Application of the Extended Language Lexicon for Cyber-Physical Production Systems

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Abstract. This paper presents an approach for eliciting the capabilities of Cyber-Physical Production Systems (CPPS) through an extension of the Language Extended Lexicon (LEL), referred to as LEL-C. CPPS integrate hardware, software, and physical components—often in dynamic interaction with human and environmental factors—posing new challenges to requirements engineering. To address these, we adopt the capability-oriented perspective of e-CORE and propose leveraging LEL-C to systematically capture domain knowledge across digital and physical dimensions. The proposed extension incorporates additional attributes such as component type, system and physical location, interactions, data sources, and temporal constraints. We apply LEL-C to a wildfire detection and suppression system as a use case, showing how the method supports the structured identification of current system capabilities. It is planned to advance the validation of this preliminary version of the LEL-C by developing a complete glossary for a CPSS. This will also provide improvements to the proposal. This foundational work enables a consistent strategy for capability elicitation in CPPS, contributing to the broader goal of aligning semantic models with both software and physical process properties.

Keywords: Cyber-Physical Production Systems (CPPS), Language Extended Lexicon (LEL), Capabilities elicitation.

1 Introduction

Cyber-Physical Production Systems (CPPS) represent a valuable option for achieving "Smart Manufacturing," which involves integrating Information and Communication Technology (ICT) resources into the manufacturing process.

In 2006, the U.S. National Science Foundation launched an initiative promoting research efforts toward deeper integration of physical and digital systems into a more coherent framework, emphasizing the critical role of communication networks. Within this context, Helen Gill coined the term "Cyber-Physical Systems (CPS)" to describe systems integrating physical and digital elements interconnected in real-time. Traditional manufacturing processes predominantly feature physical components supported by information systems that closely interact, often involving human mediation. By extending current industrial processes with CPS, the resulting systems are identified as CPPS. Cyber-Physical Production Systems (CPPS) are a specialized category of Cyber-

Proceedings of the 28th Workshop on Requirements Engineering (WER2025),
August 20-22, 2025, Rio de Janeiro-RJ, Brazil.
https://doi.org/10.29327/1588952.28-5

Physical Systems (CPS) applied specifically within manufacturing and production contexts. In addition to the typical elements of CPS, CPPS incorporate production-specific components such as machinery, production lines, and logistics systems. While CPS do not necessarily involve human interaction, CPPS place particular emphasis on the collaboration between humans, devices, software, and data. CPPS is a specialized subset of CPS tailored for manufacturing and production systems under Industry 4.0.

CPPS enable manufacturing industries to participate in the ongoing industrial revolution through the interconnection and digitalization of production systems, enhancing their flexibility, resilience, efficiency, and overall capabilities.

According to existing literature: "The purpose of CPPS is to transform current Physical Production Systems (PPS) towards those that, underpinned by ICT-related capabilities, could achieve a greater degree of connectivity of production entities and processes." [1]

These systems are characterized by the integration of hardware, software, and the physical world, resulting in a high level of complexity due to the quantity and diversity of components involved (people, software, hardware, physical devices, and data). If software systems are among the most complex products humanity has created, then the complexity of CPS is even greater, as it aggregates the inherent complexity of software with additional layers introduced by hardware and physical artifacts.

From a methodological viewpoint, significant challenges are posed to Software Engineering and Computer Engineering, given the differences in approaches to aspects such as representation and execution of time, modeling perspectives, and systems-of-systems frameworks. Within Software Engineering, there has emerged a conceptual metaphor proposing to replace traditional system requirements with system capabilities.

Along this direction, a successfully applied capability-oriented proposal has been developed, known as e-CORE (early Capability-Oriented Requirements Engineering).

> We posit that the notion of capability represents a most suitable metaphor that provides the means of considering the intertwining of technical, organizational and social concerns in such a way, that it is possible to connect strategic objectives and high-level organizational requirements to technological artefacts in a unified manner. The use of capability for representing the status of a business and its needs (the what) rather than focusing on the technical implementation (the how) serves as a powerful communication tool among manufacturing technologists, information technologists and business specialists. [1, p. 3]

We are currently developing a project aimed at eliciting the existing capabilities of a Cyber-Physical Production System (CPPS), leveraging the knowledge obtained through the Extended Language Lexicon (LEL) methodology [2], [3]. To achieve this goal, we propose utilizing a specialized version termed LEL-C, which includes specific extensions and adaptations of the traditional LEL, tailored to address the distinctive characteristics of CPS. This aligns with the perspective that: "… effective orchestration of software and physical processes requires semantic models that reflect properties of interest in both." [3]

Essentially, our objective is to develop an enriched LEL (LEL-C) capable of incorporating hardware and physical components intrinsic to CPS, alongside the semantic elements required to accurately represent these components and their performance characteristics, such as temporal behavior. Thus, the enhanced LEL-C aims to effectively represent the properties inherent to the physical processes involved in CPS.

The remainder of this paper is structured as follows: Firstly, we introduce CPS and their application domains. Secondly, we revisit the foundational concepts of the LEL methodology and assess their applicability within the context of CPS. Subsequently, we present the fire-detection and firefighting system case study, as developed with ChatGPT support. We then analyze selected examples of LEL symbols and present related work. Finally, we discuss future research directions, particularly focusing on the derivation of system capabilities from the LEL.

2 Cyber-Physical Systems

A Cyber-Physical System (CPS) is essentially characterized by a high degree of integration between hardware, software, and the physical environment, necessitating careful consideration of the interfaces among these components. Additionally, applications developed under this paradigm function in close relation to human actors and involve significant interaction with their operational context. CPS fundamentally entails the seamless integration of computational processes with the dynamics of the physical world.

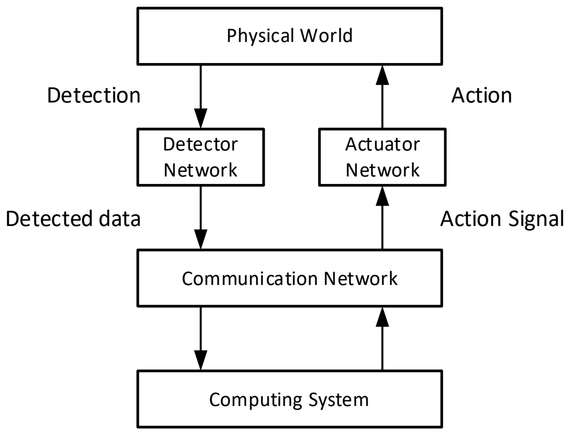

Fig. 1. Cyber-Physical System, Architecture Diagram

Software Engineering has clearly established the challenges associated with software systems and the scale shift involved when transitioning from a simple program to a fully developed product [4], [5]. In the case of CPS, this shift in scale is further magnified by the complexity arising from the integration and interaction among hardware, software, and the physical environment. Figure 1 illustrates the computational and physical components (hardware and software) and their interactions. For instance, within a Fire Detection and Suppression System, we can clearly identify typical CPS components: a smoke detector that anticipates a fire represents detection sensor; a sensor that triggers a water-release mechanism exemplifies an actuator; the piping that transports and delivers water to extinguish the flames forms part of the physical world; the communication network carries signals from detectors to actuators. All these data streams converge into a computational system responsible for information management, decision-making, or providing information to humans, who may then decide, for instance, whether to initiate fire suppression. Their applications cover a wide spectrum of domains: Advertising Entertainment/sports, Aerospace. Environmental monitoring, Agriculture Financial services, Buildings Healthcare, Cities Infrastructure, Consumer Manufacturing, Defense Science, Disaster resilience, Social Networks, Education Supply chain/retail, Emergency response, Transportation, Energy Weather

Existing CPS applications demonstrate that their operational scope encompasses a significant portion of the activities within their respective domains, thereby substantially increasing the complexity involved in their design, development, and operation. Consequently, CPS must address a variety of critical challenges, as identified by [2].

A special category of CPS is known as Cyber-Physical Production Systems (CPPS). CPPS integrate digital, physical, and social components, posing significant challenges for traditional requirements engineering due to their inherent complexity, emergent behaviors, and distributed development. Transitioning from traditional production systems to CPPS requires strategic planning that carefully considers financial, operational, and social factors. Early-stage organizational requirements play a pivotal role, significantly influencing both the design and the ultimate outcomes of the system.

The notion of "capability" provides an appropriate metaphor for modeling and analyzing requirements related to the transformation of Physical Production System in CPPS. A capability embodies the interplay among technical, organizational, and social concerns, facilitating effective communication among diverse stakeholders. [1]

The e-CORE approach (early Capability-Oriented Requirements Engineering) is fundamentally based on the notion of capability: “The general consensus is that an enterprise capability represents a conceptual service that a group of processes and people, supported by the relevant application, information and underlying technology, performs?”. The starting point of the e-CORE approach involves identifying the existing capabilities of the production system, for which it is necessary to elicit relevant information regarding these capabilities. [1]

The proposal of this article is to utilize the Extended Language Lexicon within the elicitation process.

3 Extended Language Lexicon

3.1 Original Specification of the Extended Language Lexicon

Software Requirements Engineering has developed various methodologies and techniques aimed at formulating the requirements of software systems. These methodologies constitute essential resources within a broader process that ultimately results in functional software. One prominent example is the Extended Language Lexicon.

In this article, we follow the formulation described in [2], where references to the extensive existing literature on LEL are available. The Extended Language Lexicon is essentially a structured glossary whose entries, referred to as symbols, possess specific categorizations and attributes, enabling the precise description of the language associated with the software's application domain. These entries are classified into four categories: Subject, Object, Verb, and State. Each category comprises distinct attributes: characteristics, notion, and state.

The LEL approach has proven valuable for capturing domain-specific knowledge essential to software requirements formulation, facilitating an in-depth comprehension of the application domain where the software will operate. It has demonstrated effectiveness in systems involving a diverse range of stakeholders [3]. Based on the experience acquired within software engineering, the potential arises to leverage the LEL methodology to define the requirements for CPS.

Considering the three fundamental ontologies used to model the world (including CPS)—entities, activities, and assertions—the LEL proposes four glossary entry categories: subject, object, verb, and state (see Table 1). Table 1 illustrates how each attribute has specific instances tailored to the respective categories.

Table 1. LEL Categories, Source: [4]

Category:	**Subject**	**Object**	**Verb**	**State**
Characteristics	Active elements that perform actions	Passive elements upon which subjects perform actions	Actions performed by subjects upon objects	Situations in which subjects and objects can be found
Notion	Characteristics or conditions satisfied by the subject	Characteristics or attributes possessed by the object	Objective pursued by the verb	Situation represented
Impact	Actions executed by the subject	Actions performed on the object	Steps required to complete the action	Actions required to transition to another state

3.2 Extension of LEL to CPS

The knowledge obtained through the LEL construction process contributes to determining the requirements of the software system under construction. However, this outcome inherently restricts the applicability of LEL exclusively to the digital components of a Cyber-Physical System (CPS). The objective of our work is therefore to extend the scope of LEL to encompass the entirety of the CPS. To achieve, within CPS, an outcome in requirements elicitation equivalent to that obtained for purely software systems, we propose introducing enhancements to the original LEL structure, enabling it to capture comprehensive knowledge about CPS application domains. For practical purposes, we designate this extended version as LEL-C.

In the construction of LEL-C, we have retained the original LEL categories for symbol classification: Subject, Object, Verb, and State. However, we have expanded the attributes associated with each symbol beyond "Characteristics," "Notion," and "Impact" to fully represent all critical components of a Cyber-Physical Production System (CPPS).

We introduced an identification code to facilitate management and referencing of the wide variety of components inherent to CPS, reflecting the complexity that characterizes these systems.

As previously mentioned, it is essential to extend LEL to identify, for instance, symbols related to the physical aspects of CPS and adequately represent them. For example, a sensor might function as a detector or actuator; hence, it can belong to either the "Subject" or "Object" category depending upon its specific role. This distinction underscores the necessity of adding an attribute within the category structure to accurately distinguish between such functional roles.

In both "Subject" and "Object" categories, actions fundamentally define the notion; subjects execute these actions, while objects receive them. These categories are directly associated with the diversity of components found within CPS. Many CPS elements transition through various states, becoming characterized by them. For example, sensors may actively monitor conditions or receive a signal.

The "State" category is particularly affected due to the multiplicity of artifacts present in CPS. Thus, the introduced attributes explicitly specify the artifact to which each state refers. The concept of a system state within CPS involves considerable complexity; indeed, some authors argue it is impossible to precisely determine the current state of a CPS, due to challenges introduced by relativistic conceptions of simultaneity. Consequently, our state definitions will focus explicitly on the artifacts within the CPS.

To precisely define the state of a subject or object, we adopt the viewpoint expressed by INCOSE: *"A system is in a state when the values assigned to its attributes remain constant or steady for a meaningful period of time."* [5, p. 6]

3.3 Attributes of LEL-C Symbols

The attributes added to the symbols of LEL were identified analyzing a description of CPPS with the goal of elaborate a preliminary list that will be improved applying in different cases. The following sections describe the preliminary attributes added to LEL for each symbol.

Component type. At the highest abstraction level, CPS are essentially systems-of-systems (SoS) comprising a cyber (computational) part and a physical part. In the case of Cyber-Physical Production Systems (CPPS), a social component ("people") is additionally included. The relationship between a CPPS and humans is not the same as that established by a CPS. Let's consider, as an example, an autonomous vehicle parking system and a CPPS in an automotive production plant. A few points show the significant difference in their relationship with people. From the perspective of interaction with humans, the two systems differ in several aspects: in the former, few types of interactions and profiles are involved, while in the latter, the variety is much greater. In the parking system, some functions previously performed by humans are transferred to the system, while in the CPPS, the number of transferred functions is considerably greater. They also differ significantly in the impact that a malfunction can have on people. The cyber part integrates hardware and software. Clearly identifying an element within a CPS necessitates explicitly determining the type of component being considered. Currently, there is no universally accepted taxonomy for these components;

therefore, we provisionally adopt the following List of Components Type derived from the analysis of the framework proposed by NIST [6]:

- System
- Physical Component
- Hardware Component (excluding sensors and actuators)
- Software Component (excluding communication-related software)
- Communication Networks
- Sensor
- Actuator
- Data Storage and Management
- People

System Location. Since CPS are structured as systems-of-systems (SoS), this attribute specifies the subsystem to which a symbol belongs.
Physical Location. This refers to the spatial placement or geographical position of the symbol within the CPS.
Characteristics, Notion, Impact. Standard definitions for these attributes, as established in the original LEL for traditional systems, remain applicable.
Interactions. These describe the systems or facilities with which the component is connected. For example, a Subject may exchange data with a Sensor Network or with Emergency Service Coordinators.
Data Source. Indicates the source of the data utilized by the symbol. For instance, an actuator may use data generated by the Detection System. Thus, the Data Source corresponds to another symbol interacting with the described symbol.
Time. The original LEL was developed without explicit consideration of temporal factors, consistent with traditional systems where time plays a limited role. Conversely, in CPS applications, time holds a critical role in defining clear sequences and durations of activities.

Temporal requirements are subjected to constraints grouped as follows:

- **Frequency:** For instance, sensors regularly sampling data.
- **Chronological:** Maintaining a consistent sequence of events.
- **Simultaneity:** Ensuring two events occur simultaneously from the perspective of all system observers.
- **Latency:** Defining temporal boundaries or maximum permissible delays.
- **Temporal Assurance:** Relating to security, resilience, safety, reliability, and privacy requirements. These constraints have been formulated in terms of providing mechanisms to synchronize clocks and coordinate the execution of actions within specified timeframes [8].

Table 2 presents the instantiated attributes for each category of the LEL-C.

Table 2. LEL-C Categories

Symbol	Subject	Object	Verb	State
Component Type	To which the subject belongs	To which the object belongs	To which the subject and object belong	To which the artifact, whose state is identified, belongs
System Location	Host system of the subject	Host system of the object	Host system of the subject and object	Host system of the artifact whose state is identified
Physical Location	Of the subject	Of the object	Of the subject and object	Of the artifact whose state is identified
Characteristics	Active elements that perform actions	Passive elements upon which subjects perform actions	Actions performed by subjects upon objects	Situations in which subjects and objects can be found
Notion	Characteristics or conditions satisfied by the subject	Characteristics or attributes possessed by the object	Objective pursued by the verb	Situation represented
Impact	Actions executed by the subject	Actions performed on the object	Steps necessary to complete the action	Actions required to transition to another state
Interactions	Artifacts with which the subject interacts	Artifacts with which the object interacts	Artifacts with which the subject or object interact	Artifacts interacting with the artifact whose state is identified
Data Source	Of the subject	Of the object	Of the subject or object	Of the artifact whose state is identified
Time	Moment and duration of actions	Moment and duration of actions	Moment and duration of actions	Period of time during which it remains in this state

4 Use Case of LEL-C

To execute a proof of concept for the application of the LEL-C in eliciting the capabilities of a CPPS, a Wildfire Detection and Suppression System [7] was selected as a use case. The project aims to achieve early detection and suppression of wildfires through the implementation of Internet of Things (IoT) technologies within the framework of a Cyber-Physical Production System (CPPS).

At this stage of the project, we have initiated the development of LEL-C symbols to refine the proposed syntax before proceeding with the full development of the Lexicon for the Wildfire Detection and Suppression System.

4.1 Process for Defining LEL-C Symbols in This Report

The development of the Extended Language Lexicon for CPS (LEL-C) examples presented in this report was conducted through a systematic and structured process, consisting of the following stages:

Selection and Compilation of Symbols. A manual review of the content in the "Abstract" and "1. Introduction" sections of the article *"A Cyber-Physical System for Fire*

Detection and Firefighting" was performed to compile a list of potential symbols. Only subjects, objects, and verbs were identified, as explicit candidates for the state category were not present in the text.

Definition of the Initial LEL. For the identified symbols, entries were specified using the standard LEL attribute template: characteristics, notion, and impact.

Review and Refinement of Generated Symbols. A critical evaluation of the initially generated symbols was conducted, including corrections and expansions of their attributes to enhance precision and representativeness.

Analysis and Adjustment of Attributes. The lists of subjects, objects, and verbs, along with the definitions of both traditional and newly introduced attributes, were used to generate the LEL-C.

Generation of LEL-C Symbols for States. The symbols corresponding to states were defined based on the previously identified subjects and objects, ensuring logical consistency.

Review of State Symbols. The state symbols underwent the same review and refinement process described in the third stage, ensuring consistency within the LEL-C framework. To assist in identifying state-category symbols, queries were made to ChatGPT, and the results were validated by both authors.

Selection of Representative Symbols. Four key symbols were selected as representative examples of the new LEL-C report format, aiming to illustrate its practical application and evaluate its coherence within the model (Tables 3 and 4).

4.2 Examples of Symbols

The selected symbols are:

- Firefighters
- Infrared Sensor
- Real-Time Fire Detection
- Fire Detected

These symbols were chosen due to their relevance within the Cyber-Physical Wildfire Detection and Suppression System, allowing for a detailed analysis of their interaction, impact, and role within the conceptual framework of LEL-C. We add some comments to key attributes. In tables 3 and 4 are the four selected symbols.

Physical Location: All objects are inherently assigned a physical location within a system; therefore, the inclusion of phrases like "Installed in..." are redundant. The system's architectural framework and deployment specifications already imply their placement, making such an explicit designation unnecessary.

Characteristics: These types of sensors report the measured value, while the interpretation and corresponding actions are determined by the system with which they interact. In this case, the Fire Detection System evaluates the received data to assess and determine the presence of fire or potentially hazardous hotspots.

Time: This situation represents an indeterminate reaction time, which disrupts the event sequence within the system. Due to the distances involved and environmental irregularities, the affected area may experience highly variable response intervals for firefighter arrival. In some cases, certain zones may even be completely inaccessible to firefighters. To mitigate these uncertainties, the implementation of a timing table could be considered to try to maintain event synchronization. Alternatively, if intervention becomes unfeasible, an adaptive strategy should be adopted, potentially shifting focus toward autonomous suppression systems or alternative response mechanisms.

System Location: System of Systems (SoS) serves as the privileged observer, overseeing and regulating the overall system state. Each subsystem autonomously determines its own state, which is subsequently communicated to the SoS via a messaging protocol (MQTT). However, this transmission introduces latency, causing delays in the synchronization of states. To maintain a structured sequence of response events, the SoS governs the system state, albeit imperfectly, due to the inherent communication delay. Consequently, by default, the SoS assumes the role of the primary authority in state coordination, trying to ensure operational coherence despite the synchronization challenges.

Table 3. Examples of Subject and State Symbols

Attributes	Subject	State
Symbol	Real-Time Fire Detection System	Fire Detected
Component Type	System	Real-Time Fire Detection System
System Location	Fire Detection and Suppression System	SoS
Physical Location	Fire-Prone Regions, Surveillance Towers.	Whole system
Characteristics	Instantaneous fire outbreaks active identification	The SoS has identified an active fire and is confirming its presence.
Notion	Improves situational awareness and emergency operation	Fire detection sensors, UAVs, UGVs, and AI models identify a verified ignition source.
Impact	1. Identify fire presence 2. Confirm using multiple sensor inputs 3. Trigger suppression actions	To confirm the fire and initiate alert protocols.
Interactions	Fire suppression system, environment	Fire Detection System (Ground Control Station, UAV Sensors, UGV Cameras)
Data Source	AI Fire Detection Logs, IoT Sensor Inputs, Surveillance Camera Data	Sensor logs, historical fire data, AI model predictions
Time	Detection under 1 second for emergency action	To confirm under 1 second for emergency action

Table 4. Examples of Subject and Object Symbols

Attributes	Subject	Object
Symbol	Firefighters	Infrared sensor
Component Type	People	Hardware, Sensor
System Location	Early suppression system	Thermal Fire Detection System
Physical Location	Fire stations, wildfire-prone regions, urban areas	Fire-Prone Locations, UAV, UGV[1]
Characteristics	Professionally trained personnel specialized in firefighting	Sensors detecting infrared radiation
Notion	Engages in direct firefighting and rescue operations	Measures thermal radiation
Impact	Minimizes fire damage and rescues individuals	Receive and confirms the presence of heat sources
Interactions	Fire departments, emergency response agencies, communities	Fire Detection System, Ground Control Station, UAV Sensors, UGV Cameras
Data Source	Fire behavior analytics, emergency call data, historical reports	Thermal imaging data, sensor network analysis
Time	Arrival according to the area on fire	Detection <10 milliseconds

5 Related work

A systematic review of elicitation techniques in the closely related domain of Internet of Things [8] found that the most frequently used techniques of elicitation were interviews and prototypes, two traditional techniques. Another significant finding was that stakeholders are the most common source of requirements. Wiesner [9] proposed several recommendations about the advantages of Natural Language for requirements engineering of CPS including Natural Language Processing, they do not mention any kind of lexicon or glossary as a resource of the elicitation process. Valente da Silva [10] presents a technique to support to produce “IoT software system requirements document” they mention 28 elicitation techniques none related to LEL. However, they do not consider the hardware aspect of IoT. Loucopoulos [1] proposed a process for information elicitation of CPS in the context of modernization an automotive manufacturing plant through questionnaires in natural language analyzed to extract terms for modeling purposes. The models are refined through meetings.

Souza [11] propose a promising approach to elicitation of IoT requirements based in techniques of Design Thinking, specifically Empathy Map and Mind Map. While this approach considers certain hardware aspects, it is ultimately defined solely for the software dimension of IoT systems. There are not considerations about glossaries or lexicon. The gamification approach of requirements elicitation of CPS is proposed in [12] for the special case of Product-Service Systems. However, this work also omits any reference to the use of glossaries or similar lexical resources during the elicitation phase. Through a systematic mapping study [13] is presented a review of Requirements

[1] UAV: Unmanned Aerial Vehicle and UGV: Unmanned Ground Vehicle

Engineering of IoT-based systems. They found, and analyzed, 24 primary studies. The conclusion is not optimistic about findings: "The findings of this SMS clearly show that proposals have not been well-defined and created to satisfactorily conduct the development of IoT software systems through the application of RE phases. Moreover, the literature has not placed much relevance on this topic, and the techniques implemented have been inadequately applied."

These related works do not demonstrate the use of glossary construction as a requirements elicitation technique and are primarily focused on the IoT domain. A key conclusion is that they largely overlook the hardware dimension of cyber-physical systems (CPS).

6 Conclusions and Future Work

The introduction of CPS, and especially CPPS, which represent an evolution perspective of Physical Production Systems (PPS), creates new demands on the construction processes of Software Systems and Hardware Systems. Requirements Engineering has valuable methods that need to be reworked to encompass a part of the real world that is broader and more complex than the one that originated them. Among those resources of Requirements Engineering, there is a situation in which a new metaphor has emerged from its core, which presents itself as more powerful for the construction of CPPS: capabilities; it is about providing a capabilities elicitation process.

With this goal in mind, we propose to expand the definition of an already established tool with remarkable results: the Extended Language Lexicon, since the current definition is not applicable to hardware and the physical world due to the limitations of the attributes of its categories. The LEL-C has been defined by maintaining the categories of the LEL but increasing their attributes. A template of the LEL-C symbols was developed, and with a limited case, some illustrative examples of symbols for a fire detection and extinguishing system were presented. The applicability of the template and the limitations of the LEL in addressing CPS were demonstrated.

Future work will be focused on the complete construction of LEL of a CPPS, but the number of symbols involved, and the information required for each symbol makes the development of software tools for its creation essential. To relate the LEL-C, a process will be undertaken that allows obtaining capabilities from the LEL-C.

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