# EMBED-SoSE: Drawing a Cyber-physical System of Systems

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Abstract: The general availability of a robust communication infrastructure facilitates and encourages the connection between everything and anything (Internet of Things-IoT and Cyber-Physical Systems-CPS). The composition of CPSs is a reality. Every day new systems are created from arrangements of legacy systems, referred to as CP system of systems (CPSoS). The constituent systems of a CPSoS have very peculiar characteristics, which hinder traditional systems engineering techniques. In addition, it is common for these systems to present many intangible aspects, which further increases the complexity, especially in the representation of their design. This work proposes EMBED-SoSE, an approach to the engineering of critical systems based on shared visual thinking, which aims to facilitate and reduce the cognitive effort in the systems design process.

## 1 INTRODUCTION

The ease of interconnecting pre-existing standalone computer systems leverages availability and provides a new set of services to users. Such a composition of independent and autonomous systems is called the "System of Systems".

Technologies based on the Internet of Things (*Internet of Things* (IoT)) are considered, by some authors, classic examples of SoS. In general, the IoT strives to facilitate the connection of Everything (IoE) and Anything (IoA) via the Internet as a highly complex SoS set (Bojanova et al., 2014).

Specifically, IoT focuses on the integration of smart devices, where each element can be considered an independent system, with sensors and actuators that directly observe and influence the physical environment, with the potential to provide new disruptive services to our society (Bojanova et al., 2014).

The diffusion of IoT with many connected devices consolidated the Cyber-Physical System (CPS) concept. The Cyber component controls the Physical component because the cyber component has some "intelligence" or, at least, some strategy to lead the physicist to reach a predefined goal. However, the term is used indiscriminately and has become a reference to designate any system that interacts with the physical environment, which is not true (Carreira et al., 2020). Having identifiable cyber and physical components is not enough for a system to be considered cyber-physical; not every IoT is a CPS. So, what characterizes a CPS? It is well accepted that CPS consists of a large-scale SoS, with a large number of components (Constituent Systems (CS)), interconnected, highly adaptive, and that includes human and socio-technical systems (Carreira et al., 2020). More appropriately, these large-scale systems are called Cyber-Physical System of Systems (CPSoS).

Emergent behavior is a fascinating and, at the same time, a disturbing phenomenon in SoS. According to Maier (1998), the operational independence of CSs and emergent behavior is noted as a common characteristic of SoS (Maier, 1998). This feature, which only becomes active or visible when CSs start to cooperate, can provide new disruptive services to our society. On the other hand, risks are associated with unexpected or unintentional behavior resulting from the combination of systems that have individually complex behavior.

As in traditional systems, CPSoS, in a higher degree of complexity, can be represented by a set of tangible and intangible aspects that provide the delivery of actual or perceived values to satisfy the business's needs. The intangibles represent the major engineering and financial efforts required to design and maintain many of today's complex systems. Tangible and

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intangible are, linguistically, terms that refer to elements that may or may not be touched. A car or a satellite, for example, are tangible, while the project plan of these systems, although they can be documented, has an incorporeal existence – therefore, intangible.

The formulation of emergent behaviors can be described by the interaction between intangible aspects of the CSs, which can deliver a new service that will undoubtedly be intangible from the systems engineering point of view. Intangible aspects increase the complexity and cognitive effort to design and develop a CPSoS free of ambiguity.

The considerable cognitive effort required to understand, document, and design a complex system such as CPSoS is intrinsically linked to the difficulty of representing and communicating intangible aspects to project stakeholders. According to Wujec (2009), to define the meaning of something, our brain creates a series of mental models based on the experiences of each individual; that is, each engineer will be able to create his materialization of the intangible aspects of the system. As a result, each project stakeholder will create infinite possibilities for materializing the same intangible aspect, undoubtedly imprecise, uncertain, and full of gaps.

In general, non-functional requirements are addressed by traditional Systems Engineering (SE) and its successors such as Model-Based System Engineering (MBSE); however, the intangible aspects of a complex system such as CPSoS do not receive the same attention due to the difficulty in expressing them. The concern with the intangible aspects is latent in Systems Engineering (SE) and methods that can be more effective in understanding, communicating, documenting, and designing a system that delivers practical value to the business.

In order to meet this need, and considering that emerging behaviors pose the greatest challenges for CPSoS design, this work presents the **EMergent BEhavior-Driven System of Systems Engineering (EMBED-SoSE)**. The main objective of EMBED-SoSE is to bring awareness of emergent behavior to decrease the cognitive effort to represent intangible aspects dynamics and evolution to CPSoS design, to establish a solid conceptual model that provides: a well-defined overview to describe CPSoS, to help investigate emerging behavior and thus create an incremental and iterative cycle of analysis and development to support CPSoS and its maintenance.

The EMBED-SoSE a methodological approach to Systems Engineering (SE) based on two (2) principles: i) to guide engineers in a design concerned with emergent behaviors, one of the CPSoS/SoS characteristics that most impose intangible aspects. ii) support Systems Engineering (SE) through the paradigm of shared visual thinking, with the primary objective of reducing the cognitive effort necessary to understand the intangible aspects of the project and transform them into collective knowledge. This work introduces the new method and is limited to presenting only the first of the processes (EMBED-SoSE Discovery Canvas).

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This article is organized as follows: Section 2 concerns the theoretical basis of the article, briefly discussing the main challenges in a CPSoS; Section 3 presents the main related works; Section 4 presents how the proposed approach (EMBED-SoSE) empowers systems engineering; Section 5 presents its application in a real case of CPSoS, the National Center for Monitoring and Alert Natural Disasters (CEMADEN); Finally, Section 6 presents the Conclusions and Future Work.

## 2 CPSoS CHARACTERISTICS

CPSoS are complex to build due to the inherent complexity of the problems they are intended to solve. In general, they consist of coordinating actions to optimize multiple (possibly contradictory) objectives in systems with a large number of sensors and actuators. The other source of complexity is more of an accidental nature and has to do with the heterogeneity of the systems that constitute it (Carreira et al., 2020).

CPSoS are considered a class of SoS and inherit all their characteristics and pose new challenges in forming a system. CPSoS, according to *Lee (2008)*, are integrations of computing and physical processes. Embedded computers and networks monitor and control physical processes, often with feedback loops in which physical processes affect computations and vice versa. In other words, CPSoS uses the cyber component to interact with physical processes in order to add new resources to physical systems (Lee, 2008) (Tröls et al., 2021).

SoS is the set of independent systems cooperating with a common goal. Independent systems are technically known as Constituent Systems (*Constituent Sys-*

*tems* (CS)).

The ISO/IEC/IEEE 21839 (ISO, 2019) standard provides a definition of SoS and CS: (a) **System of Systems (SoS):** Set of systems or elements of the system that interact to provide a unique capacity that none of the constituent systems can realize on their own. Definition extensible to **CPSoS**. (b) **Constituent Systems (CS):** Constituent systems can be part of one or more SoS. Each constituent is an independent and useful system in its own right, having its own development, goals, and management resources, but it interacts within the SoS to provide the unique capability of SoS. Definition extensible to **CPS**.

Emergent behavior is noted as a common feature of SoS(Maier, 1998). Kopetz (2016) uses a quote attributed to Aristotle to describe the fascinating emerging phenomenon: *"The whole is greater than the sum of its parts"* (Kopetz et al., 2016). The interactions of the "parts" can generate a "whole" with properties that go beyond those of any of its constituent "parts". Moreover, this property makes SoS a system capable of breaking down some barriers of knowledge, generating situations/opportunities that were hitherto unknown.

We use the term "phenomenon" to refer to emergent structure, behavior, or property. In many cases, these phenomena are described and explained only after their discovery, which in most cases are accidental. Formulating all emergent phenomena is an almost impossible task and requires much cognitive effort and financial resources, and indeed, the system's dynamism would lead us to fail in this mission. The first appearance of an emergent phenomenon is often a surprise to an observer (Kopetz et al., 2016). Fig. 1 shows a scheme for the classification of emergent phenomena.

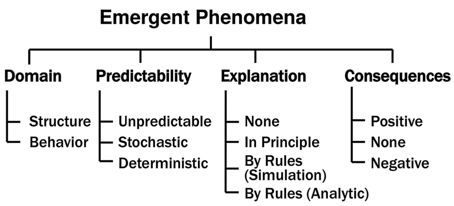



Figure 1: Emerging phenomena classification (Kopetz et al., 2016).

While this "phenomenon" is explainable in principle, we may not be able to explain or predict this behavior in practice due to our ignorance of the full scope of CPSoS, the precise temporal interactions between CS and communication channels hidden behind the interfaces of a CS (Kopetz et al., 2016).

## 2.1 Challenges

In the CPSoS project, not all combinations allowed by Fig. 1 are of interest; in fact, we are particularly interested in the domain of behavior, that is, behavioral emergence. Fig. 2 classifies the emergent behavior of a CPSoS from the point of view of the consequences of this behavior in the general mission of a CPSoS and the prediction or awareness we can have about the emergence of emergent behavior.

| | Beneficial | Detrimental |
|---|---|---|
| Expected | 1 Normal Case | 2 Avoided by Design Rules |
| Unexpected | 3 Positive Surprise | 4 Problematic Case |

Figure 2: Emergent behavior consequences(Kopetz et al., 2016).

The expected and beneficial emergent behavior is the normal case (quadrant 1) that results from a conscious design effort. Expected detrimental emergent behavior can be avoided by adhering to proper design rules (quadrant 2). Unexpected and beneficial emergent behavior is a positive surprise (quadrant 3). The problematic case is quadrant 4, unexpected detrimental emergent behavior (Kopetz et al., 2016). In safety-critical CPSoSs, unexpected detrimental emergent behavior can cause a catastrophic accident.

A conscious design discipline aims to move, as knowledge progresses, more and more emergent phenomena from quadrant 4 to quadrant 2, where measures can be taken to mitigate, eliminate or prevent the harmful emergence (Kopetz et al., 2016).

Still, our knowledge of CPSoS can remain limited, and our ignorance of them can hardly be reduced sufficiently, especially when considering COTS components and legacy constituent systems. Most CPSoS are built by incorporating LEGACY and COTS about which very little is known and where the flow of information is often quite hidden (Kopetz et al., 2016).

# 3 RELATED WORKS

Authors have presented works intending to reduce the complexity and the cognitive effort necessary to understand the behavior of a SoS through the application of appropriate simplification strategies (Kopetz, 2011) (Ceccarelli et al., 2016). The considerable cognitive effort required to understand how a large SoS works the primary engineering and financial effort required to design and maintain many of today's SoSs. The main works/projects that have produced advances in the CPSoS engineering process are presented below:

1. **COMPASS - (2014):** The *Comprehensive Modeling for Advanced Systems of Systems* (COMPASS) project was officially completed in 2014. The proposed approach was based on the relationships and guarantees of the constituent systems that are explicitly recorded in a formal language (*"COMPASS Modeling Language"* (CML)) and analyzed by new tools that exploit the formality of the semantics of the CML to assist in the analysis and guarantee of SoS properties (Holt et al., 2014); 2. **DANSE - (2015):** The *"Designing for Adaptability and evolution in System of Systems Engineering"* (DANSE) project was officially concluded in 2015. The DANSE project developed a set of methodology and tools for the technical management of an SoS. DANSE's methodology and tools are mainly based on the *frameworks* DoDAF, MoDAF and NAF (Mangeruca et al., 2013); 3. **AMADEOS - (2016):** The project *"Architecture for Multi-criticality Agile Dependable Evolutionary Open System-of-Systems"* (AMADEOS) had as the main objective of the AMADEOS project was to bring awareness of time, dynamics, and evolution to *design* of SoS, to establish a solid conceptual model that provides: a well-defined language to describe SoS, to investigate emergent behavior; outline a generic architectural *framework*; and an SoS design methodology that is supported by modeling tools (Bondavalli et al., 2016); 4. **NIST - Framework for Cyber-physical Systems - (2017):** The *CPS Framework* was developed by the *Cyber-Physical Systems Public Working Group* (CPS PWG), an open public forum established by the *National Institute of Standards and Technology* (NIST). The ultimate goal of the *CPS Framework* is to provide a common language to describe interoperable CPS architectures so that these systems can interoperate within and across domains, allowing the formation of an SoS; 5. **MPM4CPS - Multi-paradigm Modeling for Cyber-physical Systems (2018):** The *"Multi-Paradigm Modeling for Cyber-Physical Systems"* (MPM4CPS) project was officially completed in 2018. In 2020 the book "Foundations of Multi-Paradigm Modeling for Cyber-Physical Systems" was published, compiling the design results, which is based on the fact that there is no super formalism to support the multiple design dimensions of a CPSoS, were to design effectively, engineers (in the role of modelers) need to be versed in multiple formalism's (Carreira et al., 2020).

Table 1 demonstrates the comparison between the projects and emphasizes that the EMBED-SoSE does not intend to replace any of the proposals of the projects but rather to cover the gap regarding the concern with intangible aspects and bring emergent behavior's awareness through visual project plan and models. The EMBED-SoSE must use frameworks and models to generate many of the system artifacts necessary for a CPSoS, and in this way, combining the projects can offer great resources for system engineers.

Table 1: Projects comparison.

| Characteristic | Project | | | | | EMBED SoSE |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Artefacts models | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Framework design | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Emergent behavior awareness | | | ✓ | | | ✓ |
| Visual project plan | | | | | | ✓ |
| Concern with Intangible aspects | | | | | | ✓ |

## 4 EMBED-SoSE: DRAWING A CPSoS

In general, the traditional design of a system is developed and documented linearly; that is, a group of artifacts is generated during the project life cycle to support the solution design. However, the relationship between these artifacts is not immediately evident from a cognitive point of view. When seeking to understand the solution, an engineer must interpret and analyze the generated artifacts, and in this process, the answer to doubts may be dozens of pages ahead. Although the project plan and its artifacts are developed linearly, the relationship between its components is multiple, parallel, simultaneous, and branching. In this way, to understand the solution as a whole, it is necessary to create a global view with all the artifacts, which can be pretty complex in systems such as CPSoS.

Specifically, in CPSoS, this complexity is multiplied by the number of constituent systems and the possibilities of emergent behaviors. In this way, the proposal to facilitate the cognition of complex systems is to represent them through shared visual models based on visual thinking. The proposal is to have a model of the system created collectively and, in this way, prevent each engineer or stakeholder from materializing their version of the system. In addition, the proposal uses the strategy of influencing engineers in a design concerned with emergent behavior; that is, the method leaves this concern latent throughout the design process, activating the unconscious creative process. The principle is the same used in subliminal marketing messages. A subliminal message is any stimulus or information exposed to a receiver imperceptibly at a conscious level in an attempt to influence opinions and decisions.

According to Wujec (2009), the better we understand the functioning of the human brain and how it creates meaning and meaning, the better we will be able to communicate and share information; that is, we will facilitate cognition.

In this way, this work proposes the EMergent BEhavior-Driven System of Systems Engineering (EMBED-SoSE), an interactive, visual, and continuous method to facilitate cognition in the process of development and maintenance of a system of systems, as represented in the cycle Fig. 3a.

In general, as proposed by the EMBED-SoSE life cycle, the formation of the System of Systems (SoS) will be directly influenced by its constituent systems (CS) and by the systemic thinking about the emergence behavior. The processes predicted in an iterative and continuous cycle must be executed and supported by visual tools, passing through the processes:

(a) **Discovery:** Its objective is to drive the discovery and evaluation of the solution. This process is one of the main ones responsible for activating the creative process of engineers and stakeholders in the search for the solution; (b) **Requirements:** Its objective is to document and facilitate the requirements elicitation and assessment of a SoSs; (c) **Design:** It aims to build the solution design based on the previous processes; (d) **V&V:** Includes the verification and validation process of the proposed solution; (e) **Development:** Solution development proposed in the previous processes; (f) **Integration:** Solution integration to pre-existing SoSs; (g) **Operation:** In this process, monitoring, evaluation, and maintenance activities of the SoS solution must be performed.
In general, all processes must be based on the EMBED-SoSE visual thinking paradigm, which defines that the entire engineering process must, first of all, evaluate the SoS operation concept after keeping mind in a Think Emergent Behavior, Draw Solutions, Look and Share, as described Fig. 3b.

This work proposes the EMBED-SoSE Discovery Canvas to guide the discovery process through a visual tool where all engineers and stakeholders can collaborate to construct a SoSs or CPSoS. EMBED-SoSE Discovery Canvas is presented by Fig. 4a, and in addition to considering the premises of visual thinking, it takes into account the characteristics and challenges of a CPSoS, as described in the 2 and 2.1. In this way, the Discovery process represents one of the most critical stages of the EMBED-SoSE life cycle, which, in addition to supporting all processes, is based on the EMBED-SoSE visual thinking paradigm. The first canvas model used within companies was created by Swiss Alexandre Osterwalder, the Business Model Canvas (Osterwalder and Pigneur, 2010). The model has become famous throughout the corporate world and has several applications.

The EMBED-SoSE Discovery Canvas was structured to lead and activate the unconscious creative process of engineers and stakeholders, facilitating cognition and inducing the search for emergent behaviors. Based on the challenges presented in the section 2.1, and focused on transforming unexpected detrimental emergent behavior into known and expected cases, the process proposed by the EMBED-SoSE Discovery Canvas must activate and facilitate the neurological mechanisms by which our brain creates its meanings and seeks to solve problems (Kopetz et al., 2016).

Inspired on Roam (2009), it is possible to visually clarify any problem through a visual classification of six basic questions (*who, what, how much, where, when, how and why?*).

EMBED-SoSE Discovery Canvas was structured based on Roam's (2009) observations on problems structuring, in *"WHERE"*, *"WHAT"* and *"HOW"* to facilitate cognition, in the same way to make the consumption of information neurologically as natural as possible, as shown in Fig. 4b.

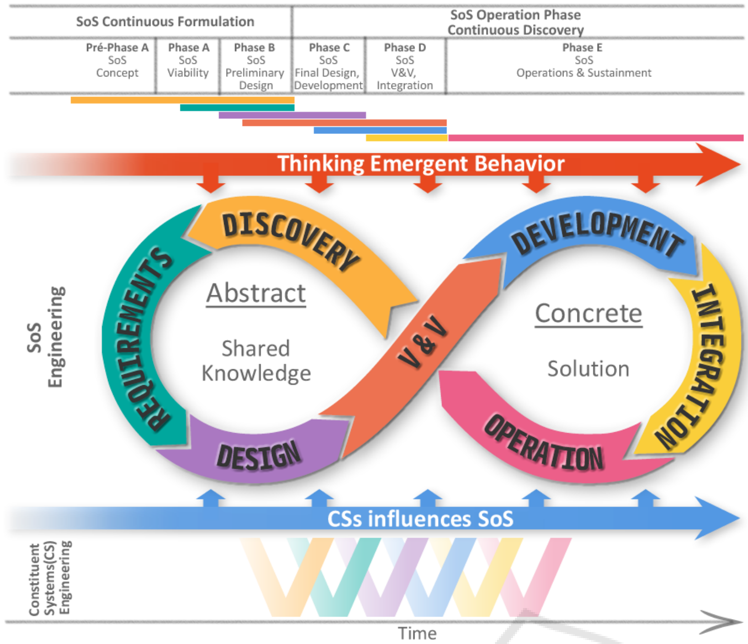
In summary, the EMBED-SoSE Discovery Canvas is a large screen where information about the system architecture will be positioned to create an integrated and shared view of all possible information of interest. The screen has been divided into "WHY?", "WHERE?", "HOW?" and "WHAT?".

The "WHY?" section defines the motivation for which the CPSoS should exist; that is, important information that should support the existence and evolution of the CPSoS is structured. This section is divided into: Justification(Rationale), Objective, Benefits, Strategic Needs, Information Needs, and general rules of the CPSoS.

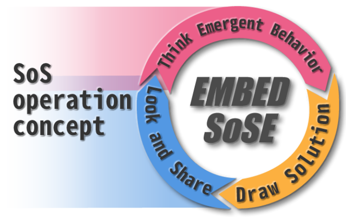
In the "WHERE?" section, the environments where the CSs are located are defined. Understanding the environment where the constituent systems (CS) are located helps anticipate future needs and design appropriate mechanisms (e.g., architectural) that allow adapting the CPSoS adequately to changes in the environment.

The "HOW?" section defines how the CPSoS formation process will be, that is, what are the constituent systems (CS), the interfaces, and their information, as well as how this information will flow.

The "WHAT?" section defines what supports the formation of the CPSoS. CSs Goals are the common and conflicting goals between the CS; and CSs Ca-

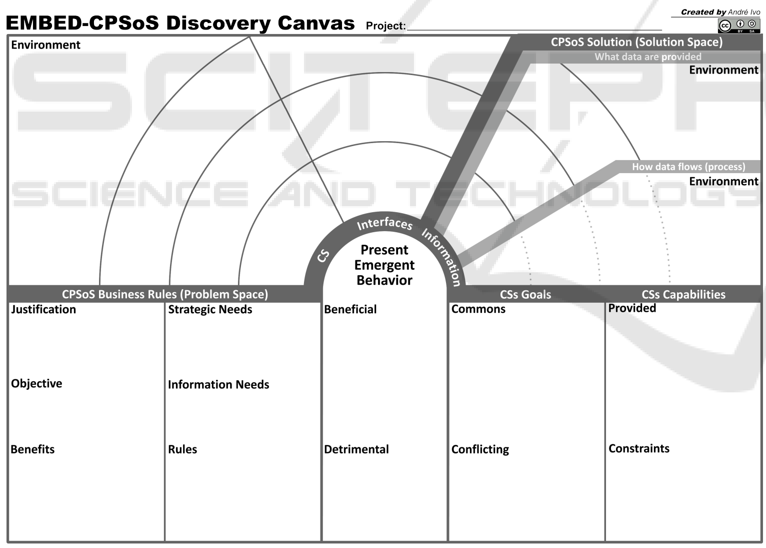



(a) Life Cycle.

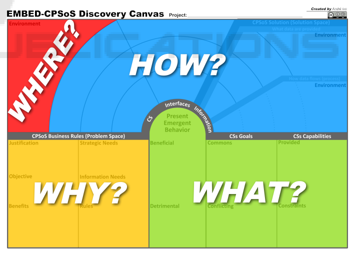



(b) Visual Thinking Paradigm.

Figure 3: EMBED-SoSE.




(a) Canvas.




(b) Explain.

Figure 4: EMBED-SoSE Discovery Canvas.

pabilities and restrictions of each participant system. This section must also capture the main emerging behaviors present in the CPSoS.

In the CSs Goals section, stakeholder needs should be captured as goals. Goals can be captured at various levels of abstraction, from high-level strategic objectives to low-level technical objectives. High-level goals are refined and modeled as AND-OR goal trees. Goals can represent functional and quality expectations. This approach can also be valuable in identifying conflicting goals between constituent systems (CS) and between the CPSoS itself and the constituent systems (CS). It is essential to identify and understand these conflicts because individual systems often prioritize achieving their own goals.

In the CS Capabilities section, the goals of each provided capability must be mapped, in addition to the capabilities and constraints themselves. The mapping of capacity goals can represent advantages and help in the CPSoS definition process. Goals provide a good starting point for identifying the capabilities needed at the system level and relating the problem domain to the solution domain. Capabilities are responsible for providing resources for interaction between CSs.

In the life cycle proposed by the EMBED-SoSE Life Cycle, Discovery is the first and most important of the processes to understand the formation of a CPSoS and directing the development of collective knowledge to the requirements gathering phase that must follow the same philosophy as Discovery.

# 5 APPLICATION EXAMPLE

This section presents an example for improving the national natural disaster alert system, a significant CPSoS maintained by Brazil's Federal Government.

The National Center for Monitoring and Early Warning of Natural Disasters (Cemaden) aims to monitor and issue alerts of natural threats in mapped risk areas of Brazilian municipalities. Besides that, Cemaden also conducts research and technological innovations to improve its early warning systems. (Brazil, 2011). Cemaden operates 24 hours a day, without interruption, monitoring 958 municipalities classified as vulnerable to natural disasters (mainly floods and landslides).

In general, the national flood risk monitoring systems are unconnected to the city siren and containment reservoirs' floodgates control systems. Thus, Fig. 5 presents the EMBED-CPSoS Discovery Canvas application for the design of the Flood Prevention System that connects the systems.

Considering the above, the construction of the EMBED-SoSE Discovery Canvas requires nothing more than a few materials available in the office: those adhesive blocks known as post-it notes and flip chart sheets (Format A1). The sheet in A1 format, segmented according to Figure 4a will be used as canvas. The sheet should be large enough for stakeholders to meet around it and collaborate in the construction process. In practice, the Canvas is built as the concepts represented by the post-its are placed on the sheet orderly and create the necessary relationships between these concepts. Post-its offer an explicit restriction of writing space, which leads to more objective writing.

The first step in the example in Fig. 5 is to identify and fill in the "WHY?" section. Start the process by identifying the problem to be solved. Describe Justification/rationale, objectives, and benefits. Also, in the "WHY?" section, describe the needs and rules/restrictions. The second step is identifying the constituent systems (CS) candidates to contribute to the solution in the "HOW?" section. From the identification of the system, also are identify the environments where they are associated in the "WHERE?" section. Still in the "HOW?" section, the next step is to identify which integration interfaces are available for each identified CS, besides how information can flow between systems and their interfaces. Finally, the "WHAT?" defines what supports the formation of the CPSoS.

The discovery process is iterative, where the visual creation process allows activating the creativity in the group. In this way, the discovery canvas for the flood prevention system was built collectively and visually. Allowing Cemaden engineers to develop the design of the solution in a shared way, where the main difficulties related to the integration interfaces could be discussed and evaluated more efficiently than the traditional engineering model.

# 6 CONCLUSIONS

EMBED-SoSE empowers systems engineering (SE) with the ability to generate a maturity profile for critical and complex systems like CPSoS. In addition, the new paradigm based on visual thinking proposed by this work can generate a radical change in the systems engineering process, allowing the collective construction of a more straightforward and more effective design for the integration of heterogeneous systems such as CPSoS without sacrificing rigor.

The paradigm based on the visual thinking of EMBED-SoSE, when concerned with emerging behaviors that deliver value to the business, will consequently be concerned with the main intangible aspects of the system and how to materialize them collectively, which allows the creation of shared knowledge, reducing the cognitive effort to understand the project among the Stakeholders.

The ability to simplify the engineers' cognitive process allows for a much more straightforward assessment of system-level behavior and, depending on accuracy, can simulate emerging CPSoS behaviors early in the project lifecycle. In addition, unwanted behaviors and failures are highly likely to be identified earlier in the project.

According to Fig. 2 (Kopetz et al., 2016), emergent behavior can also be unexpected, and the effort becomes to make it known and expected. In this way, the EMBED-SoSE Discovery Canvas process must be interactive, incremental, and collaborative; that is, it

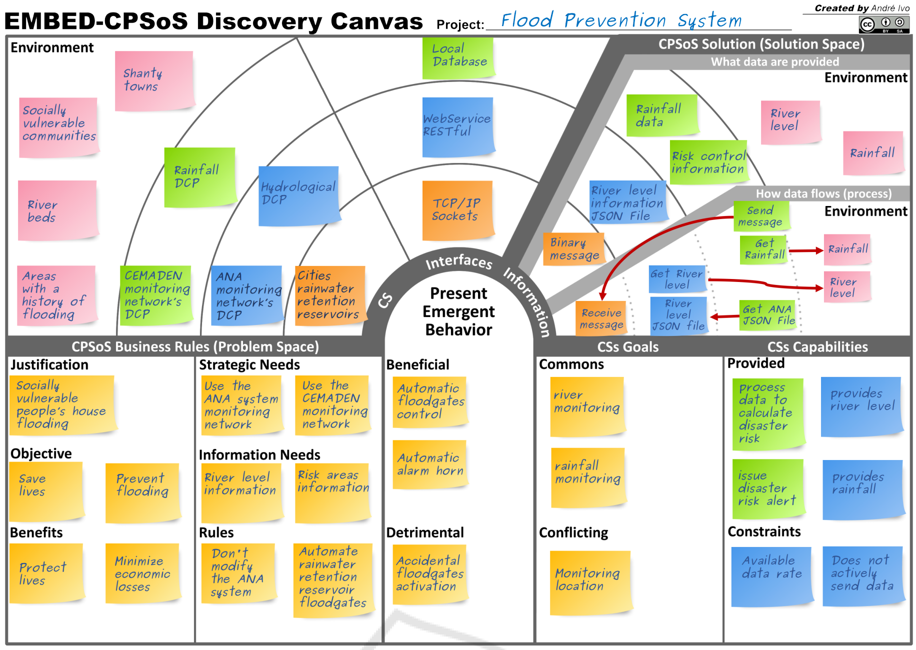



Figure 5: Flood Prevention System Discovery Canvas.

must be revisited to discover new emerging behaviors.

It is essential to clarify that the EMBED-SoSE Discovery Canvas is not a flowchart of the project since the flowchart represents a sequence of steps, while what is essential in the Discovery Canvas are the relationships between concepts. In some cases, the Canvas itself can only represent a single and consistent project plan, however in other projects, the rigor of formalism may be required, so the Canvas can be used as a primary tool to confront the logic of the project and relate the concepts, serving as a basis for the transcription of a project plan in the traditional model required by formalism.

There is no doubt that knowledge about CPSoS and its unexpected emergent behaviors can be limited; however, with a well-structured process, the EMBED-SoSE Discovery Canvas proposes a way to increase the ability to evidence these types of behaviors through stimulation and engineers' creative ability. In summary, EMBED-SoSE proposes an approach to systems engineering (SE), especially to complex systems such as a CPSoS, which moves away from the linearity of classical design and makes the connections between the parts evident, reducing the cognitive effort of engineers and stakeholders.

The next step for this work is to develop a case study for proposal validation. In addition, the work can generate opportunities for new research and the development of tools based on the paradigm of visual thinking.

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