of the system, listening to each stakeholder’s personal experiences for the specific topic is a great way to start to ground the understanding. DT suggests several tools to help in this step, such as talking about different mindsets, developing creative confidence, embracing ambiguity, building empathy by knowing different people, scenarios, and perspectives. This step is another attempt that can deal with communication barriers, bounded rationality, and biases. For the case study, sharing personal experiences about the taxi experience is an opportunity for every stakeholder to have a panoramic view on the subject. This step requires the designers, developers, and producers of the ITS to look at the experience with an eye of the user.

- **Explore analogous situations:** The sixth step requires the stakeholders to explore analogous situations. This exploration is a common tool for a design thinker. The analogous research aims to inspire solutions by looking at the problem from a different angle or looking for situations where similar problems have been addressed (Burn, Winfield, Ish, & Wakely, 2016). This step has the potential to help stakeholders to relate to different problems and solutions and discuss their thoughts on earlier solutions and their relationship with the current problem space. For instance, one can explore the fleet of self-driving taxies project from different perspectives, such as transportation, business, shared mobility, environment and so on, list different solutions that are already in place and share how each can be implemented for this new innovative solution.
- **Identify themes:** The seventh step guides stakeholders to identify themes. This step involves grouping various phenomena into categories and identifying several properties and constituent elements. Identification of themes requires an interactive discussion to achieve a shared understanding of the categorization criteria (Gharajedaghi, 2011). One should define themes clearly and avoid confusion about what each theme is representing at any given time. These themes later would help the limitations related to the information management and interoperability barriers. When developing new ideas on autonomous taxies project, stakeholders are required to categorize the problem space, identify the properties and components of the system and identify the themes accordingly.

Afterward, the methodology identifies places to intervene in two consecutive steps:

- **Make the system visible:** The eighth step requires making system variables visible. Visual analytics become a very powerful tool in this step because they have the potential to improve the understanding of the interrelationships (Gürdür, El-Khoury, Seceleanu, & Lednicki, 2016). Making the system visible through the visualizations is a direct attempt to overcome limitations related to human memory capacity and information capturing abilities of humans. By showing important aspects of the system through data, stakeholders would have insights about the system, share this overview with each other and have a data analytics support to capture important information about the system.
- **Determine leverage points:** The ninth step is about determining leverage points. After making the system variables visible and understanding their relationships, one can easily detect the leverage points by using visual analytics. Different clustering and filtration techniques would guide the stakeholders to see which variables affect which results. Moreover, visually representing these variables helps the stakeholders to discuss problem symptoms, intermediate causes, and root causes. For example, one can have simulations for different parts of the autonomous taxi fleet and through these simulations extract important leverage points. By this way, limitations, such as human memory capacity and information capturing abilities of humans, can be addressed.

Finally, the methodology moves the insights to actions by concentrating on solutions in the last three steps:

- **Brainstorm many solutions:** The tenth step asks stakeholders to brainstorm many solutions. Brainstorming is one of the primary methods employed by both DT and ST in different stages of the processes. It is a great way to generate many ideas by leveraging the collective thinking of the stakeholders. In this step, DT tools especially suggest focusing on one problem/idea, challenge the thinking process with short time, build on each other's ideas/responses and be playful to generate as many potential solutions as possible by being non-critical. After passing all the steps we have described earlier, the team of stakeholders will have a common understanding of the problem, the needs of each individual and common needs of all. They will also have built trust with each other. Throughout this step, providing a non-judgemental and playful environment is the key to innovative solutions. This would not only annihilate limitations, such as bounded rationality and biases but also will help to overcome communication and even interoperability barriers. For instance, it is possible to have an innovative solution idea that normally several stakeholders would not agree to pursue since it has not done before. With the help of earlier steps, the existing trust and empathy would make stakeholders accept and try disruptive ideas easier.

- **Prototype promising solutions:** The eleventh step requires building low-resolution prototypes for the promising solution(s). Prototyping is an important stage of DT. It is also part of ST during the design phase. Prototypes can be used as a hypothesis. Low fidelity prototypes are very useful to test the concept solutions in a short time and, since they are rough representations of the solution, it is easy to change. This step requires the stakeholder to converge and be critical about the solutions as opposed to the earlier step. With the help of virtual prototyping environments, stakeholders can capture the information easier. Simulating autonomous taxies, or visualizing key performance indicators with data provided by different stakeholders, could be used in different iterations of the prototypes.
- **Experiment to test solutions:** The twelfth and final step is about experimenting and testing the solution(s) with users. In this step, the prototype should be iteratively changed according to the users' feedback. This could require more time and different type of experiments, case studies, tests and so on. An important point to keep in mind is to not lose the user-centric approach that has been highlighted throughout the blended methodology. Discussing different prototypes in workshops, meetings or seminars with bigger audience could help the stakeholders to experiment the test solution. This is also an important milestone to re-evaluate several limitations, such as information management and interoperability barriers.

6 Discussion

Philosopher Charles Sanders Peirce (1883) argued that no new idea could be proved deductively or inductively using past data. He found out that new ideas arose when a thinker observe data that didn't fit with the existing model(s). And he concluded that wondering is the key to abductive reasoning and abductive reasoning is the act of thinking creatively. Today we need creative thinking not only in art but also in our organizations and, certainly, when we deal with complexity in CPS.

Organizational theorist James March (1991) comments that:

> *"Homogeneous groups are great at doing what they do well, but they become progressively less able to investigate alternatives. They spend too much time exploiting and not enough time exploring."*

One way towards future CPS is through incrementally innovating the current systems, product, service, process, organization or methods. Small upgrades, improvements in efficiency, productivity and slow innovation rate could be a solution to different parts of the complexity related challenges we are facing today. However, to make a disruptive innovation, to completely changing the existing systems, services or methods, we have to include new methodologies and think differently.

In earlier sections of the paper, we have discussed a way to disturb homogeneous groups by inviting different stakeholders, including the users of the CPS, to take part in decisions related to the systems. Blending DT with ST does not aim to make any of them less influential but rather to integrate the strengths of both to overcome complexity in CPS development.

Usually, there are several stakeholders, divisions, and departments that are interested in user behavior and needs. However, it is nearly impossible to have direct contact with users when we develop complex CPS. This methodology requires the stakeholders to reach out to users, include them as part of the blended approach and listen, empathize, ideate, prototype and test the solutions together. Irrespective of the innovation type or speed we are choosing for innovating CPS to overcome complexity, the human-centric blended approach is a promising tool.

During this study, the blended methodology and its application through visual analytics is discussed. However, the data models, data collection methods, technologies and so on is not proposed. One reason is that the main focus of the paper is to introduce a new way of approaching complexity challenges in CPS other than giving a detailed technical solution. In our earlier study (Gürdür et al., 2018), we have already illustrated how important it is to implement a minimalistic data model for monitoring key performance indicators related with the CPSs development and operations. As a future work, we will focus on the technical and technology related decisions of the solution for this case study to exemplify how a visual analytics approach can be implemented as web-based dashboards.

7 Conclusion

Today, complexity-related challenges are part of every discussion about CPS. These challenges concern software, interfaces, interrelations, processes, organizations, and education. We know that these concerns will continue to be there for a long time and that current methodologies are limited to deal with them. Future CPS will require new approaches to deal with these challenges.

In this paper, we have suggested using an approach to blend systems thinking with design thinking and the use of data visualizations and visual analytics as a tool throughout this blended methodology to develop user-centric and innovative CPS.

Firstly, we described challenges in CPS and explained ST and DT approach in detail. Then, we identified several steps to blend these approaches and used this blended methodology with an example use case to describe applicability, highlighting throughout how and when data visualizations and visual analytics can be used.

This blended approach is not only practical, it is also an innovative way to include different stakeholders and empathize, define issues/needs together, ideate solutions playfully and without criticizing, and come up with prototype solutions in a non-possessive manner. We believe this blended approach incorporates the strengths of both ST and DT approaches. Hence, it is a promising direction to overcome the future needs of CPS.

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