Knowledge Extraction in Cyber-Physical Systems Meta-models: A Formal Concept Analysis Application

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Abstract: Industry 4.0, also known as the “Fourth Industrial Revolution”, “smart manufacturing”, “industrial internet” or “Factory of the Future” is a trend and highly discussed topic nowadays. Therefore, this topic drew attention to research and practice and opened many doors to shed light on the future path of engineering approaches. Cyber-Physical Systems (CPSs) play an important role as one of the core components in the industry 4.0 approach, as they connect the physical objects in production systems to the virtual ones. Indeed, CPSs are the main sources in Industry 4.0 through which data can be transformed into information and consequently extracted as knowledge. To be able to derive the required knowledge from the transformed information, it is essential to excavate the concept of CPS and associate its characteristics by which the system is identified. However, the current literature lacks a systematic study which analyses the characteristics of CPSs and the relationships among them. And so forth, this study will focus on CPS meta-models and their characteristics. Formal Concept Analysis (FCA), as a clustering technique, will be used to investigate any hypothetical relationship among the characteristics.

1 INTRODUCTION

Industry 4.0 technologies related to Cyber-Physical Systems (CPSs), Internet of Things (IoT), Big Data and cloud computing can generate benefits and positively contribute to the circular economy paradigm since they allow design for circularity based on the information gathered from customers as well as through the whole production process. CPSs represent more than networking and information technology or even information and knowledge being integrated into physical objects. By integrating perception, communication, learning, behaviour generation, and reasoning into such systems a new generation of intelligent and autonomous systems may be developed. A large-scale CPS can be envisioned as millions of networked smart devices, sensors, and actuators being embedded in the physical world, which can sense, process, and communicate the data all over the network. The proliferation of technology-mediated social interactions via these highly featured and networked smart devices has allowed many individuals to contribute to the size of Big Data available. The contextualised form of data generated by CPS makes the data comprehended as information, which makes CPSs, in the context of Industry 4.0, a huge source of information which also carries, often implicitly, relationships between the environment and the working domain. This information and relationships are dormant sources of knowledge that must be extracted, formalised, and potentially reused. To do so, it is necessary to extract knowledge to better understand the characteristics of the under-examination systems and the methods they use to employ them according to their potential. This dormant knowledge can be identified by using different methods like clustering, relationships extraction, concept frequency finding, and anything related to the information retrieval domain.

Therefore, this study focuses on extracting characteristics from various meta-models presented in the literature. As the first step, and in investigating the CPS characteristics, a thorough study of cyber-physical system meta-models and the characteristics has been done. The study was to discover more about CPS knowledge representation in different scientific domains like manufacturing processes, Informatics,

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health, architecture and so on. During the study, two main issues were investigated: (1) How are CPS meta-models described and characterized? (2) How is Knowledge represented in CPS meta-models? The results were then analysed using the Formal Concept Analysis (FCA) method to classify and discover hidden relationships between the inner existing meta model's components. The FCA method, in this way, gives the possibility to extract new implicit knowledge.

The remainder of the paper is organized as follows: the next section provides a literature overview on the CPS meta-models. A short description of the research methodology is presented in section 3. Furthermore, section 4 presents the CPS meta-models' characteristics, while section 5 provides a clustering assessment of CPS characteristics using the Formal Concept Analysis method. A detailed discussion of the results is presented in section 6. Finally, the main conclusions of this study are provided in section 7.

2 LITERATURE OVERVIEW ON CPS META-MODELS

CPS meta-models have been widely discussed in the literature. They have been designed and proposed to address various issues in the context of Industry 4.0. (Yang Liu et al. 2017) thoroughly discusses the characteristics and architecture of CPSs and then investigates different research on Information Processing of CPS, CPS Software Systems, CPS System Security and CPS System Testbed. Studying all, they conclude that the most called for challenge in development of CPS is the limitation on existing theory and technology of computation, communications, and control technology. Furthermore, (Vogel-Heuser et al. 2021) introduced a comprehensive domain-specific language (DSL) to design a meta-model to reduce the Cyber-Physical Production Systems (CPPSs) downtime during the operation of the glass bottles in a yogurt manufacturing plant. The proposed DSL, DSL4hDNCS, will address hardware/software architectures or network-related delays and uncertainties and will increase safety, calculation power, and network transmission time. Therefore, it can act as a unique method to support the formalized, cross-disciplinary engineering of distributed CPPS, including the description of real-time, safety, and deployment aspects. After an investigation of the structure of CPS, (Someswara Rao, Shiva Shankar, and Murthy 2020) makes a comprehensive search on different domain applications of CPS such as handling energy, network security and data transmission and management. Afterwards, they briefly explored the models and methods driven for the development of CPSs; domain-specific modelling (DSM), the prominent model-driven development (MDD) and model-integrated computing are a few to mention. On the other hand, (Cheh et al. 2017) categorizes the application domain of CPS into 10 main categories and discusses the work done in each category. Agriculture, education, energy management, environmental monitoring, medical devices and systems, process control, security, smart city and smart home, smart manufacturing and transportation systems are the 10 groups CPSs are discussed in the mentioned work. CPPS, its design and application are the focal points of the study run by (Wu, Goepp, and Siadat 2019). The 5C architecture of CPS (Smart Connection Level, Data-to-Information Conversion Level, Cyber Level, Cognition Level and Configuration Level) is also deeply discussed regarding the CPPS. (Maidl et al. 2021) defined a taxonomy for relevant attack actions for the security of CPSs and formed the taxonomies as a meta-model. This meta-model presents the ways the taxonomy relates the attack action to the endangered part of the cyber-physical system. In addition, it prefilters the attack actions and documents them in the threat model systematically. Therefore, it can provide various visions of the threats for the cyber-physical systems and manages to focus on the relevant aspects for the verified task.

3 RESEARCH METHODOLOGY

The present study forms a state of the art based on cyber-physical system metamodels, and the characteristics represented. The focal point of the study is based on CPS knowledge representation in different scientific papers. To do the investigation, a sequence of questions have been answered through the work: 'How CPS metamodels are described and characterized?', 'How Knowledge is represented in CPS metamodels?' consequently, papers were identified using a structured keyword search on major databases and publisher websites (Scopus, Elsevier and ScienceDirect). General keywords such as "cyber-physical systems" and "metamodel" were combined using AND. All the searches were applied in the "Title, Keyword, Abstract" field. At this search level, no exclusion area was considered, and all CPS application areas and domains were studied. As for the content analysis, the material connection was conducted as mentioned above and a systematic analysis was run to assess the papers in terms of what CPS characteristics are explicitly or implicitly discussed.

4 OVERVIEW OF CPS META-MODELS' CHARACTERISTICS

CPSs are often engineered systems and are differentiated from other types of engineered systems as they are built on the integration of cyber and physical components. It is, therefore, agreed upon that CPS functionalities come from the tight integration of the cyber and physical sides and create CPS characteristics in different terms. On the other hand, CPSs should be characterized by well-defined components. They should provide components with well-known characteristics described using standardised semantics and syntax. Therefore, defining and shaping key characteristics of CPSs will pave the path to better development and implementation management within and across various domains of the CPS application (Griffor et al. 2017). However, the literature lacks a systematic study of the characteristics of CPS meta-models, their definition and whether there is a relationship among them. Therefore, and to better investigate how CPS meta-models are characterised and defined, the focus point of the present study has been put on exploring the CPS characteristics in the various domain in scientific papers. The investigation will get even deeper by trying to see if they are explicitly connected or not.

Napoleone et. al (2020) discussed the technological characteristics of CPSs in manufacturing emergent from existing literature in detail. They carried out a structured review to investigate the CPS characteristics that have been studied in scientific papers. In the end, they came up with 19 most cited lower-order characteristics, and then providing their literature-based descriptions and explaining the reasoning, they aggregated them to eight higher-order characteristics. Since the same need can originate the present study, a base CPS characteristic list was considered on account of their work aiming at delineating CPS metamodels. Therefore, the choice of the content analysis for our work was established deductive, however, during the procedure of analysing the papers and digging deeper into the study, the list of the characteristics that were gone through for the analysis was modified to what can be seen in Table 1.

Table 1: CPS characteristics extracted for this study.

CPS Characteristics		
Resiliency	Modularity	Intelligence/smartness
Redundancy	Autonomy	Cooperation
Complexity	Self-Capabilities	Collaboration
Heterogeneity Encapsulation	Integration	Reconfigurability
Interoperability	Virtualization	Adaptability
Connectivity	Real-Time capability	Scalability
Networking Capability	Computational Capability	Diagnosability
Predictability	Uncertainty	Fault-tolerant
Composability	Reliability	Safety and Security
Stability		

5 CLUSTERING ASSESSMENT ON CPS CHARACTERISTICS USING THE FORMAL CONCEPT ANALYSIS METHOD

To investigating the main two issues of this study, "(1) How are CPS metamodels described and characterized?" and "(2) How is Knowledge represented in CPS meta-models?" the papers were gone through whether they discuss, implicitly or explicitly, the CPS characteristics enlisted in the previous section.

Hence, Formal Concept Analysis (FCA), as a clustering technique, was chosen to help us first to describe the CPS meta-models and then scrutinize the CPS characteristics and the hidden relationship between them in the chosen papers.

FCA is a branch of lattice theory (Wille 1982) and it is best used for knowledge representation, data analysis, and information management. It detects conceptual structures in data and consequently extraction of dependencies within the data by forming a collection of objects and their properties (Wajnberg et al. 2018). The FCA method starts with the input data in a form of a matrix, in which each row represents an object from the domain of interest, and each column represents one of the defined attributes.

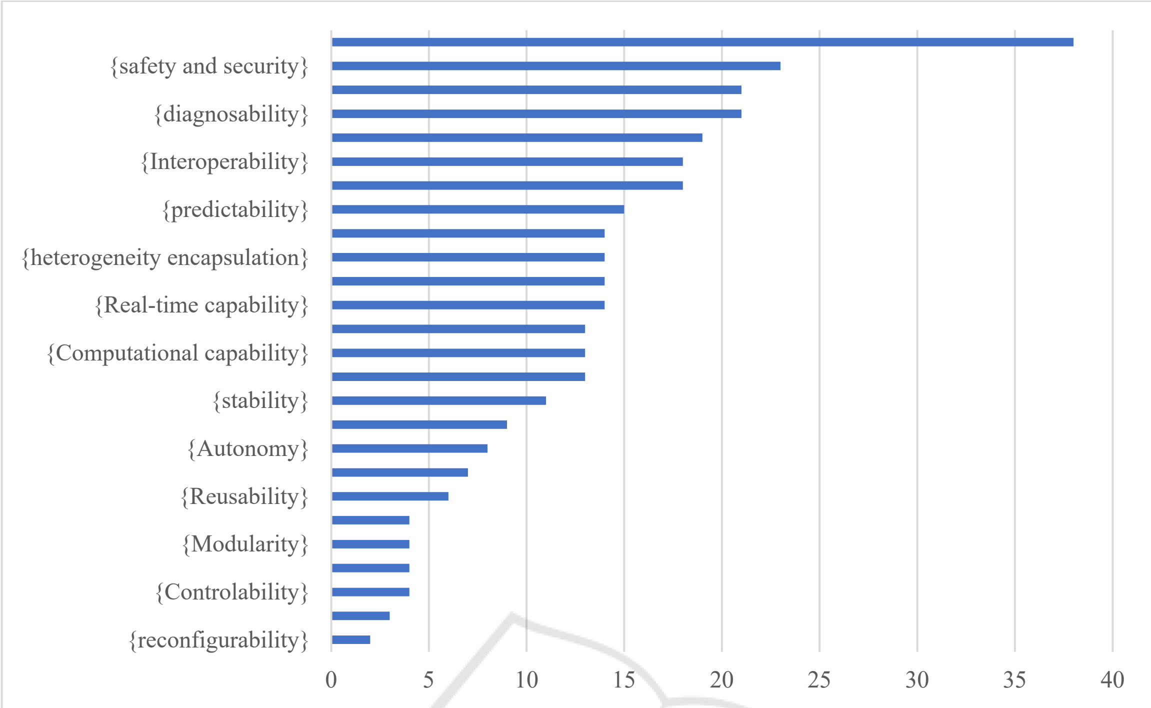

Figure 1: Single clustering of CPS Characteristic.

If an object has an attribute, a mark (e.g., symbol "●") is placed on the intersection of that object's row and that attribute's column. Otherwise, the intersection is left blank. The matrix is called the "formal context" and for the present study it was formed as the papers which implicitly or explicitly investigate the CPS characteristics in their meta-model as the objects and the characteristics of CPS as attributes. In general, FCA results in two sets of output data: a hierarchical relationship of all the established concepts in the form of a line diagram called a concept lattice and a list of all found interdependencies among attributes in the formal context (Škopljanac-Mačina and Blašković 2014). The latter is what has been used for the analysis of the CPS characteristics in the present work.

Figure 1 represents the result of FCA on single clustering of CPS characteristics. As it is clearly seen, "Resiliency" was the one characteristic that stood on the top of the list, with a noticeable difference from the rest, as the most reflected characteristic in the literature whether to be explicitly or implicitly mentioned. Characteristics like "Fault-Tolerant", "Diagnosability", "Redundancy" and "Safety and Security" come next in the list with a noticeable difference between Resiliency and ignorable divergence among themselves. On the other hand, characteristics like "Reconfigurability", "Collaboration", "Controllability", and "Self-Capabilities" are at the end of list, which does not refer to the lack of importance on the characteristics though. The main reason might mostly be that they are the characteristics that are fundamental and taken for granted in the design and application of CPSs.

Figure 2 on the other hand, shows what was extracted from the coupling demonstration of characteristics in the analysed papers through FCA. Going through the results, the combination of Resiliency with other characteristics are the ones been observed the most, which was somehow predictable by the analysis of the single characteristics. However, the pair of {Resiliency; Redundancy}, {Resiliency; safety and security},{Resiliency; Fault-Tolerant} and {Resiliency; diagnosability} are at the top-ranking respectively which one way or another can show the close relationship between the concepts; the outcome that establishes the backbone of the upcoming discussion.

As it has been described above, FCA is a conceptual framework that can make data more understandable. It is based on the lattice theory and defines a formal context to represent the relationship between objects and attributes in the studied domain. In addition to what was formerly explained, FCA employs association rule mining which is a method for discovering interesting relations between variables.

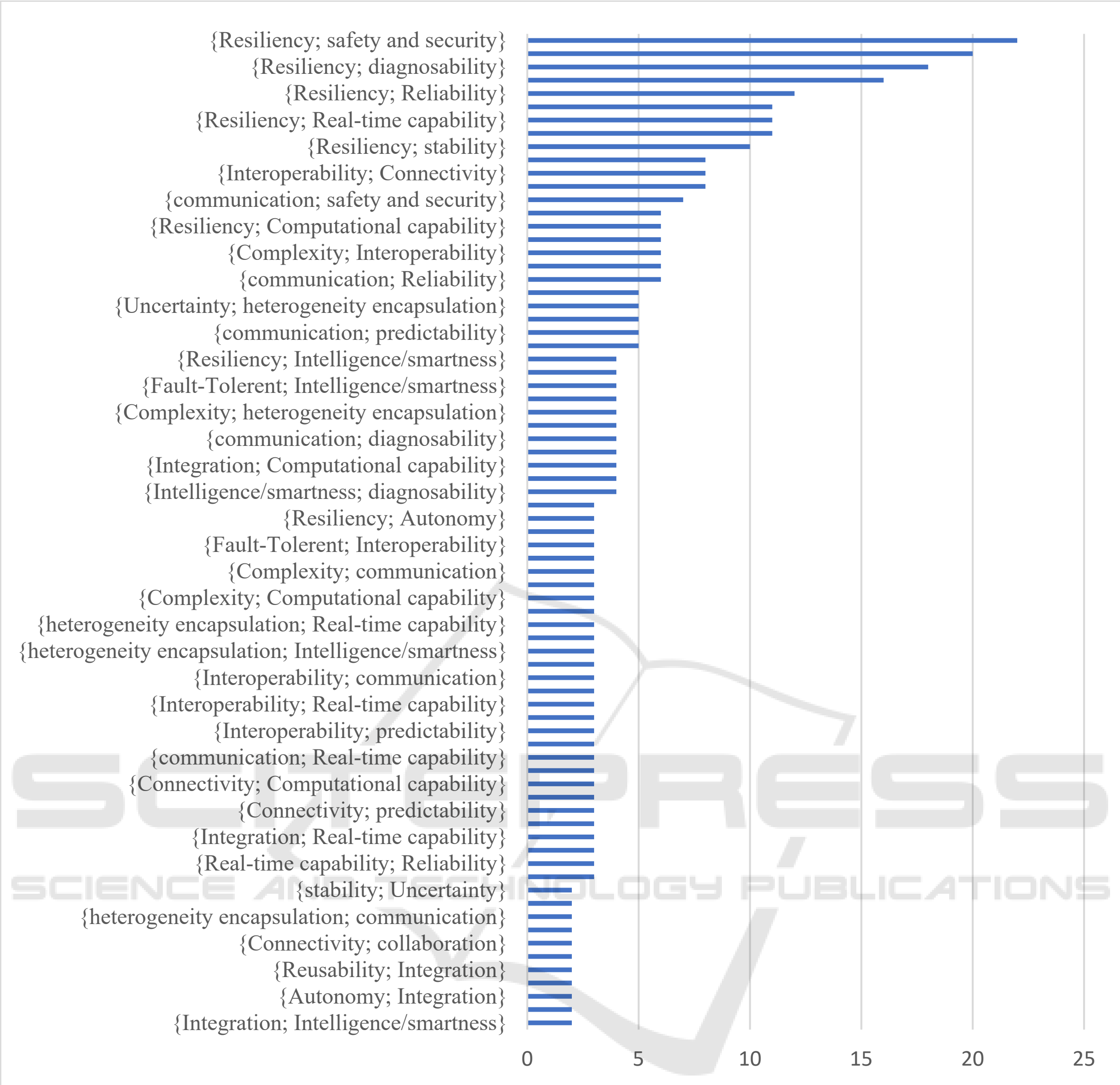

Figure 2: Double clustering of CPS Characteristics.

Table 2: CPS characteristics extracted for this study.

#	antecedent	=>	consequence	support	confidence
1	Resiliency	=>	Redundancy	27.02%	52.63%
2	Resiliency	=>	diagnosability	24.32%	47.36%
3	Resiliency	=>	Fault-Tolerant	21.62%	42.10%
4	Resiliency	=>	safety and security	29.72%	57.89%
5	Fault-Tolerant	=>	Resiliency	21.62%	84.21%
6	diagnosability	=>	Resiliency	24.32%	85.71%
7	safety and security	=>	Resiliency	29.72%	95.65%
8	Redundancy	=>	Resiliency	27.02%	100.00%

Let I = {i_1,i_2,...,i_n} be a set of n binary attributes called items. Let D = {t_1,t_2,...,t_m} be a set of transactions called the database. Each transaction in D has a unique transaction ID and contains a subset of the items in I. A rule is defined as an implication of form $X \Rightarrow Y$ where $X,Y \subseteq I$ and $X \cap Y = \emptyset$. The sets of items (for short itemset) X and Y are called antecedent and consequent of the rule (Hornik, Grün, and Hahsler 2005). The defined rule can mean that if X is chosen then it is likely that Y is also selected. However, to be able to extract rules measures are defined to help the process of decision making. The best-known measures are Support and confidence (Y. Liu and Li 2017) that are used in the present study. The support supp(X) of an itemset X is defined as "the proportion of transactions in the data set which contain the itemset." For example, if the support of itemset X is 0.4 it means that the itemset occurs in 40% of all transactions. On the other hand, the confidence of a rule is defined conf $(X \Rightarrow Y)$ = supp $(X \cup Y)$/supp(X) and can be interpreted as "an estimate of the probability P(Y |X), the probability of finding the antecedent of the rule in transactions under the condition that these transactions also contain the consequent". For example, if the conf $(X \Rightarrow Y) = 0.5$, it means the rule $X \Rightarrow Y$ is correct in 50% of the transactions containing X and Y (Hornik et al., 2005). However, the aim is to find frequent itemset (the CPS characteristics in the present study) and the probability of the frequency. To serve the purpose, the software LATTICE MINER 2.0 was adopted on the result of the analysis done. The association rules between the selected CPS characteristics were extracted considering the minimum support level as 20% and minimum confidence level as 20% and shown in Table 2. The minimum levels were defined by a try and error procedure.

Looking through the association rules, the probability of achieving resiliency through fault tolerant, diagnosability, safety and security and finally redundancy goes over 84% which itself confirms the result for the first step in FCA. It also worth noting that, resiliency is in all the itemset that have support levels above 20% and a confident of 50% and above.

6 DISCUSSION ON THE RESULTS

With reference to the results of FCA achieved in the previous part, resiliency draws the attention to itself among other characteristics. Going through the papers that have investigated the characteristics, 68% of the papers were recently published (2014 forward) among which 31% is dedicated only to the interval of 2018-2019 which shows the high rise of the importance of the concept in the literature. Different terms were used and established in the literature to refer to a CPS be 'resilience' such as survivable (Wan and Alagar 2014) or Fail-safe (Chemashkin and Zhilenkov 2019).

Furthermore, the present study investigated the CPS characteristics considered and studied in the papers, whether the characteristic and their effect were explicitly or implicitly discussed in the scientific papers. To name a few, Lezoche and Panetto (2018) tried to reach resiliency through modelling the functions and also the links between the components of the meta-model by the help of FCA. Looking at the hierarchical inclusion of the CPS meta-model and thanks to the created lattice, they could find control over redundancy and therefore elevate resiliency of the system. Sangiovanni-Vincentelli et al., (2012) addressed the systems engineering of cyber-physical Contract-Based Design by employing structured and formal design methodologies to finally increase the reliability and consequently the resiliency of the CPS meta-model. Although Zhao and Rao (2017) did not mention resiliency directly as an objective of their study, they have had it implicitly targeted through an integration of the physical layer, the network layer and the business layer, which finally leads to a better investigation of the hardware status information, software, patches and other information to perception, acquisition and control. The integration results in a platform by which controllability, diagnosability and fault-tolerant of the CPS is increased which will be directed to more survivability of the system.

Given the importance of the concept, different paths were taken to reach and increase the resiliency of a CPS. Due to the results observed, the main two tracks were passed over the two characteristics: 'safety and security' and 'fault-tolerance'. For example, (Bakirtzis et al. 2020) believes that only by unifying safety, security and resiliency it is possible to reach adaptable and dynamic design patterns that are able to take into account the intended functions of a system. Chemashkin and Zhilenkov (2019) explored fault tolerant control systems (FTCS) and mentioned that they are able to withstand the failures and errors of the components of the system itself and to preserve the system performance to the maximum, therefore they can survive and be resilient.

Digging a bit deeper, resiliency of a system was thrown together with recognizing different defies and risks along with defining proper metrics to protect the endangered system and estimating plant states in spite of attacks (Na, Park, and Eun 2019; Lezoche and Panetto 2018). Encountering such observations, brought about another level of attempts to elevate resiliency of the system: revolving around characteristics like predictability and diagnosability which also stood at the high ranks of the FCA double clustering.

Redundancy and reliability were also the characteristics that coupled well with resiliency in FCA and were also discussed closely with the concept in the literature. As mentioned by (Na, Park, and Eun 2019), redundancy is the principle that can be advantageous in estimating resiliency in majority of the systems. On the other hand, the intention of redundancy in the system can be increasing its reliability since it relies on employing multi-pronged solutions rather than a single technique which also improves the security and resiliency of the system (Lezoche and Panetto 2018).

In addition to all, stability was also a characteristic that was paid attention to on reaching safety, security and consequently the resiliency of the system since fast reconfiguration of attacks can lead to maintaining the stability of the system which keeps it safe and helps it retain normal operation (Potteiger, Zhang, and Koutsoukos 2020).

7 CONCLUSIONS

The paper presented a study on Cyber Physical Systems meta-models and their representative characteristics. To this extent, two main steps were taken to find out about ‘How are CPS metamodels described and characterized?’, and ‘How is Knowledge represented in CPS metamodels?’ through which CPS meta-models were profoundly investigated regarding what characteristics they are designed to mirror in the metamodels.

Implementing Formal Concept Analysis (FCA) as the clustering technique, the most aimed characteristics in CPS meta-models were studied. Due to the results, “resiliency” was the dominant characteristic that was targeted implicitly or explicitly in the scientific paper. “Fault-Tolerant”, “diagnosability”, “redundancy” and “safety and security” were the ones followed resiliency in the list but with noticeable difference. Implementing the association rules by the clustering technique has also confirmed the results and showed that with a probability of 85% and above, resiliency is the one characteristic looked for in CPS meta-model, implicitly or explicitly.

In a sequel, the work makes a contribution in the concept of Cyber Physical Systems characteristics in a way that it not only lists the characteristics that has been studied implicitly or explicitly in meta-model constructions, it also takes care of the road map to the most focused characteristic in CPS metamodels. Thanks to FCA and its association rules, it was possible to find the hidden relationship between the characteristics that mainly characterize the CPS meta-model.

The present work can be an initial point of development of a CPS-family metamodel. The goal is to improve the actual metamodel with the dynamic part and all the inner semantics that is mandatory for an evolutive and adaptive CPS.

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