Project management best practices for cyber-physical systems development
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Resumo

A integração do mundo computacional com o mundo físico em um único sistema é chamada de Sistemas Ciberfísicos (SC). SC visam melhorar a compreensão e influência nos fenômenos físicos por modos computacionais. A interação do mundo computacional com o físico, através do uso de sensores, atuadores e redes de comunicação frequentemente levam o desenvolvimento de SC à projetos de alta complexidade e multidisciplinares. Gestão de Projetos (GP) é uma prática que aumenta as chances de sucesso de um projeto, monitorando e controlando aspectos relevantes do desenvolvimento do projeto. O PMBOK é uma combinação de boas práticas relacionadas à GP, no qual descreve dez áreas do conhecimento, visando auxiliar gerentes de projeto de qualquer área. Embora o PMBOK proponha uma abordagem genérica, algumas práticas especializadas para áreas particulares podem beneficiar projetos com alto nível de desafio. Neste contexto, esta proposta de Mestrado visa desenvolver um conjunto de boas práticas para projetos de desenvolvimento de SC. Esta abordagem é chamada de CPS-PMBOK e é baseada em três áreas do conhecimento: escopo, recursos humanos e partes interessadas. A CPS-PMBOK inclui um modelo de caracterização de SC o qual auxilia a compreensão do sistema a ser desenvolvido; e especializações das áreas do conhecimento, as quais fornecem um novo processo para a gestão do escopo do projeto, além de melhorias específicas de técnicas conhecidas do PMBOK, dos processos de gestão de recursos humanos e partes interessadas. O objetivo da CPS-PMBOK é melhorar o desempenho do projeto e qualidade do SC, abrangendo o gerente de projeto e desenvolvedores. Com esta pesquisa, pretende-se auxiliar no aumento da adoção das práticas de GP nos projetos de desenvolvimento de SC.

Palavras-chave: Gestão de Projetos. Sistemas Ciberfísicos. Sistemas Embarcados.
Abstract

The integration of the computational world and the physical world in a single system is called Cyber-Physical Systems (CPS). CPS aims to improve comprehension and influence in physical phenomena by computational means. The interaction of computational with physical world, through the use of sensors, actuators and network communications often lead the development of CPS to high complexity and multidisciplinary projects. Project Management (PM) is a practice that enhances the chances of success of a project, monitoring and controlling relevant aspects of project development. PMBOK is a compound of best practices regarding PM which describes ten knowledge areas, aiming to support project managers from any area. Although PMBOK proposes a generic approach, some specialized practices for a particular area may benefit projects with high level of challenge. In this context, this Masters proposal aims to develop a set of best practices for CPS development projects. This approach is called CPS-PMBOK and is based on three knowledge areas: scope, human resource and stakeholder. The CPS-PMBOK includes a CPS characterization model which supports the comprehension of the system to be developed; and specializations of the knowledge areas, which provides a new process for project scope management, besides specific improvements of known techniques from PMBOK process of project human research and stakeholder management. The objective of CPS-PMBOK is enhancing project performance and CPS quality, embracing project manager and developers. With this research, it is intended to support the raising of PM practices adoption in CPS development projects.

Keywords: Project Management. Cyber-Physical Systems. Embedded Systems.
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1 Introduction

In the last decade a new technological area of systems has appeared, aiming to integrate physical processes to computational resources, called Cyber-Physical Systems (CPS) (RAJKUMAR et al., 2010; SHA et al., 2009; KIM; KUMAR, 2012). CPS can be defined as the interaction between physical world – representing physical phenomena and environmental behaviors – and computational world – representing embedded systems, microprocessors, microcontrollers and other computational platforms (LEE, 2008). The interactions occur through sensors – technologies able to read or measure physical quantities, e.g. temperature, pressure, light, and convert into electrical signs, – and actuators – mechanical or electrical devices able to be stimulated by electrical signs, influencing the physical world with other electrical signs, movement, radiofrequency (RF) transmissions, among others. Examples of peripherals that can be considered sensors and actuators, since they behave as inputs and outputs of the CPS respectively are: cameras, antennas, electrical motors, pneumatic valves, lasers or simple video monitors. The basic operation of a CPS is: sensors reading the physical world, transmitting information for computers, which in turns process the information with specific algorithms for the environment, and transmit the appropriated information for actuators’ action in the physical world again, often changing it. This change is read back by the sensors, starting the operation over again (LEE; SESHIA, 2014). The specific algorithms may be image processing, protocol analyses, trajectory estimation, pattern recognition, digital signal processing, among others.

The development of this kind of systems emerged by the need to understand the physical world, associated to the possibility to control it, bringing benefits as: reliability in all kind of vehicles; enhance of telecommunications; and improvement of medical treatments and sustainable energy technologies (BAHETI; GILL, 2011; RAJKUMAR et al., 2010; SHA et al., 2009). This overlap of physical and computational concepts features CPS as unusual applications, merging different technical knowledge and requiring a wide variety of competences (SHA et al., 2009; LEE 2008; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014).

Project management (PM) is the activity of controlling and measuring the development progress of a project, applying knowledge, skills, tools and techniques aiming to ensure project requirements accomplishment and consequently success. A project is any collective and temporary effort to accomplish a result, being the development of a product, creation of a service or a determined and limited set of activities (PMI, 2013). PM is a
practice present in many professional areas, as software development, construction, marketing and many industries (COOKE-DAVIES; ARZYMANOW, 2003). According to studies made by the Project Management Institute (PMI), PM practices include the management of different areas involved in the project directly or indirectly, called knowledge areas and thoroughly described in its body of knowledge (PMBOK) (PMI, 2013). The knowledge areas are: integration, scope, time, cost, quality, human resources, communication, risk, procurement and stakeholder. The approach of each knowledge area may vary according to the area of application and the main success factor of the project (LESTER, 2014). The proper application of PM practices allow enhancing project results and improve project team skills for next projects application (PMI, 2013; LESTER, 2014).

1.1 Motivation and justification

The adoption of PM practices has becoming part of routine of companies or any organization engaged in activities with similar concept to project development: a temporary effort to reach a determined result. PM practices can be found in research and development (R&D), industrial manufacturing or instantiation of a well-defined product (COOKE-DAVIES; ARZYMANOW, 2003). The increasing formalization and application of tools, techniques and methodologies by industry are studied by Fortune et al. (2011), showing that PM may be object of study of many researchers and has a continuous need of improvement. According to Mir and Pinnington (2014), the benefits of PM and the impact of appropriate practices over the results may vary and can be seen by different views, as: project team; PM techniques used; project manager leadership; kind of results and organizational characteristics of the company. PM practices may improve the control of the project development, enhancing the schedule accomplishment in projects where time is the major constraint; adapting project team according to coverage scope needs; suiting costs in budget restrict projects; or closely monitoring the risks, in critical projects (LESTER, 2014).

The development of a CPS can be faced as a project which management is necessary, as well as any other technological development. Many CPS are developed to improve technologies already in use, leading to a high level of innovation (RAJKUMAR, 2012; PARK et al., 2014). The investigative aspect of CPS as a new technology enabler or a proof of concept’s development require large and heterogeneous team participation, besides adding risks to results of project, as seen in the CPSs described by White et al. (2010). Another characteristic of CPS projects is the contact with hazardous environment and even human
lives (LAKSHMANAN, 2010). Rajkumar et al. (2010) and Baheti and Gill (2011) argue that multidisciplinary team and segments involved plus a high level of abstraction models to communicate all members of the project team are one of the main challenges of CPS development. These factors illustrate the need for managing CPS projects properly.

Although it is a consensus that PM brings benefits, the way that the project should be conducted, to enhance project results, may be adjusted for each case (WINTER et al., 2006; COOKE-DAVIES; ARZYMANOW, 2003). It may depends on the way that project is funded, as project for government, as approached by Grimsey and Lewis (2002); on area of application of project, as construction (ASSAF; AL-HEJJI, 2006; SHEN et al., 2015) or defense (BOYDSTON; LEWIS, 2009); or even on a specific technology present on project, as web services and e-learning projects (IRANI et al., 2005; CHAN; PAN; TAN, 2003). A focused approach of PM practices allows to concentrate efforts in specifics possible problems, enhancing the overcome possibility or to adapt practices of easily controlled issues, by the nature of project, e.g. projects with flexible time of conclusion or a very large budget, saving efforts for other areas of knowledge.

Aiming to investigate the challenges in development of CPS, considering its complexity, different combination of disciplines and the often high level of innovation, a set of studies is conducted by many CPS authors and professionals. The IEEE Proceedings published a special issue about CPS in 2012, which highlights technical challenges as security (MO et al., 2012; SRIDHAR; HAHN; GOVINDARASU, 2012) and reliability of critical systems (BANERJEE et al., 2012), but also some administrative and software engineering challenges, as software development methodologies (EIDSON et al., 2012), abstraction models of architecture (SZTIPANOVITS et al., 2012) and system overall modeling (DERLER; LEE; VINCENTELLI, 2012). For Baheti and Gill (2011), advances in CPS can be accelerated by close collaboration between many disciplines in computation, communication, control, engineering and computer science. Broman et al. (2012) studied a set of viewpoints, formalisms, languages and tools that could be useful for CPS development standardization and project definition. In a similar work, Derler et al. (2013) describe design contracts as a way to define systems properties among different teams and professionals. Motivated by these evidences of PM need and these initial studies of CPS challenges, this work aims to use a well-consolidated guide for PM (PMI, 2013) for CPS projects, according to following objectives.
1.2 Objectives

In view of the evidences of PM contributions and improvement possibilities of PM practices in the area of CPS, this research project aims to consolidate a set of best practices to be used while managing CPS projects. The best practices allow expanding PM professionals’ perception of CPS, enabling them to focus their activities on recurring issues, with appropriate approaches. To reach this objective, the following specific objectives are fetched:

- Analyze existing PM approaches in CPS development based on PMBOK (PMI, 2013) practices and knowledge areas.
- Establish a set of more efficient, applicable and structured practices from the studied approaches.
- Propose best practices for CPS PM based on PMBOK (PMI, 2013) practices, knowledge areas and studied approaches.

Assess the applicability of the practices against traditional practices.

1.3 Structure of document

This document is divided in the following sections: Chapter 2, depicting a contextual background through theoretical foundation; Chapter 3, providing the methodologies used in the research; Chapter 4, presenting the proposed approach in development and initial results; Chapter 5, containing the planning and schedule for the sequence of the work; Chapter 6, presenting the final considerations; References; Appendix A providing an article, result of the conducted systematic literature review related to subject of this project, applied to IEEE Proceedings.
2 Contextual background

This chapter presents the basic concepts related to CPS and embedded systems, including examples of application in scientific, industrial and technological contexts. Different points of view of the challenges faced in such areas are presented, attempting to embrace the major consent of the located authors. Basic definitions of the PM practices and technical detailing are also presented, including the descriptions of Knowledge Areas (knowledge area) as well as their main usages.

2.1 Cyber-physical systems

The term “Cyber-Physical Systems (CPS)” was coined by Helen Gill at the National Science Foundation (NSF) Workshop on Cyber-Physical Systems in 2006 (NSF, 2006) to describe a new generation of engineered systems capable of high performance in information, computation, communication and control, as for example: smart power grids, where the power line healthy and consumption can be monitored at distance all the time; online and robotic medical surgeries; and the autonomous vehicles, as trains, cars, drones or UAVs (Unmanned Aerial Vehicles). CPS represents a new way of interaction based on possibility of full understanding of phenomena and exchanging of contextualized information between the computational and the physical worlds, just like people interact with each other using the internet (RAJKUMAR et al., 2010). In a previous scenario, the components of computer world was bigger, more expandable and the communication (wireless or not) capacity was limited, while the physical world was only witnessed by computer world. The computational world includes all kind of computational platforms, able to process and provide information for people or other technologies. The physical world includes physical processes and phenomena that can be found in the environment. From the side of computational world, it is possible to find elements as: Unix based computers; microcontrollers; microprocessors; embedded systems; Digital Signs Processors (DSP); Programmable Logic Controller (PLC); field-programmable gate arrays (FPGA) and signal acquisition hardware. From the physical world side, it is possible to find phenomena as: temperature; electrical current and voltage; atmospheric pressure; motion (velocity and direction); lighting; Radio Frequency (RF); sound; and even time. Physical processes are a combination of some of these phenomena with a context, e.g. the ambient temperature of a room, which changes over the time and the
amount of people inside; the pressure of an airplane that changes according the altitude of the flight; and the current provided by an electrical engine proportional with the load. To bring these two worlds together in a way that the interaction be possible, some intermediate elements are used, called sensors and actuators. The sensors may be any technology capable to transform one of the quoted phenomena into electrical or other signs more readable by computers. Actuators are specific hardware technologies able to generate electrical signs, sound, RF, indirect motion or others phenomena in order to stimulate elements in a physical process. The actuators can also stimulate sensors of others elements of a CPS (LEE; SESHIA, 2014). Thus, this interaction consists in computers reading the physical world and controlling it, in an iterative way, reading it back again and adapting the controlling through computation in the next interaction (LEE, 2008). Figure 1 presents an illustrative example of a generic CPS architecture, where three main elements can be seen: the physical plant, the platforms and the network fabric. The first, is the representation of physical world, including the physical processes as the phenomena described previously. Lee and Seshia (2014) add human operator as part of physical processes. The platforms represent the cyber world, including computers and operating systems, besides sensors and actuators as physical interface. The last part is described as the mechanisms for the computers to communicate, as wireless networks or industrial protocols and buses, and can be considered part of the cyber world.

Figure 1 - Illustrative example of a generic CPS architecture

Source: Lee and Seshia, 2014
CPS can be addressed through a multidisciplinary view, since they are a confluence of embedded, real-time, distributed sensors and control systems. This requires a diversity of professionals working together from different areas, such as: computer science; network engineering; civil engineering; mechanical engineering; biology; control engineering; software engineering; human interaction; learning theory; electrical engineering; chemical; biomedical; material science; signal processing (SHA et al., 2009; LEE 2008; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014).

In this context, issues related to reliability, safety, robustness, security and Quality of Services (QoS) are very relevant since wrong actuation or misinterpretation of signs in a physical world may cause accidents, and still open technical challenges, as prevent cyber-attacks in non-Unix systems (LEE, 2008; SHA et al., 2009; RAJKUMAR et al., 2010). In order to properly address CPS, computing and networking abstractions needs to be redesigned, since in physical world time can define the required computational approach and concurrency is intrinsic, which are not considered in today’s computing and networking abstractions (LEE, 2008). Moreover, network components should be remodeled to fit the new technologies of computational platforms (SHA et al., 2009) and as many industrial CPS are designed to decoupling the control system design from hardware/software implementation details, the trend of creating new models of abstraction and architectures can be seen (BAHETI; GILL, 2011). In terms of technological challenges regarding the development of CPS, mobile devices integration as well as distributed sensors and actuators can be mentioned (SHA et al., 2009). On another hand, in terms of methodological issues, architecture patterns, composition of protocols, and new modeling languages and tools can be mentioned (RAJKUMAR et al., 2010).

There are many possible areas for potential application of CPS, such as: advanced automotive systems, including autonomous vehicles; agriculture; avionics and airplanes; critical infrastructure control; defense systems; distributed actuators; distributed robotics; distribution; electric vehicles; energy conservation; environmental control; health care; instrumentation; intelligent buildings; medical devices and systems, including medial prostheses; mobile devices; power generation; real-time systems; space vehicles; traffic control; (SHA et al., 2009; LEE 2008; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014). Moreover, some existing technologies can acquire these CPS features, such as: cognitive radio, Radio Frequency Identification (RFID); and other technologies of assets tracking (LEE, 2009). According to Sha et al. (2009), three main areas can be cited as
the biggest challenges to CPS: global warming; energy shortage; and health care services for chronic diseases.

More recently, approaches related to CPS have been addressing concerns related to: (i) previous design with a detailed networked control systems model to calculate communication delay, packets loss and system placement (KIM; KUMAR, 2012); (ii) clock synchronization between Wireless Sensor Network (WSN) elements (KIM; KUMAR, 2012); (iii) a framework to support the choice, by the developer or by the client, of existing modeling languages and tools for CPS stakeholders, which is based in three elements – viewpoints, mathematical formalism and languages and tools (BROMAN et al., 2012); (iv) design contracts, as agreements on some properties and concepts of a system used to equalize the definitions understanding, as a way to reduce the lack of communication between the different areas of professionals involved in the development and design of CPS (DERLER et al., 2013).

2.1.1 Embedded systems in cyber-physical systems

CPSs are closely related to embedded systems (LEE; SESHIA, 2014). Embedded systems are characterized by having a specific hardware running specific software, developed to perform a limited set of tasks with limited resources. Embedded systems technologies, such as hardware and programming languages, has allowed developing relative low cost and reliable dedicated applications. With the technological advances of microchips, microprocessors and operating systems, the resources became not so limited so that embedded systems ended up being present at many different applications. Nowadays, embedded systems are found in vehicles, appliances, mobile devices, manufacturing industries, aircraft and so on. This means that currently, the main challenge related to embedded systems is its environment, and not the size or performance. Nevertheless, these attributes frequently are object of improvement, besides power consumption (LEE; SESHIA, 2014).

Specific embedded systems became similar to CPS seeing that areas of applications started to demand more increased features and networked devices, besides the need for interaction with physical environment, founded in CPS (LEE, 2008). Furthermore, features related to time processing and synchronous data exchange between different devices typify many embedded systems as real-time applications. Accordingly, improved operating systems are currently called Real Time Operating Systems (RTOS), which are usually embedded ones (LEE, 2008).
In summary, the need for interaction with the physical world leads to CPS while the need for a specific hardware with specific software running a determined set of tasks leads to embedded systems. As a result, in terms of relationship between CPS and embedded systems, any computational element present in figure 1, which represents a generic CPS architecture, could be an embedded system. Nevertheless, embedded systems exist regardless the CPS domain as well as there are CPSs that not use embedded systems, although very rare. An example of a CPS with no embedded systems could be a laboratory controlled by an ordinary desktop computer and some data acquisition hardware. On another hand, an example of an embedded system out of a CPS domain, which is easier to find, could be an alarm clock or an mp3 player.

2.2 Project management

A project is a temporary effort, to reach a specific objective (usually the creation of a product or service) taking into account some time, cost and requirements constraints. The objectives and constraints may vary according to organizations environmental factors and policies. The Project Management Institute (PMI) defines a project as a temporary endeavor undertaken to create a unique result and it comes to an end when the objectives are reached or it is impossible to reach them (PMI, 2013). The British Standards Institution (BSI) describes a project as a process with a set of controlled activities with start and finish dates, adding as constraints the resources besides time and cost (BSI, 2000).

According to PMI (2013), Project Management (PM) means to apply knowledge, skills, tools and techniques over the development to assure the achievements of the project’s requirements. PM is also defined as a process of definition, planning, monitoring, controlling and delivering projects (APM, 2012). PMI keeps a base of knowledge called PMBOK (Project Management Body of Knowledge) that presents a set of best practices to be used in PM. Similarly, the Association for Project Management (APM) also keeps its set of PM best practices called APM Body of Knowledge. As PMBOK is the most worldwide used, this research uses its best practices as base for comparison for approaches studied.

The main constraints that PM practices should be concerned are related to scope, quality, schedule, budget, resources and risks; but they are not limited to these. All these constraints are dependently interrelated, i.e. if one change, at least some other one is affected by it (PMI, 2013). For example, PMBOK states that if the schedule of a project is shortened, the budget needs to be increased to allocate additional resources; or if the scope changes, the
risks may have changed as well, creating new risks or changing the severity of the existing ones. According to Lester (2014), the project’s objectives must meet three fundamental criteria: timely completion, completion within budgeted cost; and compliance of quality requirements.

As well as the PM techniques, the project success criteria – also known as critical success factors (CSF) – may vary according to organization or project approach. The main or primary objectives established for the project defines which concerns or criteria must be met for the project success criteria. Generally, all the objectives proposed for the project must be met by considering a project completed. However, a project can be considered successful, if the primary objectives were achieved, while the secondary are impossible to reach. For example, the project of a civil construction must be in time for the inauguration day, even if all the paintings were not finished yet. If in time, the project could be considered successful according to success criteria. In this case, cost and a part of the scope had to be sacrificed to meet the time constraint, and these other objectives may be finished later (LESTER, 2014). Another possible success factor, mainly in CPS projects, is safety, where a system or application can only be used if doesn’t offer any harm to the users or security in cases of a cyber-attack may cause huge consequences (AXELROD, 2013). In these cases, if a project is finished in time, but its safety features are not enough, it can be considered completed but not successful. In a general manner, PMBOK defines project success criteria as completing the project within realistic and achievable constraints of scope, time, cost, quality, resources and risk.

Researchers have been studying the factors that lead the project to success, attempting to focus the PM practice (COOKE-DAVIES, 2002). Mir and Pinnington (2014) found that PM performance and PM staff are the most significant variable regarding to PM success contribution. PM performance measurement is a way to evaluate the effectiveness of PM practices and techniques applied by an organization or project development team. The indicators used to compose the performance measurement are called Key Performance Indicators (KPI) (MIR; PINNINGTON, 2014). KPI can be a specific part of the project such as a milestone or a particular deliverable and may be a subjective metric (LESTER, 2014). Another point of view given by Kerzner et al. (2010) is that the CSFs and the KPIs must be defined by both customer and project team, i.e. all the stakeholders. As mentioned by PMBOK, the KPI gathering and reporting can be carried by using a Project Management Information System (PMIS), which are a set of computational tools used to support the PM practice. Cooke-Davies and Arzymanow (2003) explore the difference of PM focus and
maturity among industry segments. The PM focus, organization environment and policies then may influence the definition of project success criteria (COOKE-DAVIES; ARZYMANOW, 2003). In summary, the project success criteria or CSF are the measurement of the results experienced by the customer, while KPI are the measurement of the quality of the process to reach the desired results, i.e. measures within the PM and project team (KERZNER et al., 2010).

2.2.1 Project management processes

The execution of PM practices in order to achieve project success, through determined success criteria, requires concrete and formal processes. A process can be defined as a set of activities performed to reach the specified stage of project development. It is characterized by its inputs, the tools and techniques used, and the outputs resulted (PMI, 2013). The processes adopted may change according to each project or organizational environment. The PMBOK describes five groups of project management processes: initiating, planning, executing, monitoring and controlling, and closing. The processes are interlinked and may have iterative aspects, repeating throughout the project or project phase of development.

The lifecycle phases of a project are not the process groups, but different stages of project maturity, defining when a project is in the beginning, middle or getting close to the end. Different groups of process are conducted during the phases of lifecycle project and its transitions. For example, it is possible to find processes from planning group when the project is in its final activities or close process from close group upon a change of activity in the middle of the project. This means that the process groups may be as overlay activities (PMI, 2013). Details of the activities performed on each process group are presented as follow:

1. **Initiating process group**: include processes performed to define a new project or a new phase of an existing project. The initial scope and financial resources are defined and committed. Internal and external stakeholders are identified and the project manager is selected if not selected yet. Along with stakeholders, the success criteria are verified.

2. **Planning process group**: include processes performed to establish the total scope, define and refine the objectives and develop the course of action required to achieve those objectives, including strategies and tactics to successfully complete the project or phase.
3. **Executing process group:** include processes performed to complete the work defined in the project management plan to satisfy the project specifications. It involves activities as coordinating people and resources and managing stakeholders’ expectations.

4. **Monitoring and controlling process group:** include processes performed to track, review and orchestrate the progress and performance of the project, besides identify any areas in which changes to the plan are required and initiate the respective changes. This allows identifying areas requiring additional attention by the manager.

5. **Close process group:** include processes performed to conclude all activities started across the project. The following activities may be executed: obtain acceptance of the project by the customer; document lessons learned; apply updates to organizational process assets; archive all relevant project documents; close out all procurements activities; and perform team members’ assessments and release project resources.

The figure 2 shows a possible application of all processes groups during the development of a project and their overlaying.

**Figure 2 - Process groups interact in a phase or project**

Source: PMI, 2013
2.2.2 Knowledge areas

For a complete and successful PM, it is necessary to deal with different dimensions of organizational administration, different professional fields, or even specialization areas (PMI, 2013). Accordingly, PMBOK splits its PM practices into ten knowledge areas: integration, scope, time, cost, quality, human resource, communications, risk, procurement, and stakeholder. Each knowledge area represents a set of concepts, terms, activities, tools and techniques that should be used as appropriate to manage a project. The PM processes may involve one or more knowledge area depending on the lifecycle phase of the project (PMI, 2013). Although there are other PM strategic divisions, this work explores only this structure adopted by PMBOK (version 5), which are deeper presented as follows:

1. **Project integration management**: responsible for identifying, defining, combining and coordinating all the PM processes and activities. Basically, it organizes and prepares all the process and activities present in the other knowledge areas activities. It includes the use of a Project Management Information Systems (PMIS) as well as the change management planning. It may also include configuration management practices. The main documents produced by this area are: (1) the project charter and (2) the PM plan. The involved processes are: (1) develop project charter; (2) develop the PM plan; (3) direct and manage project work; (4) monitor and control project work; (5) perform integrated change control; and (6) close project or phase.

2. **Project scope management**: responsible for ensuring that all the work required to complete the project successfully were predicted and is been executed. It defines what is and is not included in the project, i.e. the scope and the non-scope. The main documents produced by this area are: (1) scope management plan; (2) requirements documentation; (3) scope baseline and (4) Work Breakdown Structure (WBS). The involved processes are: (1) plan scope management; (2) collect requirements; (3) define scope; (4) create Work Breakdown Structure (WBS); (5) validate scope; (6) control scope.

3. **Project time management**: Manage the Time of a project means to monitor if the activities will be finished in the stipulated time and control the possible delays and advancements in a manner that the project stay comprehensible and achievable. The planning and definition of the milestones, if used, are made in this activity. PMBOK defines the Project Time Management as the processes to manage the
timely completion of the project. The main documents produced by this area are: (1) schedule management plan; (2) activity list; (3) activity duration estimates; (4) activity attributes; (5) milestones list; and (6) project schedule. The involved processes are: (1) plan schedule management; (2) define activities; (3) sequence activities; (4) estimate activity resources; (5) estimate activity durations; (6) develop schedule; and (7) control schedule.

4. **Project cost management**: The projects generally have an approved budget to be executed. The amount depends on the origins of the project and the organizations involved. To perform the project within the approved or authorized budget, the Project Cost have to be Managed, which consists in plan, estimate and control the costs as the activities are finished, the results are delivered and although rare, the approved budget change (PMI, 2013). The main documents produced by this area are: (1) cost management plan; (2) activity cost estimates; and (3) cost baseline. The involved processes are: (1) plan cost management; (2) estimate costs; (3) determine budget; and (4) control costs.

5. **Project quality management**: Quality of a project is directly related to the results delivered to a customer and its satisfaction regarding it. It is related also to overcoming the Stakeholder’s expectation about the overall project progress. PMBOK defines Project Quality Management as the process that ensure that the project and product requirements are met and validated, but the Quality criteria may depends on organizational policies and the nature of the developed project. The main documents produced by this area are: (1) quality management plan; (2) process improvement plan; (3) quality metrics; and (4) quality checklists. The involved processes are: (1) plan quality management; (2) perform quality assurance; and (3) control quality.

6. **Project human resource management**: The Human Resource Management includes processes to organize, manage and lead the project team, which is comprised of all people with assigned roles and responsibilities for completing activities of the project development (PMI, 2013). The project team members may have varied skills, according to their roles in the project. Their participation time also vary, may be full time or added or removed as the project progresses. According to PMBOK the inclusion of all team members in project planning and decision making is beneficial because improve motivation and commitment, besides to add their expertise in the process. The main documents produced by this
area are: (1) human resource management plan; (2) project staff assignment; (3) resource calendars; and (4) team performance assessments. The involved processes are: (1) plan human resource management; (2) acquire project team; (3) develop project team; and (4) manage project team.

7. **Project communications management**: To ensure that all the project information is appropriately shared and stored, the Communications Management is necessary. The objective of Project Communications Management is to create effective communication methods so the diverse Stakeholders and project team may understand each other. The cultural, technical and organizational background difference are the primary sources of misunderstanding that can offer risks to the project progress and overall quality and can be avoided by managing the communications. The documents produced by this area are: (1) communications management plan; and (2) work performance information. The involved processes are: (1) plan communications management; (2) manage communications; and (3) control communications.

8. **Project risk management**: The risks of a project are any event that can change or frustrate project performance, quality, acceptance and results. The event can be unexpected or foreseen but controlled. According to PMBOK a risk is also a positive event that improves some result, cost saving, delivery time or affect any other knowledge area. Assuming that, the Project Risk Management is to plan, identify, analyze and control the risks, increasing the impact of positive events and decreasing the impact of negative events in the project. The documents produced by this area are: (1) risk management plan; and (2) risk register. The involved processes are: (1) plan risk management; (2) identify risks; (3) perform qualitative risks analysis; (4) perform quantitative risk analysis; (5) plan risk responses; and (6) control risks.

9. **Project procurement management**: The Project Procurement Management includes the processes necessary to purchase or acquire products, services, materials or any results needed from outside the project team (PMI, 2013). This knowledge area involves legal treatment of official documents such as agreements, contracts and Non-Disclosure Agreements (NDA). The Project Procurement Management includes suppliers management, that leads to a reliable relationship network among the organizations. The main documents produced by this area are: (1) procurement management plan; (2) procurement statement of work; (3) source
selection criteria; (4) selected sellers; (5) agreements; (6) resource calendars; and (7) closed procurements. The involved processes are: (1) plan procurement management; (2) conduct procurements; (3) control procurements; and (4) close procurements.

10. **Project stakeholder management**: The Stakeholder represents all the interested in project success people, groups or organizations and that could impact or be impacted by the project (PMI, 2013). The Project Stakeholder Management includes processes required to identify them, analyze their expectations and impact on project, and to develop appropriate management strategies for effective engaging them. The engagement of the Stakeholder in project decisions and execution is essential for their satisfaction, and according to PMBOK this should be managed as one of the main objective of the project, through continuous communication and understanding of their needs and expectation. The documents produced by this area are: (1) stakeholder register; (2) stakeholder management plan; and (3) issue log. The involved processes are: (1) identify stakeholders; (2) plan stakeholder management; (3) manage stakeholder engagement; and (4) control stakeholder engagement.

### 2.3 Cyber-physical systems project management

The management of a project of any field may bring many benefits, and depending on the methodology used, it is possible to deal with issues of all areas involved in the project, as showed previously. A focused in a specific field methodology can enable project teams to enhance the chances of success and improve its technical skills to solve future similar problems (COOKE-DAVIES; ARZYMANOW, 2003). According to Lee (2008), the problems to be solved with the development of CPS are not entirely new, but are problems solved by mixing many different fields. The CPS approach as a specific discipline, focused in these kind of problems, enable the scientific community to research neatly and the organizations to invest in appropriate technologies. The CPS areas of application lead to create, besides new type of issues, challenges and technological advancements, a new kind of users (RAJKUMAR et al., 2010). They are a mixing of biologists, chemist or still being lay users, but dealing with systems that interacts with something more complex than just computers. As well as the team members are a mixed kind of professionals, turned into a
single team that may work together and are responsible for project development (RAJKUMAR et al., 2010).

Although CPS projects management may prove challenging due its novel aspect, some initiatives have been done to focus the organization and administrative practices of CPS projects. Furthermore, development methodologies were adapted to fit in dynamical nature of CPS development. To explore these new trends of research, a Systematic Literature Review (SLR) was conducted aiming to evaluate the aspects of CPS management. The main objectives were to evidence when a CPS project was managed and list the knowledge area (PMI, 2013) involved, besides the analyses of challenges faced and workarounds found. The SLR included embedded systems projects management studies due its similarity with CPS.

The SLR found that some specific knowledge area were subjects of the authors when managing CPS and embedded systems projects. A trend of embedded systems expression replacement by CPS in the literature was also observed, with a decreasing number of works about embedded systems related with PM found against an increasing number of papers describing PM practices in CPS projects development, as seen in figure 3. The SLR studied researches describing the development of systems but with a focus on administrative or management issues, and not specific technical matters. The SLR also dismissed educational and other areas than computation articles. The results shows a that scope, human resources and stakeholder management concerns were most punctuated according to the relevance score, with 608, 437 and 222 respectively, explained by the dynamic aspect of CPS and embedded systems projects, besides multidisciplinary teams and technologies used.

Among the knowledge areas identified, project scope were managed using the following practices: international standards application; design model developing; peer reviewing requirements revisions and scrum boards; development methodology; meetings with live demos; use case and hardware points technique for activities estimation; software and frameworks for requirements analysis; and modeling languages for requirements elicitation and system architecture visualization (PARKHOMENKO; GLADKOVA, 2014; INSAURRALDE; PERTILLOT, 2013; HELPS; MENSAH, 2012; HUANG; DARRIN; KNUTH, 2012; RONG; ZHANG; JUN, 2011; SHATIL; HAZZAN; DUBINSKY, 2010; BERGER; RUMPE, 2010; SILVA; LOUBACH; CUNHA, 2009; JUN; RUI; YI-MIN, 2007; YUE; ALI, 2014; SAPIENZA; CRNKOVIC; POTENA, 2014; PENZENSTADLER; ECKHARDT, 2012; GARAY; KOFUJI, 2010). Project human resource challenges were managed with the following techniques: task distribution according to team member profile; multidisciplinary team building and an expert group for supporting; development
methodologies training; specific roles definition for team members; and team members profile estimation and classification (PARKHOMENKO; GLADKOVA, 2014; HELPS; MENSAH, 2012; HUANG; DARRIN; KNUTH, 2012; WOLFF; GORROCHATEGUI; BUCKER, 2011; RONG; ZHANG; JUN, 2011; SHATIL; HAZZAN; DUBINSKY, 2010; CHEN; WEI, 2009; YUE; ALI, 2014). Project stakeholder were managed using mainly the following techniques: face meetings; stakeholder participation on transitional phases of development; inside company stakeholder assignment; stakeholder identification and task assignment through application of algorithms and norms; and workshop meetings (HUANG; DARRIN; KNUTH, 2012; RONG; ZHANG; JUN, 2011; SHATIL; HAZZAN; DUBINSKY, 2010; YUE; ALI, 2014; SINGH, 2013; PENZENSTADLER; ECKHARDT, 2012).

It is possible to find common techniques for different knowledge area, besides a recurrence of use by different authors. Examples of these techniques are: periodically meetings; role definitions for team members, generally empowering them for decisions making; multidisciplinary team building, mixing competences; and elements of agile development methodologies, as scrum boards for activities monitoring. Table 1 shows the articles studied and its knowledge areas identified and table 2 the techniques used in each knowledge area. Figure 4 shows the main results from the SLR, presenting the number of articles found per knowledge area in the graph on the left and the relevance score, based on quantity of citations and emphasis given by the authors, per knowledge area in the graphic on the right. The relevance score was estimated using keywords that were relevantly recurrent on each knowledge area approach, as seen in table 3.

Table 1 - Studied articles

| #  | Authors                                      | Year | Keywords | KA       | RS |
|----|----------------------------------------------|------|----------|----------|----|
| 1  | Parkhomenko, A. V. and O. N. Gladkova.       | 2014 | ES       | H.R. 5   |    |
|    |                                              |      |          | Scope 29 |    |
|    |                                              |      |          | Communication 11 | |
|    |                                              |      |          | Time 15  |    |
|    |                                              |      |          | Cost 3   |    |
| 2  | Insaurralde, C. C. and Y. R. Petillot.       | 2013 | ES/CPS   | H.R. 10  |    |
|    |                                              |      |          | Scope 10 |    |
|    |                                              |      |          | Risk 13  |    |
| 3  | Helps, R. and F. N. Mensah.                  | 2012 | ES/CPS   | H.R. 24  |    |
|    |                                              |      |          | Communication 12 | |
|    |                                              |      |          | Procurement 1   | |
|    |                                              |      |          | Cost 23  |    |
|    |                                              |      |          | Time 28  |    |
|    |                                              |      |          | Quality 12 |   |
|    |                                              |      |          | Risk 9   |    |
|    |                                              |      |          | Scope 18 |    |
|    |                                              |      |          | Stakeholder 18 | |
| 4  | Huang, P. M., A. G. Darrin and A. A. Knuth.  | 2012 | ES       | H.R. 24  |    |
|    |                                              |      |          | Communication 12 | |
|    |                                              |      |          | Procurement 1   | |
|    |                                              |      |          | Cost 23  |    |
|    |                                              |      |          | Time 28  |    |
|    |                                              |      |          | Quality 12 |   |
|    |                                              |      |          | Risk 9   |    |
|    |                                              |      |          | Scope 18 |    |
|    |                                              |      |          | Stakeholder 18 | |
Table 2 - Techniques and methodologies used

| #  | KA                        | Practices                                                                 |
|----|---------------------------|---------------------------------------------------------------------------|
| 1  | H.R.                      | Tasks distribution according to team members profile                       |
|    | Scope                     | ISO/IEC 12207:2008                                                        |
|    | Communication             | Atlassian JIRA and Confluence                                             |
|    | Time                      | Atlassian JIRA                                                            |
|    | Cost                      | Hardware architecture analyses                                            |
| 2  | Scope                     | Hierarchic design using JAUS standard                                     |
|    |                           | Framework* for predetermined tasks division                              |
| 3  | H.R.                      | Multidisciplinary team division (Human Computer Interface, Information Assurance and Security, Electrical and Computer Engineering) |
|    | Scope                     | Design Model* (Creativity, Specification, Prototyping and Deployment phases) |
| Risk | The iterative aspect of the created Methodology |
|------|-----------------------------------------------|
| H.R. | Creation of small experienced team |
| Communication | Deputizing key team members and co-locating them |
| Scrum board |
| Procurement | Evaluation of COTS options plus vendor integration versus homemade low cost solutions |
| Cost | Non-linear process development flow |
| Time | Idem above / Scrum board |
| Quality | Early hw/sw test and integration / peer reviewing |
| Risk | Early hw/sw test and integration |
| Scope | Peer reviewing / Scrum board |
| Stakeholder | Often face-to-face status meeting with the sponsor |
| H.R. | Self planning and multidisciplinary sub-teams |
| Communication | Core team consisting of sub-project managers, lead engineers and overall project manager |
| Time | Core team meetings with Critical Chain PM |
| Quality | Core team meetings |
| Risk | Core team meetings with Critical Chain PM |
| Scope | Goal Driven Development |
| H.R. | Goal owner assignment / GDD training |
| Time | Weekly team meetings |
| Goal Question Metrics / Earned Value Management |
| Quality | Weekly team meetings |
| Goal Question Metrics / Software defect inject and removal technique |
| Stakeholder | Participation of each last launch phase / Goal profile report |
| Communication | Weekly team meetings / Goal profile report |
| Quality | Business day meeting performing live demos from last iteration |
| Agile Development Methodology using daily and on each iteration metrics |
| Time | Agile Development Methodology using daily and on each iteration metrics |
| H.R. | Roles definition (Tracker, Process Engineer and Architect) |
| Communication | Roles definition (Tracker, Process Engineer and Architect) |
| Scope | Business day meeting performing live demos from last iteration |
| Stakeholder | Proxy customer (the main system engineer) instead of the real one |
| Cost | Knowledge sharing |
| Quality | Developers as customer for previous iteration |
| Agile Development Methodology |
| Scope | Regression simulation for code production |
| Agile Development Methodology |
| Scope | Use Case Points Technique / Hardware Points* |
| Cost | Table of Hardware Relevant Factors |
| Hardware Points Technique* |
| Procurement | Table of Hardware Relevant Factors |
| Integration | Set of practices by Software Releasing and Product Delivering |
|    | Product Data Management                                                                 |
|----|---------------------------------------------------------------------------------------|
| 11 | Quality                                                                               |
| 12 | Integration                                                                           |
|    | Scope                                                                                 |
|    | Scope                                  |
|    | H.R.                                   |
|    | Stakeholder                             |
| 13 | Integration                                                                           |
| 14 | Scope                                  |
|    | Stakeholder                             |
| 15 | Scope                                  |
|    | Communication                          |
|    | Stakeholder                             |
| 16 | Scope                                  |
|    | Communication                          |
|    | Stakeholder                             |
| 17 | Scope                                  |

Source: Filipe Palma, 2015

Figure 3 - Number of studies found and relevance score per knowledge area respectively

Source: Filipe Palma, 2015

Table 3 - Knowledge areas and respective keywords for relevance score estimation

| KA          | Keywords                                        |
|-------------|-------------------------------------------------|
| Integration | Configuration management, PM, project processes.|
| Scope       | Requirements, function, properties, specification.|
| Time        | Schedule.                                       |
| Cost        | Cost, Budget.                                   |
| Quality     | Quality, QoS, reliable, trust, robust.           |
| Human Resource | Team, people, skill.                         |
| Communications | Information, document.                    |
| Risk        | Risk.                                           |
| Procurement | Acquire, purchase.                              |
| Stakeholder | Stakeholder, sponsor, customer.                 |

Source: Filipe Palma, 2015
3 Methodology

Both main areas involved in this project – CPS and PM – are intrinsically related to daily problems. The PM practice emerged to systematically solve business problems or to support challenges resolution. On another hand, CPS is a new approach to deal with the raise of technologies and interaction possibilities between real world and digital world. In this context, this research project uses the design science research paradigm (HEVNER et al., 2004) as drive of the development methodology. This section describes the design science concept and its application in the context of this research as well as details of the Systematic Literature Review (SLR) conducted as part of the methodology.

3.1 Design science research

According to Hevner et al. (2004), design science research is a problem-solving paradigm that works by creating innovative artifacts, which define ideas, practices, technical capabilities and products. Specifically in the Information Technology (IT) area, design science research creates and assesses IT artifacts intended to solve organizational problems. These artifacts are represented in a structured form that may vary from software, formal logic or rigorous mathematical to informal natural languages descriptions (HEVNER et al., 2004). When following design science research, the produced artifacts must meet at least one of the four classifications below (HEVNER et al., 2004):

- **Constructs**: related to contextualization elements providing vocabulary and symbols used to define problems and solutions.
- **Models**: related to representations of problems and solutions connections, using the constructs to enable real world representation and exploration of the effects of design decisions and changes.
- **Methods**: related to processes to solve the problems and may range from formal algorithms to textual description of best practices or a combination of them.
- **Instantiation**: related to demonstrations of the feasibility of the artifacts to its intended purpose, by applying the created constructs, models and methods in a working system.

Design science research should be distinguished from a simple “routine design” or “system building” (HEVNER et al., 2004). Routine design is described as the application of
already existing knowledge to organizational problems, using best practices artifacts existing in the knowledge base, while design science research addresses important unsolved problems in unique or innovative ways. Design science research may also improve known problems solutions by applying more effective or efficient ways. Accordingly, results obtained from design science research codified in the knowledge base become best practices. Finally, system building is the routine application of the knowledge base to known problems in systems development (HEVNER et al., 2004).

The process of design science research can be explored from the perspective of three cycles: relevance, rigor and design (HEVNER, 2007):

- **Relevance cycle**: described as a bridge between the contextual environment of the research and the activities of design science research. It is related to problems and opportunities identification and representation in an actual environment. It often provides requirements for research and defines acceptance criteria.

- **Rigor cycle**: connects the activities of design science research with the knowledge base of scientific foundations and past experiences, providing innovative aspect assurance of the research. This connection is made in order to guarantee that the designs produced are research contributions and not some application of already known process, characterizing routine design. It is imperative the application of the appropriate theories and methods to evaluate and develop the artifacts, that are dependent of the researcher skills.

- **Design cycle**: aimed to develop the methods and other artifacts. It is the core activity of design science research. It iterates by building and evaluating the artifacts and process. This cycle uses requirements from relevance cycle and theories from rigor cycle. And, for each iteration, it provides feedback for design improvement for the following iteration.

The first step was an exploratory search for PM studies related with CPS, following by a systematic state of art study. The exploratory search allowed assuring evidences of CPS’s PM relevance, as well as to develop the conceptual background of the research. Study cases describing technologic projects development, including all similar terms as embedded systems, hybrid systems and system-of-systems were explored, resulting in the decision of adopting the convergent term CPS. The systematic state of art study consisted of a SLR, which aligned with the relevance cycle of design science research, aimed at searching for the main challenges and gaps of CPS’s PM.
Applying the strategies described in the rigor cycle of design science research (HEVNER, 2007) and comparing the knowledge areas proposed in the PMBOK, it is possible to identify that the SLR resulted in three most addressed knowledge areas in CPS’s PM: scope, human resources and stakeholder. Once found the recurrence of these specific knowledge areas, the PM practices used on each study of the SLR were analyzed and compared with practices described in PMBOK. It was possible to find some new practices and some instantiations of already known practices. The SLR protocol is described in the following section.

Based on rigor cycle of design science activities, this Master project aims to analyze the results obtained by the identified PM practices, besides the use of practical previous experience and propose a set of PM best practices for CPS. These best practices may include models of classification, standardized forms and organizational strategies approaches, which is intended to validate at least partially with real projects of a company.

Accordingly, in the CPS’s PM context, the artifacts evaluated are the PM practices as described in the PMBOK but applied specifically in the CPS context. While the PMBOK describe constructs, models and methods, there are some specific cases that demonstrate their instantiations in the CPS context, such as the studies found in the SLR. The artifacts to be produced as result of this Master project will be adaptations of the PMBOK practices for the CPS context. Additionally, new instantiations may be produced by applying this new set of PM artifacts to problems and conditions related to CPS.

3.2 Systematic literature review protocol

In order to find works related to the context of CPS’s PM as well as the related problems described in such works, a SLR was conducted following the guidelines and phases proposed by Kitchenham (2007) in order to keep the reproducibility by other researchers. The main objective was to correlate the PM practices observed in CPS development with respect to the best practices of the PMBOK. Thus, studies describing any type development related to CPS, but focusing on some PM aspect, were analyzed. Considering the conceptual similarities, as described in section 2, this SLR included also considered the embedded systems in addition to CPS.

The planning phase of the SLR aimed at developing a research protocol, which defines the purposes and procedures to be adopted over the SLR. In order to drive the objectives, four
research questions were elaborated. They are responsible to lead the results to comprehensive conclusions and collaborations. The elaborated research questions are:

- **Research question 1**: Are there evidences of practical application of PM practices in the development of CPS or embedded systems?
- **Research question 2**: Which PMBOK’s knowledge areas and suggested methods and tools are addressed in the found approaches?
- **Research question 3**: For each specific PMBOK’s knowledge area addressed, which are the results presented by the found methods and tools?
- **Research question 4**: Are there challenges are gaps that are mentioned as still not solved with the approaches found?

These four research questions aimed at answering the main research objective thoroughly, indicating the PMBOK’s knowledge areas used, the results of their applications, and existing gaps or challenges. They help to refine the search for results and emphasize the contribution of the SLR.

During the conducting phase, the first step was to define a search engine that may provide relevant studies. As an indexer of the main databases, Scopus was selected, allowing obtaining papers from ACM Digital Library, IEEE Explore, Springer, among others. With this, works regarding computer science, engineering and business, among others, could be found. The search string defines the main keywords used to search papers that may be consistent with the research. Specifically for this case, the keywords had to express both CPS and PM, besides embedded systems. Variations over these three words were used, resulting in two main research strings, as shown in table 4.

| String Focus         | Exact used string                                                                                                                                                                                                                                                                                                                                 |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CPS                  | (TITLE-ABS-KEY("Cyber-Physical System*" OR "Cyber Physical System*" OR "Cyberphysical System*")) AND TITLE-ABS-KEY("Project" OR "Manag*")) AND PUBYEAR > 2004 AND (LIMIT-TO(SUBJAREA, "COMP") OR LIMIT-TO(SUBJAREA, "ENGI")) AND (LIMIT-TO(DOCTYPE, "cp") OR LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "ip")) AND (EXCLUDE(LANGUAGE, "Chinese") OR EXCLUDE(LANGUAGE, "German") OR EXCLUDE(LANGUAGE, "Portuguese") OR EXCLUDE(LANGUAGE, "Spanish")) |
| Embedded Systems     | (TITLE-ABS-KEY("Embedded") AND TITLE-ABS-KEY("Project Manag*")) AND PUBYEAR > 2004 AND (LIMIT-TO(SUBJAREA, "ENGI") OR LIMIT-TO(SUBJAREA, "COMP")) AND (LIMIT-TO(DOCTYPE, "cp") OR LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "ip")) AND (EXCLUDE(LANGUAGE, "Chinese") OR EXCLUDE(LANGUAGE, "French") OR EXCLUDE(LANGUAGE, "Japanese") OR EXCLUDE(LANGUAGE, "Slovene"))                                                                                                                                 |

Source: Filipe Palma, 2015
Moreover, two Inclusion Criteria (IE) and eight Exclusion Criteria (EC) were elaborated to be applied on the results obtained from the engine, based on the search strings, to guarantee the relevance of the final set of studies. The IC and EC elaborated and used to define the studies are as follows:

- **Inclusion criteria:**
  - IC-1: The paper addresses CPS/embedded systems as main theme.
  - IC-2: The paper describes some experience in PM.

- **Exclusion criteria:**
  - EC-1: The paper addresses only technical details and challenges of the CPS application area with no type of contribution from the PM perspective.
  - EC-2: The paper aims at contributing with other areas than PM, such as education, medicine, chemistry or logistics.
  - EC-3: The term “management” is used in the context of technical resources management, i.e. performance, security, reliability, robustness or autonomy.
  - EC-4: The paper dates before 2006, since the first time CPS was proposed was in 2006.
  - EC-5: The publication was not a peer-reviewed.
  - EC-6: The paper is written in other language than English.
  - EC-7: The paper is not electronically available.
  - EC-8: The paper is a secondary study, such as a review or a survey of other studies.

Title and abstract section of each work returned in the search in Scopus were read, applying these inclusion and exclusion criteria, evaluating it correlation with the research. When needed, part of introduction and conclusion also were read. Once identified the selected papers, called primary studies (KITCHENHAM, 2007), the entire paper were read, evaluating them to answer the defined research questions and summarizing the main topics of each work. The results of this SRL, which has been already finalized is summarized in section 2.
4 Proposed approach – CPS-PMBOK

This section includes the details of use and the concepts that led to propose the so-called CPS-PMBOK approach. The proposed approach consists in provide a CPS project characterization model and a specialization of the PMBOK’s PM processes related to “scope”, “human resources” and “stakeholders” management to the specific context of CPS development processes. These three knowledge areas were the outcomes of the SLR conducted for this Master’s research, which aimed to identify the most studied knowledge area. Applying a relevance score, based on number of times that all primary studies addressed keywords regarding each knowledge area, scope, human resources and stakeholders appeared with a relevance score above average, as described in section 2. The CPS characterization model aims to enhance the comprehension of the project to be developed for the project team, besides to support project size estimation. In a general way, another important advantage of a model is formalizing the systems’ characteristics (DERLER; LEE; VINCENTELLI., 2012). The knowledge areas specialization aims to provide a set of best practices particularly applicable for CPS development projects. According to Cooke-Davies and Arzymanow (2003), focused PM practices can bring benefits as innovation, adaptability aiming the project success and an effective lessons learning practice, improving the experience of project team.

The presentation of the CPS-PMBOK approach, is organized in three subsections: (1) approach overview, which includes general considerations about: the applicability of the CPS-PMBOK approach; the applicability of the remaining practices described in PMBOK; and the other areas of knowledge; (2) CPS characterization model, which includes a set of possible technical characteristics and its influence in a CPS project characterization, separated in “CPS environment” and “CPS complexity”; and (3) PMBOK’s knowledge areas specialization, which includes best practices regarding scope, human resources and stakeholders management for CPS project development.

4.1 CPS-PMBOK approach overview

Although this approach focus on scope, human resources and stakeholders management, some considerations about general PM practices of CPS development are presented, familiarizing project managers with CPS projects. The goal is to provide to project
managers, the comprehension of CPS-PMBOK’s construction enough to adapt their behavior on managing CPS projects, and not only the literal instantiation of the practices proposed.

The CPS-PMBOK is based on subject and team multidisciplinary, an usual aspect of CPS (SHA et al., 2009; LEE 2008; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014). Multidisciplinary means that the project team consists of many different specialties professionals due the computational and physical world integration. In this context, understanding that possible communication boundaries between organization departments should be broken, is essential for project development. The project manager should facilitate communication in a general way and accordingly, the PMBOK provides a set of best practices regarding communications management that are applicable for CPS projects, but greater attention among the most disparate specialties professionals may be required. Ways to response this need of greater attention include: to keep up the project disclosure; and to assign the role of explainer for some senior professional, for each team specialty group, that also can be responsible for updating tasks progress. Huang , Darrin and Knuth (2012) and Wolff, Gorrochategui and Bucker (2011) used the team leader empowerment practice, obtaining effective team communication and commitment.

Based on professional experience and concerns mentioned by Huang , Darrin and Knuth (2012) and Silva, Loubach and Cunha (2009), it is observed that depending on the company, external resources may be necessary as outsourcing elements to be integrated to the CPS. This occurs because some specialties are so specific and its need of use is so sporadic that is uneconomical to build a team with such specialties. Examples of that are: heavy industrial machining, dielectric packing and simulations, e.g. antenna radiation, physical robustness or heat dispersion. Outsourced organizations may be included as project partners since the first project phases so that they can contribute to the system specification. A partnership based approach may be necessary in the process of hiring the outsourced companies, using non-disclosure contracts that provide some benefits for both sides, for example. Although not specifically partnership based, the procurement knowledge area, described in PMBOK deals with practices for appropriate outsourcing and hiring management.

Due to still unknown integrated technologies and even some new specific area of application, as robotic medical surgery, autonomous vehicles and smart building, CPS tends to have an innovative aspect (RAJKUMAR, 2012). Another source of innovation necessity is the high complexity to modeling the physical world and its phenomena. This innovation-related scenario leads to constant requirement changes, due to: stakeholders’ conception
realign; further issue understanding; rise of new technologies; and adaptation of unstructured processes. A late discovery of new requirements is inevitable due to the exploratory development methodology required and adopted by many organizations (HUANG; DARRIN; KNUTH, 2012). CPS project managers should properly search for new requirements in a constant way, bringing up the changes as soon as possible. Besides contribution for system specification, a partnership based approach with outsourced company enables to fulfill the development of the constantly changing requirements involved outsourced company.

All these considerations regarding CPS aspects must be assessed by the project manager, while conducting a CPS project development, independently to using the CPS-PMBOK approach. Moreover, the previous considerations help to understand in which context the CPS-PMBOK approach is proposed. According to the SLR outcomes, it is understood that the other areas of knowledge offer less influence in CPS project development success, being the PMBOK practices enough to well manage the project.

4.2 CPS characterization model

The CPS characterization model proposed was developed based on the most frequent technological characteristics found in CPS projects or similar applications, such as embedded, obtained through professional experience, exploratory review and the SLR conducted for this Master’s research. These characteristics cover: CPS’s influence on the environment, due the ways of use or applicability; and technologies that can be part of the system. The model proposed doesn’t intend to create a closed set of characteristics, but an open model that makes possible future expansion, adding different points of view from different authors’ experiences and technological improvements. At first, the model covers CPS environment and CPS complexity views.

The application environment of a CPS is composed by all the elements that determine the use of its compound systems, including: (1) people involved; (2) physical infrastructure or localization; and (3) routine of use. Two categories related to the application environment of a CPS are defined: “well-defined processes” and “dynamic”, as stated below:

1. **Well-defined processes:** in a well-defined processes application environment, the CPS performs limited tasks and interacts with a known group of people. The physical infrastructure is generally standardized by industrial rules and the influence of the physical world is minimal. The low dynamic of the environment
embraces applications where sensoring often occurs slowly and the application may be stand alone, communicating and actuating with a limited and known number of devices. A well-defined processes application environment can generally be found, for example, in: (i) industrial applications, as automated tests (SCHWEIGHOFER; RAAB; BRASSEUR, 2003); (ii) construction, with structure health monitoring (CHANG; FLATAU; LIU, 2003); and (iii) power supply, as smart grids (FANG et al., 2012; ZABALLOS; VALLEJO; SELGA, 2011).

2. **Dynamic:** in a dynamic application environment, the CPS deals with unexpected situations and with unknown behavior of people. The processes which the CPS is interacting with can be modeled, despite its complexity. CPS applications in this kind of environment are generally located into hard access, mobile or hazardous structures. From the point of view of use, these applications are often intelligent, presenting such autonomy and a large implementation of sensors. The actuators may include large engines and high rate radiofrequency signals. Examples of the use of such dynamic application environments are in: autonomous vehicles (INSAURRALDE; PETILLOT, 2013); surgical interventions (BALLANTYNE, 2002; TAYLOR; STOIANOVICI, 2003); and nuclear plant monitoring (LIN; WANG; SUN, 2004; FANTONI et al., 2003; MA; JIANG, 2011).

In order to make possible the interaction with the physical world, the CPS development may need to deal with several different technologies as well as some existing and running systems. Therefore, the complexity of a CPS may depends on how many other systems influence the tasks performed by it or are influenced by its existence; i.e., the CPS complexity is represented by the amount of systems integrated to the CPS, or the role played by the CPS, such as the role of systems that completely replace a human activity and the role of an industrial factory support system, used to show data so that an operator can make the decisions. Although the more systems are integrated, more complex the CPS is, it is also possible to find examples of CPS formed by only one system but with a large number of sensors, actuators or high computational cost that enhance its complexity. A set of common technological items able to be integrated to a CPS is categorized as follows:

1. **Mechanical structure:** CPS often must be built over a structure or have a supporting mechanics. In this case, the mechanical structure is part of the CPS development project and must be considered as part of the CPS. Some important examples of CPS that use mechanical structures are robotic applications such as
drones, rescue vehicles or even industrial assembling machines. Common constraints regarding mechanical structures include weight and robustness.

2. **Network:** the necessary network among the CPS devices is a relevant factor in applications in which communication is necessary, for example when wireless sensors networks and smart power grids are involved. The entire link can be part of the CPS, including the antenna, the demodulation and the messages decoding.

3. **Sensors:** sensors represent the bridge between the physical and the computational worlds. Sensors mainly allow a CPS to read the variables around it, providing information to adapt its processing or performance. Mostly, a CPS is integrated to at least one sensor, which can be a camera or other physical input, e.g. to acquire radiofrequency signals.

4. **Actuators:** actuators are responsible for interpreting environment readings previously performed by the sensors and giving the feedback of such readings. Actuators may appear in the way of switches, engines action or electrical signals. CPS may be not integrated with actuators, responding to environment readings through a simple graphical user interface.

5. **Data storage:** many CPS can collect a huge amount of data, leading to the need for adequate data storage resources. Such data can be processed later or be used more than once. Due to the high level of details necessary to precisely digitalize physical world's analogic signals, CPS often requires specialized solutions for data storage and retrieval usually associated to the so called “big data”.

6. **User interaction:** a user interface is an optional technological item since not all CPS are used or operated by people, such as totally embedded systems. Otherwise, specific standards that make analogies to other software or hardware involved in the users’ activities may be necessary to those CPS that will be accessible to people, i.e., when users or operators can act in place of a CPS or a CPS depends on users’ judgment to continue the operation.

7. **Legacy systems integration:** as CPS can be developed to automate human tasks or making possible unfeasible tasks, they can commonly interact with some existing system. Such so called legacy systems can include: existing software; semiautomatic machines; mechanical structures; and even industrial processes. All these variables may turn a simple into a complex application, and represent a different approach of a CPS implementation, aiming at a productive enhancement and transparency for the users of the system in the way that was before.
8. **Power energy system:** many CPS are autonomous and mobile systems or even works in an isolated environment, far from power source. This implies in designing an alternative and self-sustainable power source. The power source must be appropriate for type of equipment involved and environment of application and may require specific professionals of energy systems design.

In summary, the complexity of a CPS being developed can be measured by verifying the existence of one or more of the previous eight technological items. This characterization model can be applied as some estimation method, through application of weights for each characteristic according its influence, frequency or amount of use, besides support the understanding of the entire CPS development project. Frame 1 shows an example of CPS characterization model according to both classifications previously presented in terms of “environment” and “complexity”. It uses percentage for CPS environment and pre-established weights for CPS complexity, and can be used for project size estimation.

Frame 1 - CPS characterization model

| CPS classification model |
|--------------------------|
| CPS environment          |
|                          | (%) | (%) |
| Well-defined processes   | Dynamic | |
| Complexity               |     |     |     |
| Integration with:        | Few | Avg | Many |
| • Mechanical structures  |     |     |     |
| • Network                |     |     |     |
| • Sensors                |     |     |     |
| • Actuators              |     |     |     |
| • Data storage           |     |     |     |
| • User interaction       |     |     |     |
| • Legacy systems integration |   |     |     |
| • Power energy system    |     |     |     |

Source: Filipe Palma, 2015
4.3 Knowledge area adaptations

Aligned with the CPS and CPS characterization model presented in the previous sections, the PM processes related to the scope, human resources and communications knowledge areas were specialized to meet such specific characteristics in order to establish the new CPS-PMBOK version proposal. According to the conducted SLR outcomes, these three knowledge areas may represent the most efforts to manage a CPS project, with relevance scores above the average, as described in section 2. The specializations of these PM processes allow CPS-related project managers and project teams to deal earlier with common challenges faced in the development of this type of project, such as continuously and sudden discovery of requirements, originated from the unexplored application which is the CPS; and lack of communication among team project and stakeholders, due the multidisciplinary of technical subjects involved. The three adapted knowledge areas inside the CPS-PMBOK context are presented in the following sections.

4.3.1 Project scope management

According to PMBOK, the processes related to the scope management aim to ensure that the planning and development of the project include all the tasks needed to complete it. The work necessary to achieve the project goals are defined and described according to the scope planning processes and the work execution is verified according to the scope monitoring and controlling processes. The planning processes offer special challenges for CPS development projects due the innovative aspect of applicability, as discussed previously (SHA et al., 2009; LEE 2008; RAJKUMAR et al., 2010; BAHEti; GILL, 2011; LEE; SESHIA, 2014).

Specifically for CPS-PMBOK, due to the evolution characteristic of CPS development projects and consequent the constantly changing scope, a whole new process is proposed for this knowledge area. The new process, named “review requirements”, is proposed as part of the monitoring and controlling process group. This process is a practice resulting of previous professional experience, observing the behavior of many customers, whom used to make revisions of their own project’s goals and definition. The review requirements process aims to advance these revisions, bringing up the changes as soon as possible, so it can be treated timely. The review requirements process generates change requests such as control scope
process, described in PMBOK. The difference is that in the CPS-PMBOK approach, review requirements is a creation focused process, considering less the already known requirements and revisiting the highest definitions of the project in search of new requirements, while the control scope process focuses on ensuring the accomplishment of defined scope, and when needed, the appropriate processing of changes. The review requirements process uses as inputs: (1) project management plan; (2) requirement documentation; and (3) requirement traceability matrix. The tools and techniques suggested are: (1) meetings; (2) interviews or surveys; and (3) processes simulations. The outputs: (1) change requests; (2) project management plan updates; (3) project documents updates; (4) organizational process assets updates.

Aiming to supporting the collect requirements and define scope processes described in PMBOK, the CPS-PMBOK proposes the use of pre-elaborated lists of requirements, based on CPS complexity and environment attributes of the CPS characterization model proposed. The use of pre-elaborated lists may improve requirements detailing and coverage of scope definition. Furthermore, if constantly updated according to requirements changes, the pre-elaborated lists may enhance lessons learned, reducing uncertainly of requirements for future similar projects. A pre-elaborated list of hardware requirements were applied by Silva et al. (2009) aiming to estimate the necessary effort for development. The technique is called hardware points analysis and were used in an aerospace project context (SILVA, LOUBACH; CUNHA, 2009). The pre-elaborated list can be used for support the requirements elicitation from different point of views. Frame 2 presents an example of use of the hardware points technique, using weight punctuation meaning necessary effort assigned for every technical question. Frame 3 presents a proposal of pre-elaborated list of software requirements as a tool for initial requirements collection, indicating a general level of subject on the left, and respective technical questions on the right. This list is proposed in the context of the CPS-PMBOK approach.

Frame 2 - Example of hardware points technique applied

| Factor                                                                 | Given Weight |
|------------------------------------------------------------------------|--------------|
| How many communication interfaces the hardware has? (e.g. USB, Ethernet, RS-232) | 5            |
| How the electric power system will be?                                 | 2            |
| Topic                                                                 | Description                                                                 |
|----------------------------------------------------------------------|----------------------------------------------------------------------------|
| Is it a distributed system?                                          | 5                                                                          |
| Are there any communication interfaces that need data output using extra hardware? (e.g. LCD) | 1                                                                          |
| Are there any communication interfaces that need data input using extra hardware? (e.g. Keyboard) | 1                                                                          |
| Will the hardware be interrupted to answer external asking? (e.g. To update some attribute, to give its status) | 3                                                                          |
| Is there any need to execute more than one task or process on the processor? (e.g. multiprocessor system) | 4                                                                          |
| Is there any need to use a Real-Time Operating System (RTOS)?        | 4                                                                          |
| What is the skills’ level the involved technical team has, considering embedded systems development? | 5                                                                          |
| Is it needed to develop any Board Support Package (BSP) to integrate the RTOS and hardware platform or development kit? | 4                                                                          |
| Will the hardware components be developed or integrated?             | 5                                                                          |

Source: Adapted from Silva, Loubach and Cunha, 2009

Frame 3 - Overall software requirements topics

| Topic               | Description                                                                 |
|---------------------|-----------------------------------------------------------------------------|
| Automation level    | How much human intervention is required?                                    |
| Processing load     | How complex the data collected processing is?                              |
| Data storage        | How large is the data type acquired?                                        |
|                     | Which technology is used to storage results?                                |
| Graphical interface | How should the graphical interface look like?                               |
| Running period      | For how long does it need to run?                                          |
| Parameters insertion| May it be possible to register new parameters?                              |
| Web access          | May it be necessary web visualization or operation?                         |

Source: Filipe Palma, 2015

In further steps of this Master research, it is intended detailing the review requirements process assessing its relation regarding other processes of scope management and from other
areas of knowledge, such as quality, cost, time and integration management, fitting the process in conformance with other PMBOK processes. For pre-elaborated lists of requirements, it is intended to create more specifics, detailed and complete lists, considering more cases of literature and basing on CPS characterization model proposed as part of the CPS-PMBOK approach.

4.3.2 Project human resource management

PMBOK describes that the main challenges for managing team members relationships are: different industry experience; language; and even working styles. Considering the multidisciplinary context of CPS development projects, the human resources that may be part of a project team can be from very different areas of specialization, what increases the challenge of managing relationships and technical communications (WOLFF; GORROCHATEGUI; BUCKER, 2011). In a practical example, a project to develop a smart power grid system may include professionals from electrical supply, hardware design, telecommunications and software development. Professionals from electrical supply and software may be not familiar with hardware technologies, while telecommunications professionals and hardware designers come from a very different school, where software is not object of study, and so on. These different academic approaches applied in a same product or project result may cause misunderstanding between team members, influencing requirements comprehension and even task priorities.

To minimize the misunderstandings and enhance project development performance, the CPS-PMBOK proposes a specialization of the cross training of people, briefly cited in PMBOK as preventive action for team member changes. Unlike only prevent changes, an intense cross training approach may improve communications, commitment and skills development. A cross training is an allocation strategy which consists in a double assignment of tasks: one person, more experienced should be the main responsible, and a second professional not familiarized in that area following the task development, learning and even making some minor deliveries. In this approach, the second professional is becoming able to discuss technical issues and could be the main responsible for a similar task in a next project. This approach focuses on multidisciplinary teams with multidisciplinary people and would be part of “develop project team” process described in PMBOK. The drawback is that it may spend a resource delivering less than others, enlarging the budget of the project.
Another practice proposed by CPS-PMBOK is to pre-divide the team into sub-teams, according to specialties commonly found in CPS, supporting the “plan human resource management” process, described in PMBOK. Helps and Mensah (2012) applied a team division based on academic profiles, such as electrical engineering, computer engineering and information technology. Similar to Helps and Mensah (2012), the CPS-PMBOK approach is based on CPS complexity of the characterization model, with more generic specializations, and it may be used for support designing organizational breakdown structures (OBS) or resource breakdown structures (RBS). Team divisions may include varied departments or even external organizations; and they may exist or not, according to project needs. Considering the main applications visualized by Rajkumar (2012); Sha et al. (2009); and Kim and Kumar (2012), and CPS project complexity characterization model, team divisions for CPS-BPMOK are proposed as follows:

1. **Mechanical design team:** consisting of mechanical and mechatronics engineers or technicians, this team is responsible for all the structural design, including materials to be used, technical drawings and actuator specifications and configurations.

2. **Hardware design team:** consisting of experts in automation and control, digital measurements, digital signal processing, hardware architecture, among other specific areas needed according to the project environment. This team is responsible for specifying the equipment used for data acquisition, processing and communication, including, for example, computers, embedded processors, microcontrollers, programmable logic controllers, sensors, cameras and actuators. It also supports basic equipment configuration and programming.

3. **Electrical design team:** consisting of electrical engineers and technicians, this team is responsible for elaborating the electrical specification and installing the supporting components, based on both mechanical and hardware settings.

4. **Network design team:** consisting in telecommunication engineers and technicians, this team is responsible for defining the network hardware and standard specifications, including, for example, proper antennas or cables, and protocols used for the communication devices. For wireless networks, special attention may be given to regulations concerned to radiofrequency propagation in the environment. For industrial networks, compatibility and security issues may be taken into account.
5. **Information system development team:** consisting in computer and software engineers, this team is responsible for software development, data storage architecture design and implementation, and graphical user interface development.

This team division is proposed in order to improve performance of CPS development projects and avoiding inappropriate assignment of responsibilities, and is based on general needs of CPS, but it can be adapted according to specifically project needs, based on context of application of the system. An alternative division is to base on deliverables or partial results of the project, assigning a focused team for each logical deliverable part of the CPS developed. For further developments of this research, intends to create new team divisions, embracing project development processes independently of technical profiles, such as the division described by Shatil, Hazzan and Dubinsky (2010) which defines roles of: process tracker, in charge of maintaining the status communication; process engineering, in charge of development planning; and architect, in charge of development of the system.

### 4.3.3 Project stakeholder management

Project stakeholders in a context of CPS development projects are usually very technical or close to the final users of the system. This occurs mainly in joint projects of research with universities, where the stakeholders are professors and students. Another occurrence is in industrial projects aiming to improve production performance, where many stakeholders are production leaders with knowledge of many existent technologies of the area (RAJKUMAR, 2012; BAHETI; GILL, 2011).

In this context, the CPS-PMBOK approach proposes specialization of techniques of the manage stakeholder engagement process, described in PMBOK. Stakeholders engagement brings benefits to the project as mutual understanding of requirements, project quality and project performance. The interpersonal and management skills described in PMOK for stakeholder engagement management may be improved, considering technical skills demonstration for the specific area of application of the CPS. In CPS-PMBOK proposal, the skills for a project management may include: building technical trust, which can be fulfilled by an expert team member or an external consultant. The technical trust may improve stakeholders’ satisfaction, due their proximity of technical issues.

As stakeholder management is closely related with communications, quality, human resource and scope management, the proposed practices may influence other processes of
these knowledge areas. The PMBOK cites the communication methods described in communications management as a technique to manage stakeholder engagement, but as observed in the outcomes of the SLR conducted, this may be not enough to keep stakeholders properly updated. Huang, Darrin and Knuth (2012) use face-to-face meetings to update the status of project to stakeholders. Rong, Zhang and Jun (2011) include stakeholders’ participation in every last weekly follow-up meeting of development iterations. Penzenstadler and Eckhardt (2012) organize weekly workshops for system demonstrating, aiming to update stakeholders. Considering the previous practices, CPS-PMBOK approach proposes a combination of these meetings, according to project phase and stakeholders availability: (1) regular face-to-face meetings in the initial stages, for stakeholder trust building and project needs comprehension improvement, influencing the scope management; (2) sporadic participation of stakeholders in internal and technical meetings in the development stages, for technical trust building, feedback providing and new requirements analyses; and (3) project workshops with live demonstration of CPS developed, with stakeholders participation, occurring as soon as possible to visualize the system.

These practices aim to enhance stakeholders’ engagement and consequently satisfaction, providing opportunities to improve project quality as unexpected requirements are discovered. For further developments of the CPS-PMBOK approach, it is intended to correlate the influence of the proposed meeting in the other knowledge areas, besides proposes new techniques for manage and control stakeholder engagement processes.

4.4 Approach evaluation

To evaluate the CPS-PMBOK approach proposed, the developed best practices will be applied to real CPS development projects in a private research and development company. The objective is to get the evaluation of the project team and project management team regarding the influence of the CPS-PMBOK for project development. It will be applied objective questionnaires specific for both sides: the project team questionnaire including questions regarding the impact (benefits or losses) in work environment, communication and comprehension of the activities; and the project management team questionnaire including questions regarding the impact (benefits or losses) in team commitment, project performance and stakeholder satisfaction.

Due the possible difficulty to apply the CPS-PMBOK approach in already running projects, different practices will be evaluated in different projects. The projects can be from
different complexities, application, size and running in different moments of development. Therefore, to avoid missing evaluation of some part of the proposal, two parallel evaluations will be applied:

- **Finished projects:** the CPS-PMBOK practices will be presented and explained for recently finished projects’ teams and projects management’s team, and then the questionnaires will be applied, instructing the participants to list the main difficulties found in project and consider the application of CPS-PMBOK in the most challenging issues among scope, human resources and stakeholder.

- **Running projects:** the CPS-PMBOK practices will be presented and explained for project management teams and the application of each practice will be negotiated, respecting the organizational policies and availability of project team. The questionnaires will be applied after the negotiated period of evaluation and the duration of the applied practices will be considered in the questionnaires analyses.
5 Work plan

For the sequence of development of this Masters project, it is expected to achieve the following steps:

6. Improve CPS characterization model through exploratory literature review, considering more CPS development project case studies.
7. Develop details of scope management, contextualizing the review requirements process to the PMBOK standard.
8. Improve examples of the pre-elaborated lists of requirements through exploratory literature review, considering more CPS development project case studies, in order to extend the usability of the lists.
9. Review the team division practice for human resource management, considering more case studies and professional areas.
10. Review and improve stakeholder management practices.
11. Evaluate the CPS-PMBOK approach, following the steps:
   - Select running projects.
   - Negotiate availability of CPS-PMBOK practices application.
   - Apply CPS-PMBOK explanation and respective practices.
   - Select finished projects.
   - Apply CPS-PMBOK explanation and respective questionnaires.
   - Apply questionnaires for running projects participants.

The schedule containing the subprojects and deliveries necessary to finish this Master’s project is presented in Frame 4, which includes the following activities:

A. Disciplines accomplishment of Master’s course.
B. Exploratory analysis regarding the subject.
C. Master’s project subject definition.
D. Systematic literature review conduction.
E. Prior definition of proposed approach.
F. Systematic literature review improving and inclusion of more recent studies.
G. Approach detailing.
H. Development of document for Qualification exam.
I. Qualification exam.
J. CPS-PMBOK approach improvement and finalization.
K. Evaluation of proposed approach.
L. Elaboration of dissertation.
M. Dissertation defense.

Frame 4 - Schedule of activities

| Activity | 2014 | 2015 | 2016 |
|----------|------|------|------|
| A        |      |      |      |
| B        |      |      |      |
| C        |      |      |      |
| D        |      |      |      |
| E        |      |      |      |
| F        |      |      |      |
| G        |      |      |      |
| H        |      |      |      |
| I        |      |      |      |
| J        |      |      |      |
| K        |      |      |      |
| L        |      |      |      |
| M        |      |      |      |

Finished activities
Planned activities

Source: Filipe Palma, 2015
6 Final considerations

Cyber-Physical Systems (CPS) are complex technological systems, originated by the integration of computational world, represented by computers, operational systems, sensors, actuators and software; and the physical world, represented by the modeling of physical phenomena, including human presence. A network usually connects different elements as computers to sensors, actuators to computers and even computers to computers. The development of CPS requires high level of innovation and multidisciplinary professionals involved. It is often an exploratory project aiming to create new technologies or proofs of concepts.

The project management (PM) is a practice of monitoring and controlling a project to ensure the objective and constraints accomplishments. It brings benefits for all kind of project segments, since construction to development of information systems. In this context, CPS development projects benefits from PM practices. Due the many different practices of PM, resultant from different professional experiences, academic backgrounds and cultural factors, the Project Management Institute keeps a body of knowledge with the main best practices of PM, called PMBOK.

As each specific area of application may benefit even more from focused project management practices, this Masters project aims to propose a set of PM best practices focused on CPS development projects. The approach proposed is called CPS-PMBOK and is based on knowledge areas and best practices described in PMBOK. The research identified the management of three knowledge areas as more relevant for CPS: scope, human resource and stakeholder. The CPS-PMBOK uses practices found in literature and professional experiences to propose best practices consisting in: a CPS characterization model; and a specialization of these three knowledge areas. The CPS-PMBOK approach aims to enhance project team comprehension of the developing CPS, as well as the project performance, minimizing undesired effects of the multidisciplinary team and innovative aspects of CPS. Another objective is proposes a reusable and expandable set of best practices, so it can be used for future projects. It is also intended with this research, to enhance the adoption of PM practices for CPS.
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Appendix A – Systematic Literature Review article submitted to the IEEE Transactions on Engineering Management

Project Management Practices in Cyber-Physical Systems Development: a Systematic Literature Review

Abstract
Cyber-Physical Systems (CPS) are the new generation of complex systems, keeping up with the necessities to interact and understand the physical world. Embedded Systems (ES) are the late technological platforms developed to provide powerful performance executing dedicated computational tasks. CPS concept includes ES applications as well as a lot of other technological disciplines. To lead the development of these kinds of projects to success, Project Management (PM) may be used, enhancing the understanding and controlling of internal and external variables. Some particular challenges may be faced when managing CPS projects, due to its multidisciplinary teams involved, complexity of environment and dynamic requirements.

In this paper, a Systematic Literature Review (SLR) was conducted aiming to explore the challenges faced by the scientific community while managing CPS and ES projects. The main authors’ concerns when managing and developing CPS projects could be observed as divisions in Knowledge Areas, established by PMI PMBOK. A set of use cases were listed and analyzed regarding their effectiveness.

Keywords - Cyber-Physical Systems, Embedded Systems, Project Management.

1. Introduction
There is a growing need to understand the physical phenomena as well as the capacity to produce increasingly smaller and more powerful computing platforms. These events are followed by the capacity of transferring data and communicating in long distances. Understanding the physical phenomena may be useful to improve quality of life or to develop new technologies [1]. To meet this need, some specific computing systems that interact with the physical world are developed. These systems are called Cyber-Physical Systems (CPS) [2]. The development of CPS requires a multidisciplinary team, and may involve analysts and engineers from the most varied areas, such as chemistry, physics or biology [3].

Project Management (PM) is a practice that allows a project manager to control and measure the progress of the development of a project. It also includes planning and monitoring the motivation of all individuals involved in the project [4]. The Project Management Institute (PMI) keeps a body of knowledge called PMBOK [5], compiling a set of best practices and guidelines for PM in a general purpose. It describes ten Knowledge Areas (KA) representing each one as a specific professional field inside the PM activity. They are: Integration, Scope, Time, Cost, Quality, Human Resource (HR), Communications, Risk, Procurement and Stakeholder management. PM may improve potential factors of success, which leads the project to satisfactory results. As other areas of systems development, the CPS development project should have some level of management, in order to improve the chances of success.

It is possible to find some approaches focused in a specific area of project development such as construction [6, 7], aerospace and defense (government) [8] or web applications [9,
A focused methodology of PM provides means to deal with particular issues of the area, which may not be appropriate to others. This research aims to find the particular problems in the CPS area.

The nature of the problems treated in CPS is not new, but its approach as a distinct area is recent [11]. Embedded Systems (ES) is an area of application that has very similar characteristics to those found in CPS solutions. Embedded Systems are programs that run dedicated to a limited set of tasks and usually in a specific hardware [11]. Generally these ES communicate with other equipment or modules, collecting data from real world events and translating to human comprehensive information. Another role of ES application is data logging, acquiring analog measurements from the environment and storing them for future analyses or traceability of physical phenomena.

ES can be considered as the nearest application area of CPS [2]. The difference is that CPS has a wider scope than ES, i.e. ES are the technology or architecture and CPS is the nature of the problem to be solved. Other approaches similar to CPS are: Test and Measurement [12], Test and Monitoring [13], Virtual Instrumentation [14] and Measurement and Control [15]. All these approaches are generally industrial names for automation projects developed for manufacturing industries. The CPS concept is more open to the application and collaboration between disciplines. It can involve network technologies, sensors, actuators, machine vision, among others, at the same time. A concept map is offered by Lee et al to illustrate the converging areas and concerns regarding CPS [16]. Some examples of CPS application can be seen in [17], [18] and [19]. From now on, this paper refers CPS and ES as only CPS, unless otherwise stated.

In this paper, a Systematic Literature Review (SLR) is conducted to find the challenges being faced in CPS project managing, as well as the solutions used and possible trends of improvement of some specific knowledge area approaches. The remainder of this paper is structured as follows: Section 2 presents some related works regarding CPS, ES and PM; Section 3 presents the methodology used in the conduction of the SLR; Section 4 and 5 present the results and a discussion; and Section 6 concludes this paper, summarizing the contribution and presenting future works.

2. Related Work

In order to investigate the current state of systematic researches regarding CPS and PM, works containing these keywords were searched. The expressions “Cyber-physical Systems”, “Embedded Systems” and “Project Management” were used with possible combinations of “Systematic Literature Review”, being “Systematic Review” and SLR. The data base used was Scopus [20] and there were no results returned. Thus, separated searches were made, investigating systematic researches of CPS, ES and PM individually. The results show some CPS related works dealing with Software Engineering issues, such as Development Methods [21] and Software Architecture [22]. A third work describes Software Processes involved in the ES Development [23]. Regarding the PM SLRs, three works were found, dealing with one or two Knowledge Areas related to Software Development, in general purpose. The first article deals with Stakeholder Management [24]. The second explores the perspective of the suppliers about a project success [25], considering the suppliers as one of the Stakeholders. The third work mixes Software Engineering and PM issues - more precisely, Scope Management - dealing with the users requirements transformation in model analysis [26].

3. SLR Methodology

The main goal of conducting a SLR is to evaluate some specific aspects of an area, technology, methodology or phenomena - being natural or social - providing information for
future researches. This information can be used as motivation, reference or simply a summary of these specific topics [27]. In the area of software engineering, the SLR conduction may prove more difficult in regards to separating evidence and identifying external factors that threatens its reliability, because the experiments are more able to manipulate results, as software development is an iterative activity [28]. The investigated works of a SLR are called Primary Studies, which can be works containing: a detailed description of developing systems, technique analysis or methodology evaluation. These primary studies generally are bound to a specific topic of an area. Secondary Studies are those that evaluate or summarize primary studies related to a specific topic. SLR is a form of secondary study [27].

To provide a reliable SLR, the guidelines described by Kitchenham [27] were followed. In these guidelines, some general steps are proposed to conduct a SLR, grouped into three main phases: Planning, Conducting and Results, presented in the sections 3.1, 3.2 and 4 respectively.

3.1 Planning

The planning phase aims to define the main topics and characteristics of the research, as well as the formalization of appropriate descriptions. There are three main definition steps belonging to the planning phase: a) the need for a SLR; b) the research questions; and c) the review protocol. Although Kitchenham has proposed five steps [27], the commissioning step is not applicable in the case of this research and the evaluating review protocol will be described within the review protocol development.

3.1.1 The need for a SLR

As seen in the Related Works section, no SLR regarding CPS correlating to PM was found. All the other reviews found deal with some technical issue of systems development regarding to CPS or ES. In the general PM area, the authors focused in only one or two KA. In the cases where a Survey was conducted, the papers show particular point of views describing some challenges experienced by the authors, showing non-systematic methods [29]. Despite the still important collaboration of these works, it is unquestionable that the conclusion drawn by the authors depends on their background and technical expertise.

The development of a SLR can provide a unbiased vision of the state of the art regarding CPS and ES Project Management. A well conducted SLR helps to summarize the main used CPS definitions and concepts, as well as evaluates the real use and challenges faced of PM practices.

3.1.2 The Research Questions

To lead the results to comprehensive conclusions and collaborations, one or more Research Questions must be defined. This will support the future users of the SLR to check if the goals of this research are useful for them, besides allowing the verification of conclusions against the results. The main goal of this SLR is to identify studies that relate CPS with PM, presenting its challenges and practices used to solve them. The four research questions (RQ) are defined as follows:

RQ1: Are there evidences of practical application of PM practices in CPS or ES development?

This is the primary Research Question, aiming to elucidate if the community of PM area or CPS are interested in the possible issues found by this research. It can also assess how
much and since when the scientific community has been concerned with the PM of these kind of projects. The validity of this research can be verified by evaluating the characteristics of the results presented as well as the number of related studies.

RQ2: Which PMBOK’s Knowledge Areas and suggested methods and tools are addressed in the found approaches?

The purpose of this question is to identify which KA are explored when a CPS project is managed, and which KA are presenting some level of challenge in this activity. The answer to this question may show some unknown characteristics of these projects i.e. some behavior trends that allow researchers to focus on some specific issue when managing a CPS project. The practices can be associated to the KA through this question as well, enabling researchers to judge the rate of use and its influence to PM. Another possibility is to evaluate if the already known approaches until then are enough to manage projects of this nature.

RQ3: For each specific PMBOK’s Knowledge Area addressed, which are the results presented by the found methods and tools?

This question complements RQ2, specifying when the challenges faced could be managed or not. The obtained results may be evaluated in order to verify the effectiveness of the practices applied. The purpose of this question is to identify possible weaknesses of these practices when applied to CPS projects. The goal is to stimulate future improvement of these methods, whether for exclusive use of CPS projects or general purpose. New methods or approaches could be proposed regarding the answer of RQ2 and 3.

RQ4: Are there challenges or gaps that are mentioned as still not solved with the approaches found?

The last question aims to identify the gaps found in management of CPS projects. The answer also may point to some challenges that could not be solved only with PM practices, helping to identify another kind of issue, motivating future research in CPS development.

3.1.3 The Research Protocol

The protocol of a SLR is a set of information that allows any other researcher to conduct this same SLR, validating the non-bias aspect of the results. It describes exactly the methods used to obtain the primary studies and the evaluation criteria [27]. The Research Questions viewed in the previous section may be part of the protocol [28] and the next steps are: a) Data source definition; b) Studies selection; c) Information extraction and d) Summarized Results. The step c) is described in this section but its execution is detailed in the next section: 3.2 Conducting. The step d) is addressed in section 4. Results.

a) the database used to obtain the primary studies was Scopus [20], an online search engine that indexes many databases such as ACM DL [30], IEEE [31], Springer [32] and ScienceDirect (Elsevier) [33]. These are the main sources of scientific articles and papers regarding Computation and Project Management, among other areas. The primary keywords chosen were “Cyber-Physical System” and “Project Management”, with the possible variations combined: “Cyber Physical” and “Cyberphysical”. To enhance the number of results, a symbol “*” was used at the end of the word “System” informing that plural was requested also. The same for the expression “Management” varying to Manager. As no results were found, the keyword “Project Management” was broken in two, embracing studies where
the authors describe the progress of a CPS project development and some aspects of PM can be seen. This decision was made to obtain as many results as possible, to avoid missing some significant study and allowing to eliminate undesired results later [34]. The entire search strings are shown in Table 5.

Table 5 - Search Strings

| Main Keyword | Exactly Used String |
|--------------|---------------------|
| CPS          | (TITLE-ABS-KEY("Cyber-Physical System*" OR "Cyber Physical System*" OR "Cyberphysical System*") AND TITLE-ABS-KEY("Project" OR "Manag*")) AND PUBYEAR > 2004 AND ( LIMIT-TO(SUBJAREA,"COMP") OR LIMIT-TO(SUBJAREA,"ENGI") ) AND ( LIMIT-TO(DOCTYPE,"cp") OR LIMIT-TO(DOCTYPE,"ar") ) OR LIMIT-TO(DOCTYPE,"ip") ) ) AND ( EXCLUDE(LANGUAGE,"Chinese") ) OR EXCLUDE(LANGUAGE,"German") ) OR EXCLUDE(LANGUAGE,"Portuguese") ) OR EXCLUDE(LANGUAGE,"Spanish") ) |
| ES           | (TITLE-ABS-KEY("Embedded") AND TITLE-ABS-KEY("Project Manag*")) AND PUBYEAR > 2004 AND ( LIMIT-TO(SUBJAREA,"ENGI") OR LIMIT-TO(SUBJAREA,"COMP") ) AND ( LIMIT-TO(DOCTYPE,"cp") OR LIMIT-TO(DOCTYPE,"ar") ) OR LIMIT-TO(DOCTYPE,"ip") ) ) AND ( EXCLUDE(LANGUAGE,"Chinese") ) OR EXCLUDE(LANGUAGE,"French") ) OR EXCLUDE(LANGUAGE,"Japanese") ) OR EXCLUDE(LANGUAGE,"Slovene") ) |

After a preliminary analysis of the results, the keywords “Embedded System” were included in the search, aiming to reach works that describe similar applications to CPS, as discussed in the Introduction Section. Unlike the CPS keywords, the entire word “Project Management” was used since ES is an older concept and more results showed up. This increases the chances to identify the greatest number of studies related with PM of CPS as possible.

b) as strategy of studies selection, Include and Exclude Criteria (IC and EC respectively) were established, so that only those really related to this SLR should be selected. The study must meet all the set of include criteria to be selected as a primary study and if only one of the exclude criteria was met by the study, it will be considered out of the primary studies. The criteria are as follows:

IC-1 The paper addresses CPS/ES as main theme.
IC-2 The paper describes some experience in PM.
EC-1 The paper addresses only technical details and challenges of the CPS application area with no type of contribution from the PM perspective
EC-2 The paper aims at contributing with other areas than PM, such as education, medicine, chemistry or logistics.
EC-3 The term “management” is used in the context of technical resources management, i.e. performance, security, reliability, robustness or autonomy.
EC-4 The paper dates before 2006, since the first time CPS was proposed was in 2006.
EC-5 The publication was not a peer-reviewed.
EC-6 The paper is written in a language other than English.
EC-7 The paper is not electronically available.
EC-8 The paper is a secondary study, such as a review or a survey of other studies.

The decision of the year 2005 as limit for the publications is due to the introduction of CPS concepts dating to 2006 [35], while also the practices and methods of PM have changed
since 2005 [36]. Although ES date before 2005, the main interest of this SLR is the CPS in a wider context of ES, as explained Introduction Section. In addition to the historical fact, a search by the keywords related to CPS in Scopus [20] returns a paper from the year 2006 as oldest result. The peer review exclusion criterion is a manner to ensure the quality and relevance of primary studies.

c) the information extraction strategy consists of reading the Title and the Abstract sections by identifying the primary studies. In the cases where these sections weren’t enough to identify the real contribution of the study, the Introduction section was read. Once defined as primary study, the entire paper is read, highlighting the main PM practices used. A summary or brief comments are made to speed the paper identification in further readings. At this stage a software tool called StArt (State of the Art through Systematic Review Tool [37] was used to support the organization of studies.

3.2 Conducting

This section aims to describe all steps needed for conducting this SLR. It presents the progress of primary studies identification and details the information extraction. Two basic activities were executed: i) Defining Primary Studies and ii) Extracting the Information.

i) as explained in section 3.1.3 item a), the search was divided in two stages: CPS keywords and ES keywords search. The search string was applied in the Scopus [20] engine returning 1480 results considering the sum of CPS and ES keywords. By applying the areas and sub-areas filter according to EC and the date filter according to EC 4, 5 and 6, 846 papers returned in total.

Observing the time distribution of the studies returned, the date that researchers began to explore the concepts of CPS became clearer: no results were found before 2007. Based on this fact, it was decided to use only the studies after 2006 regarding the ES string. This may allow to include only ES papers related with CPS concepts, even though the authors did not use the expression.

The IC and remainder EC (1, 3, 7 and 8) were applied in these papers, following the information extraction strategy described in section 3.1.3 c). In the cases of doubts or ambiguities regarding the compliance to IC/EC, the Introduction and Conclusion sections were read. As the papers were read, comments about the decision of inclusion or exclusion were made, registering the matching EC. At the end, 17 studies are part of the Primary Studies, considering the CPS and ES keywords searches, except the duplicates. Figure 4 shows the time distribution of the results, before the application of the IC/EC.

ii) the extraction of the information occurred by following the strategy described in section 3.1.3 c): the entire paper was read thoroughly, searching for evidence to answer mainly the Research Questions 2 and 3. The RQ 1 is answered by the application of Include Criteria, showing evidence of practical applications of PM in CPS projects. To evaluate which KA were involved in the study, the descriptions of PMBOK [5] were compared with the issues described in the studies. Thus, each paper had one or more corresponding Knowledge Areas. Even if the main concern of the authors is a specific Knowledge Area, but some aspects of others shows up, this other Area was considered, but a weaker correlation with the study was considered. Aiming to express this correlation, a Relevance Score (RS) was created, using as criterion the number of times that each issue was mentioned and the focused given by the authors for each KA. For the mentioning assessment, a set of keywords was defined for each KA, based on the previous analyses of exploratory review. Table 6 shows the possible KA, its description and possible keywords.
The identified practices were correlated to the identified Knowledge Area, and a brief description of it was made. The practices can include: procedures adopted on most variate situations and stages of the project progress; computational tools, as services or not, that support decisions, register information and generate previews of project progress; and a combination of both aiming to help visualization of overall progress of the project. Created or consolidated practices were considered.

4. Results

This section presents the outcome of the Primary Studies analysis. The studies #3, #4, #6, #7, #8 and #9 described, in addition to PM practices, some development methodologies [41, 42, 44, 45, 46, 47]. Development Methodologies are practices used to organize and execute the programming of a software. It can be used to manage teams, since the division of tasks and attribution of responsibilities are due to the Methodology adopted, as well as the following up of development progress, e.g. [21]. In the cases where only a methodology or design technique was explored, the EC-1 were applied. Some studies focused on a specific sub-area of CPS, such as #2 for autonomous maritime vehicles [40], #3 for space bus applications [42], #4 for mobile phone design [43] or #17 [55] for wireless sensor network development. This does not invalidate the inclusion of these studies, since the main goal of this SLR is to identify all kinds of PM challenges. Table 7 shows all Primary Studies, its respective KA and the Relevance Score over each Knowledge Area. Some studies mixed more than one methodology and even created a new one. Table 8 shows the used techniques and methodologies.

![Figure 4 - Time Distribution of Results](image)

### Table 6 - Knowledge Areas and its descriptions

| KA        | Description                                                                 | Main Activities                                                      | Keywords                                  |
|-----------|-----------------------------------------------------------------------------|---------------------------------------------------------------------|-------------------------------------------|
| Integration | Identification, definition and coordination of project process and activities. It may include activities related to Configuration Management also. | - Develop Project Charter and Management Plan                        | Configuration management, PM, project processes. |
|           |                                                                             | - Direct, manage, monitor and control Project Work                   |                                           |
|           |                                                                             | - Perform Integrated Change Control                                  |                                           |
| Scope | Practices regarding to ensure that the conception of the project includes all the work required and only the work required to complete it successfully. |
|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Time  | Processes to ensure the timely completion of each activity and task, as well as the overall project.                                                                                               |
| Cost  | Processes to ensure that the project can be completed within the approved budget.                                                                                                              |
| Quality| Processes to ensure the execution of the project is enough to satisfy the needs for which it was started.                                                                                           |
| Human Resource | Process that organize and lead the team members according to their skills. To ensure their commitment also.                                                                                                    |
| Communications | Practices required to ensure appropriate disposition and diffusion of project information.                                                                                                                                                                           |
| Risk   | Processes and practices aiming to forecast, control and respond to unexpected events that can generate noncompliance of requirements and dissatisfaction.                                                |
| Procurement | Process needed to purchase and acquire products and services from outside the project team.                                                                                                                                                             |
| Stakeholder | Process to identify and manage expectations of concerned people, group or companies regarding project success .                                                                                                                                            |

Table 7 - Primary Studies, its KA and RS

| #  | Authors                                             | Year | Keywords | KA  | RS  |
|----|-----------------------------------------------------|------|----------|-----|-----|
| 1  | Parkhomenko, A. V., and O. N. Gladkova.            | 2014 | ES       | H.R. | 5   |
|    |                                                    |      |          | Scope| 29  |
|    |                                                    |      |          | Communication| 11 |
|    |                                                    |      |          | Time | 15  |
|    |                                                    |      |          | Cost | 3   |
| 2* | Insaurralde, Carlos C., and Yvan R. Petillot.      | 2013 | ES/CPS   | H.R. | 10  |
|    |                                                    |      |          | Scope| 10  |
|    |                                                    |      |          | Risk | 13  |
| 3  | Helps, Richard, and Francis N. Mensah.             | 2012 | ES/CPS   | H.R. | 24  |
|    |                                                    |      |          | Communication| 12 |
|    |                                                    |      |          | Procurement| 1   |
|    |                                                    |      |          | Cost | 23  |
|    |                                                    |      |          | Time | 28  |
|    |                                                    |      |          | Quality| 12  |
|    |                                                    |      |          | Risk | 9   |
|    |                                                    |      |          | Scope| 18  |
|    |                                                    |      |          | Stakeholder| 18 |
| 4* | Huang, Philip M., Ann G. Darrin, and Andrew A. Knuth. | 2012 | ES       | H.R. | 51  |
|    |                                                    |      |          | Communication| 5   |
|    |                                                    |      |          | Procurement| 1   |
|    |                                                    |      |          | Cost | 23  |
|    |                                                    |      |          | Time | 28  |
|    |                                                    |      |          | Quality| 6   |
|    |                                                    |      |          | Risk | 4   |
| 5* | Wolff, Carsten, Idania Gorrochategui, and Markus Bucker. | 2011 | ES       | H.R. | 51  |
|    |                                                    |      |          | Communication| 5   |
|    |                                                    |      |          | Procurement| 1   |
|    |                                                    |      |          | Cost | 23  |
|    |                                                    |      |          | Time | 28  |
|    |                                                    |      |          | Quality| 6   |
|    |                                                    |      |          | Risk | 4   |
| 6  | Rong, Guoping, et al.                             | 2011 | ES       | Scope| 11  |
| # | KA | Practices                                                                                                                                 |
|---|----|------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | H.R. | Tasks distribution according to team members profile                                                                                     |
|    | Scope | ISO/IEC 12207:2008                                                                                                                        |
|    | Communication | Atlassian JIRA and Confluence                                                             |
|    | Time | Atlassian JIRA                                                                                                                             |
|    | Cost | Hardware architecture analyses                                                                                                             |
| 2 | Scope | Hierarchic design using JAUS standard                                                                                                     |
|    | H.R. | Multidisciplinary team division (Human Computer Interface, Information Assurance and Security, Electrical and Computer Engineering)       |
| 3 | Scope | Design Model* (Creativity, Specification, Prototyping and Deployment phases)                                                            |
|    | Risk | The iterative aspect of the created Methodology                                                                                           |
| 4 | H.R. | Creation of small experienced team                                                                                                        |
|    | Communication | Deputizing key team members and co-locating them                                                                                |
|    |     | Scrum board                                                                                                                               |

* Indicates a specific application
| Procurement | Evaluation of COTS options plus vendor integration versus homemade low cost solutions |
|-------------|-------------------------------------------------------------------------------------|
| Cost        | Non-linear process development flow                                                 |
| Time        | Idem above / Scrum board                                                            |
| Quality     | Early hw/sw test and integration / peer reviewing                                   |
| Risk        | Early hw/sw test and integration                                                    |
| Scope       | Peer reviewing / Scrum board                                                        |
| Stakeholder | Often face-to-face status meeting with the sponsor                                  |
| H.R.        | Self-planning and multidisciplinary sub-teams                                       |
| Communication | Core team consisting of sub-project managers, lead engineers and overall project manager |
| Time        | Core team meetings with Critical Chain PM                                           |
| Quality     | Core team meetings                                                                  |
| Risk        | Core team meetings with Critical Chain PM                                           |
| Scope       | Goal Driven Development                                                             |
| H.R.        | Goal owner assignment / GDD training                                                |
| Time        | Weekly team meetings                                                                |
| Quality     | Goal Question Metrics / Earned Value Management                                      |
| Scope       | Weekly team meetings                                                                |
| Stakeholder | Participation of each last launch phase / Goal profile report                       |
| Communication | Weekly team meetings / Goal profile report                                         |
| Quality     | Business day meeting performing live demos from last iteration                      |
| Time        | Agile Development Methodology using daily and on each iteration metrics              |
| H.R.        | Roles definition (Tracker, Process Engineer and Architect)                          |
| Communication | Roles definition (Tracker, Process Engineer and Architect)                          |
| Scope       | Business day meeting performing live demos from last iteration                      |
| Stakeholder | Proxy customer (the main system engineer) instead of the real one                   |
| Cost        | Knowledge sharing                                                                  |
| Quality     | Developers as customer for previous iteration                                      |
| Scope       | Agile Development Methodology                                                       |
| Quality     | Regression simulation for code production                                           |
| Scope       | Agile Development Methodology                                                       |
| Cost        | Use Case Points Technique / Hardware Points*                                        |
| Procurement | Table of Hardware Relevant Factors                                                   |
| Integration | Table of Hardware Relevant Factors                                                   |
| Quality     | Table of Hardware Relevant Factors                                                   |
| Integration | Set of practices by Software Releasing and Product Delivering                       |
| Quality     | Product Data Management                                                             |
| Integration | Set of practices by Software Releasing and Product Delivering                       |
| H.R.        | Fuzzy Belief-Desire-Intention approach*                                             |
| Integration | CMMI practices adaptation for ES software development                               |
Only a few studies demonstrated the use of commercial or developed computational tools. The paper #1 [39] used IBM Rational Requisite Pro to improve the Scope management registering the requirements. To manage Communication, the authors used Atlassian’s tools JIRA and Confluence as a follow up of activities, feedback of the system to be developed and sharing information. JIRA could be used to manage Time and Cost by observing the progress of the assigned tasks to the team. Although not specifically named, the authors of the study #2 [40] managed the Scope and requirements using CAD models to analyze and illustrate the discussions in the peer-review sessions. Paper #11 [49] developed a tool to support the team members allocation along the project development, based on technical and personal profiles and behaviors. The authors in #12 [50] developed a software processes management tool called “Future” based on what they call Simplified Parallel Processes, a software process specification referring CMMI level 3. Enterprise Architect with Model Driven Generation plug-in was used in paper #16 [54] to support modeling and registering project scope documentation, as well as the use of SysML and UML language modeling.

Papers #5, #10, #11, #13, #14 and #15 use many PM practices and explore some adaptations for CPS in a general way, such as team divisions, project conceptual analyses and stakeholder management [43, 48, 49, 51, 52, 53].

By applying the IC/EC, it was observed in the excluded articles that some areas showed up more frequently than others. Considering papers focused in Education techniques, Capstone development and discipline approaches, 45 results were found. The ES keywords search resulted in 46 articles regarding Construction, describing from Construction Project Management to Embedded Systems for building simulation, data acquisition for Structure Health among other applications. In the CPS keywords stage, 17 papers described practices, algorithms or techniques for Cyber Security and Network Communication improvements.

5. Discussion of Results

By the numbers presented in the 3.2 Conducting Section, it is possible to answer the RQ1: “Is there evidence of practical application of PM methods in CPS or ES development?” The time distribution presented in Figure 4 shows that such evidences are growing in a general context. Related to ES studies, they had been more expressive until 2010, when the results reversed by the CPS studies. Although the term CPS was coined in 2006 [34], it takes some time for the companies and the scientific community to start to produce studies and use
cases. It is possible to state also that PM studies related to ES are slowly decreasing, being replaced by CPS related studies.

Table 7 and Table 8 answer the RQ2: “What Knowledge Areas and methods are involved with the study?” It can be seen that most studies were concerned with more than one KA and some of them used more than one approach to deal with specific KA. Most of the studies also described the methodology or technique used as useful for more than one KA management, mainly those that described development methodologies [41, 42, 44, 45, 46]. Three studies [40, 41, 48] developed their own methodologies based entirely or partially on existing approaches. The study #2 [40] in addition explores an approach specific for the area, and the studies #4 [42] and #5 [43] used traditional approaches but for specific applications. This leads to the belief that already used methodologies can be used or briefly adapted for new kinds of problems and challenges, while some focused approaches sometimes are necessary too.

Almost all KA showed up more than once as a concern point of the studies, leaving only Integration Management with only one mention. A possible explanation is that Integration Management works like a planning of the remaining KAs, making its approach less evident. Figure 5 shows the distribution of studies per KA regarding quantity and Relevance Score. It is possible to observe that the community has the awareness of the PM importance, mainly regarding Human Resources, Scope and Stakeholder. This may be a reflection of the multidisciplinary teams involved with CPS development, as for its novel aspects and complexity. The dynamic scope and requirements of the project also collaborated to achieve these results.

The answer to the RQ3: “For each Knowledge Area, what were the results presented by the tools or techniques used?” can be summarized as prevention of project failure by most studies. It can be considered, that for each KA found, its goal described in Table 6 was fulfilled. Table 9 details the main achievements of the Primary Studies.

Table 9 - Main Achievements

| #  | Achievements                                                                 |
|----|-----------------------------------------------------------------------------|
| 1  | - Requirements structure that can be used for other embedded systems of the same type |
|    | - Information sharing                                                        |
| 2  | - Early simulations for successful system integration                        |
| 3  | - Iterative design model                                                     |
|    | - Multidisciplinary team structure                                          |
| 4  | - Structured set of practices and recommendations                            |
| 5  | - Transparent planning                                                       |
|    | - High commitment level by the team                                          |
| 6  | - Structured methods for requirements elicitation                           |
7 - Agile Development Methodology
   - Cultural issues softened
8 - Change Management strategy
9 - Hardware Estimation Methodology
10 - Formal Practices and Procedures to Software Release and Product Delivery activities
11 - Tool that suggests dynamically allocation of team members
12 - Standardization of PM through improving software processes
13 - Quick tasks assignment
14 - Requirements accomplishment through requirement driven PM
15 - Improvement of stakeholder identification
16 - Abstracting project model enhancing communication
17 - Provide general architecture for WSN project conceptualization

There was no clear answer to the RQ4: “Is there some challenge that could not be solved with the methods applied?” in most studies. Instead, it was possible to identify some unexpected challenges, although well managed. These challenges occurred mainly because of the innovative aspect of the projects, besides the adaptation of the team to the proposed methods and techniques. Table 10 shows a couple of unexpected challenges faced, limitations and unsolved issues.

| #  | Limitations                                                                 |
|----|-----------------------------------------------------------------------------|
| 1  | Only for embedded system based on microcontrollers                          |
| 2  | Focused on specific technology (autonomous maritime vehicles)               |
| 3  | Not applied yet, only conceptual so far                                     |
| 4  | Validated in a specific application (satellites)                            |
| 5  | Team members adaptation to the methods                                     |
| 6  | Team members adaptation to the methods                                     |
| 7  | Only applied by software team                                              |
| 8  | Specific for autonomous vehicles development                               |
| 9  | Not applied yet, only conceptual so far                                     |
| 10 | Different approaches for different hardware                                 |
| 11 | Not completely applied yet, missing real considerations                     |
| 12 | Software only focused                                                      |
| 13 | Only for a very large number of requirements                                |
|    | Requires a previous hard analysis of the team profile                      |
| 14 | It doesn’t consider social aspects for requirements elicitation             |
| 15 | It works better for long projects and high number of stakeholder            |
|    | Increase the complexity of project planning                                 |
| 16 | Some technical level of stakeholder is required                             |
| 17 | Too much particular elements of the authors                                |

All these Primary Studies and their outcomes may be used for the most diverse project development, even those not related to this research. A great number of practices used are the same as used in an ordinary software development context. There were some papers mentioning Agile approaches as methodologies [42, 45, 46] following the trend of the computer community [38]. A physical and computational approach is observed as an integration of hardware and software in many papers, reflecting the industrial changes seen nowadays. Another evidence of this adaptation of the scientific community is the adoption of CPS technologies by the most diverse areas, as well as Construction, Education and Telecommunication as seen in the Results Section.

Regarding the new challenges of PM in CPS, it may be included as mandatory profiles of a team: energy efficiency and network security professionals, besides Engineers, Analysts and Information Systems professionals. Another possible area of further collaboration is Database management and Information Visualization, since CPSs are great providers of raw data ready to be processed into information and future knowledge.

As discussed in the Results Section, few tools are used to manage a CPS project. This can mean a lack of specific tools for PM of these kinds of projects or the effectiveness of
techniques and methodologies is greater than the use of tools, even if focused on CPS projects.

6. Conclusion

In order to find a correlation between PM practices [5] and CPS [1, 2] development projects, a SLR was conducted including ES [11, 34] development projects, due to its similarity with CPS.

The main findings show that all KA described in PMI PMBOK [5] were objects of study for at least one paper. Human Resource, Scope and Stakeholder were the KA that most authors worked on, wherein some briefly adapted traditional techniques and methodologies were enough to deal with the challenges faced by them. The main adaption made by the authors was the approach of hardware development tied with software development. A clear evidence is the massive use of Agile Methodologies [21, 38] in the development of both software and hardware, despite the lack of a unique model to deal with these separated disciplines. Agile Methodologies are commonly used in software development where the requirements change continually. This can be considered as a characteristic of CPS, since the physical world is a dynamic environment. This explains the topic of Scope Management as one of the main results. The results of Stakeholder and Human Resource Management are due to the multidisciplinary professionals involved in CPS development, but all approaches found are specific to the author’s corporate environment, available team and product to be developed. The methodologies may have been adapted for use in other variations of these factors. As seen in the 5. Discussion of Results Section, some authors focused on the development of particular approaches for a specific area of application also, such as maritime autonomous vehicles [40] or mobile phone software development [43].

Agile development methodologies, allied with multi hierarchic teams and adequate practices of communication seems to be the trend to deal with challenges faced while managing CPS development projects. No formal and general purpose inside the CPS context model of management could be found from the results. The wide application and complexity of CPS may be the cause of such lack. The benefits of understanding the physical world and interacting with it has driven companies and academia to develop and research CPS even more efficiently, which makes the PM practices even more relevant.

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