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Project management best practices for cyber-physical systems development

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“The best way to find yourself is to lose yourself in the service of others.”

(Mahatma Gandhi)

Abstract

PALMA, Filipe Edson da Silveira Pazotto. **Project management best practices for cyber-physical systems development**. 2016. 122 p. Dissertation (Master of Science) – School of Arts, Sciences and Humanities, University of São Paulo, São Paulo, 2016.

The integration between the computing world and the physical world in a single system is called Cyber-Physical Systems (CPS). CPS systems aim to improve understanding and influence in physical phenomena and environmental behaviors by computing means. The interaction of the computing world with the physical world, through the use of sensors, actuators and network communication often leads to the accomplishment of highly complex and multidisciplinary projects. Project management is a practice that enhances the success probability of a project, monitoring and controlling relevant aspects to the project execution. Project Management Body of Knowledge (PMBOK) is a set of best practices regarding project management which addresses ten knowledge areas aiming to support project managers from any application domain. Although PMBOK proposes a generic approach, some specialized practices for a particular application domain may benefit highly challenging projects. In this context, this research work aims to propose a set of best practices specific for CPS systems development projects. The proposed approach is called CPS-PMBOK (junction of terms cyber-physical systems and project management body of knowledge) and is based on PMBOK's three knowledge areas: scope, human resource and stakeholder. CPS-PMBOK includes: *(i)* a CPS characterization model which supports the understanding of the system to be developed; and *(ii)* specializations of these three PMBOK's knowledge areas, which provide a whole new process for the project scope management as well as specific improvements of well-known techniques for both the human resource management and the stakeholders management. The goal of CPS-PMBOK is to enhance project effectiveness and CPS quality, embracing both project manager and developers. To evaluate CPS-PMBOK effectiveness and adherence, the practices were presented for project managers and developers in a R&D company. The practices: pre-elaborated list of requirements, specialized team division and technical trust showed as more relevant for each respective knowledge area, according to managers. For developers, the review requirements process, cross training and technical trust seems to contribute more for its respective knowledge areas.

Keywords: Project management. Cyber-physical systems. Embedded systems. PMBOK.

Resumo

PALMA, Filipe Edson da Silveira Pazotto. **Melhores práticas de gestão de projetos para o desenvolvimento de sistemas ciberfísicos**. 2016. 122 f. Dissertação (Mestrado em Ciências) – Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, São Paulo, 2016.

A integração entre o mundo computacional e o mundo físico em um único sistema é chamada de Sistemas Ciberfísicos (CPS – do inglês "Cyber-Physical Systems"). Sistemas CPS visam melhorar o entendimento e a influência nos fenômenos físicos por meios computacionais. A interação do mundo computacional com o mundo físico, por meio de sensores, atuadores e redes de comunicação, frequentemente leva à realização de projetos de alta complexidade e multidisciplinares. Gestão de projetos é uma prática que aumenta as chances de sucesso de um projeto, monitorando e controlando aspectos relevantes da realização do projeto. PMBOK (Project Management Body of Knowledge) é uma combinação de boas práticas relacionadas à gestão de projetos que trata dez áreas de conhecimento visando auxiliar gerentes de projeto de qualquer área de aplicação. Embora PMBOK proponha uma abordagem genérica, algumas práticas especializadas para determinadas áreas de aplicação particulares podem beneficiar projetos altamente desafiadores. Neste contexto, este projeto de pesquisa visa propor um conjunto de boas práticas para projetos de desenvolvimento de sistemas CPS. Essa abordagem é chamada de CPS-PMBOK (junção dos termos em inglês: cyber-physical systems e project management body of knowledge) e é baseada em três áreas de conhecimento do PMBOK: escopo, recursos humanos e partes interessadas. CPS-PMBOK inclui: *(i)* um modelo de caracterização de sistemas CPS que auxilia o entendimento do sistema a ser desenvolvido e *(ii)* especializações dessas três áreas de conhecimento do PMBOK, que fornecem um inteiramente novo processo para a gestão de escopo do projeto assim como melhorias específicas de técnicas conhecidas do PMBOK para os processos de gestão de recursos humanos e de gestão de partes interessadas. O objetivo da CPS-PMBOK é melhorar a eficácia do projeto e a qualidade do sistema CPS desenvolvido, abrangendo tanto o gerente de projeto quanto os desenvolvedores. Para avaliar a efetividade e aderência da CPS-PMBOK, as práticas foram apresentadas para gerentes de projeto e desenvolvedores em uma empresa de P&D. As práticas: listas pré-elaboradas de requisitos, divisão de equipes especializadas e confiança técnica mostraram-se mais relevantes para cada respectiva área do conhecimento, segundo os gerentes. Para os desenvolvedores, o processo de revisar requisitos, treinamento cruzado e confiança técnica pareceram contribuir mais para suas respectivas áreas do conhecimento.

Palavras-chave: Gestão de projetos. Sistemas ciberfísicos. Sistemas embarcados. PMBOK.

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1 Introduction

In the last decade, a new technological area of systems appeared, aiming to integrate computing resources to physical processes, called Cyber-Physical Systems (CPS) (SHA et al., 2009; RAJKUMAR et al., 2010; KIM; KUMAR, 2012). CPS systems can be defined as the interaction between the physical world – representing physical phenomena and environmental behaviors – and the computing world – representing embedded systems, microprocessors, microcontrollers and other computing platforms (LEE, 2008). The interactions occur through: *(i)* sensors, which are devices able to read or measure physical phenomena (e.g. temperature, pressure, light, etc.) and convert them into electrical signs; and *(ii)* actuators, which are mechanical or electrical devices able to be stimulated by electrical signs, influencing the physical world through other electrical signs, movements, radio-frequency transmissions, among others. Examples of devices that can be considered sensors and actuators, since they behave as inputs and outputs of CPS systems, are: cameras, antennas, electrical motors, pneumatic valves, lasers or simple video monitors.

The basic operation of a CPS system is: sensors reading the physical world, transmitting information for computers, which in turns process the information with algorithms specific for this context, and transmit the appropriated information for actuators to act again in the physical world, often changing it. The changed physical world is read back by the sensors, starting the operation cycle all over again. The used specific algorithms may be related to: image processing, protocol analyses, trajectory estimation, pattern recognition, digital signal processing, among others (LEE; SESHIA, 2014). In summary, it is possible to affirm that CPS systems allow contextualized exchange of information between the computing world and the physical world.

The development of such CPS systems emerged by the need to better understand the physical world, associated to the possibility to control it, bringing benefits such as: reliability in all type of vehicles; enhancement of telecommunication; improvement of medical addressments; and development of sustainable energy devices (SHA et al., 2009; RAJKUMAR et al., 2010; BAHETI; GILL, 2011). The overlap of physical and computing concepts characterizes CPS systems as unusual applications, merging different technical knowledge and requiring a wide variety of competences (LEE, 2008; SHA et al., 2009; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014).

Project management is the activity of planning, controlling and measuring the development progress of a project, by applying knowledge, skills, tools and techniques aiming to ensure the fulfillment of the project requirements and hence the project success. In this context, a project (to be managed) is any collective and temporary effort to accomplish some result, whether the development of a product or the establishment of a new service (PMI, 2013). Project management is a practice in many professional areas, as software development, civil engineering, marketing and many other industries (COOKE-DAVIES; ARZYMANOW, 2003).

According to studies made by the Project Management Institute (PMI), project management practices include the management of different areas directly or indirectly involved in a project, which are called "knowledge areas" and thoroughly described in its Project Management Body of Knowledge (PMBOK) (PMI, 2013). There are ten knowledge areas, which address the management of: integration, scope, time, cost, quality, human resource, communications, risk, procurement and stakeholders. The specific approach for each knowledge area may vary according to a certain application domain as well as what is the main success factor of the project (LESTER, 2014). The proper application of project management practices allows enhancing project results and improve project team skills (PMI, 2013; LESTER, 2014).

1.1 Motivation and justification

The adoption of project management practices has become part of the routine of the organizations engaged in activities with concepts equivalent to projects, i.e., temporary efforts to reach a certain result. Project management can be found in different industrial sectors such as research and development (R&D) and industrial manufacturing (COOKE-DAVIES; ARZYMANOW, 2003). The increasing formalization of projects as well as the increasing use of tools, techniques and methods by the industry are studied by Fortune et al. (2011), showing that project management has an ongoing need for improvement and can be studied by many researchers. According to Mir and Pinnington (2014), the benefits of project management and the impact of appropriate practices on the outcomes may vary and can be seen through different perspectives when considered, for example: the project team; techniques applied for project management; the project manager leadership; types of results; and organizational characteristics. Project management practices may improve control of the project execution in different ways, including: improving the fulfillment of the planned schedule in projects where time is a major constraint; adapting the project team according to the scope coverage needs; suiting costs in budget-restricted projects; and closely monitoring risks in critical projects (LESTER, 2014).

As in any other technological field, the development of a CPS system can be seen as a project which requires proper management. Many CPS systems are designed to improve existing technologies, leading to a high level of innovation (RAJKUMAR, 2012; PARK et al., 2015). The innovative aspect of the CPS systems either as enablers of new technology or as proof of concept may requires the participation of large and heterogeneous teams. In addition, this scenario adds several risks for the project execution as seen in the CPS system described by White et al. (2010). Another recurrent feature of CPS projects is the close contact with hazardous environments and even human lives (LAKSHMANAN et al., 2010). Rajkumar et al. (2010) and Baheti and Gill (2011) argue that addressing multidisciplinary teams and segments coupled with models with high level of abstraction to allow communication with all members of the project team are among the main challenges when developing CPS systems. These issues and features illustrate the need to properly manage CPS projects.

Although it is consensus that project management brings a number of benefits, different projects may be conducted through specific and modified ways in order to obtain even better results (COOKE-DAVIES; ARZYMANOW, 2003; WINTER et al., 2006). Such adjustments may also be required for CPS projects. The need for different settings can depend on: *(i)* how the project is funded (e.g., government projects, as discussed by Grimsey and Lewis (2002)); *(ii)* the application domain (e.g., civil construction as addressed by Assaf and Al-Hejji (2006), Shen et al. (2015) or defense as addressed by Boydston and Lewis (2009)); and *(iii)* a specific technology used (e.g., web services or e-learning as addressed by Irani et al. (2005), Chan, Pan and Tan (2003)). In fact, there is a set of research works that proposes to adapt management practices for different cases, focusing on social or technological aspects, although none of such adaptations is related to CPS systems. Some examples of such adaptations are proposed by Deshpande, Beecham and Richardson (2013), Golini and Landoni (2014), McKay, Marshall and Grainger (2014), Pandi-Perumal et al. (2015), Errihani, Elfezazi and Benhida (2015), Reusch (2015).

A focused approach to project management practices may allow to focus effort on specific potential issues, increasing the probability of overcoming them. In addition, a focused approach can allow to drive efforts to the most problematic knowledge areas rather than those areas with easily controlled issues due to the project nature, such as projects with flexible schedule or unrestricted budget. This view can be seen as valuable also for CPS projects since they usually present specific issues.

A number of studies has been conducted by different CPS-related experts and other professionals with the purpose of investigate the challenges to develop complex CPS systems considering the wide combination of involved disciplines and the large amount of involved innovation. Proceedings of IEEE published a special issue on CPS systems in 2012, highlighting some technical challenges as security (MO et al., 2012; SRIDHAR; HAHN; GOVINDARASU, 2012) and critical systems reliability (BANERJEE et al., 2012), and also some challenges related to management and software engineering such as software development methods (EIDSON et al., 2012), architectural abstraction models (SZTIPANOVITS et al., 2012), and general system modeling (DERLER; LEE; VINCENTELLI, 2012). For Baheti and Gill (2011), advances in CPS systems can be accelerated through close collaboration among different disciplines in engineering and computer science. Broman et al. (2012) studied a series of viewpoints, formalisms, languages and tools that could be useful to standardize the development of CPS systems as well as to define the projects. In a similar work, Derler et al. (2013) describe design contracts as a way to set system properties among different teams and professionals.

1.2 Goals

Motivated by the evidences of benefits raised by focused project management practices (cf. section 1.1), coupled with the lack of a project management model specific for the development of CPS systems, this work aims to propose a set of best practices for CPS projects which are based on the consolidated PMBOK guide (PMI, 2013), called CPS-PMBOK (junction of terms cyber-physical systems and project management body of knowledge). The proposed best practices should widen the perception of project management professionals in relation to CPS systems being developed, allowing such professionals to focus their activities on recurring issues to this context and with appropriate approaches.

In order to reach the objective of this work, the following specific goals are pursued:

- Proposing the best practices for CPS project management that consolidate or are adherent to different single approaches found in the literature.
- Proposing the best practices for CPS project management that are more general, applicable and structured than those found in the literature.
- Proposing the best practices for CPS project management based on the practices and knowledge areas of PMBOK along with related works found in the literature.
- Proposing the best practices for CPS project management aiming their applicability in real CPS projects.

1.3 Structure of document

This master dissertation is divided in the following sections: chapter 2 which presents a contextual background through a theoretical foundation; chapter 3 which presents the research method followed in this research work; chapter 4 which presents the proposed approach for PMBOK specific for CPS projects; chapter 5 which presents the approach evaluation; chapter 6 which presents the final considerations. In addition, appendix A, B, C and D present the questionnaires and responses, respectively used in the approach evaluation, for the project managers and for developers, respectively. Appendix E provides a paper, result of the conducted systematic review related to subject of this project, applied to Hawaii International Conference on System Sciences 2017 (HICSS-50). Appendix F presents a paper published and presented at the IX Theses and Dissertations Workshop on Information Systems (WTDSI) at XII Brazilian Information Systems Symposium (SBSI).

2 Contextual background

This chapter presents the basic concepts related to CPS systems, including application examples in scientific, industrial and technological contexts. Different perspectives of the challenges faced in such an area are presented. Moreover, basic concepts related to project management practices are also presented, including the descriptions of PMBOK's knowledge areas as well. Finally, the found related works are presented bringing together the project management and CPS fields.

2.1 Cyber-physical systems

The expression "Cyber-Physical Systems (CPS)" was coined in 2006 by Helen Gill at the National Science Foundation (NSF) Workshop on Cyber-Physical Systems (GILL, 2006) to describe a new generation of engineered systems capable of high performance in information, computing, communication and control. Some examples of such systems are: smart power grids, in which the power line health and consumption can be monitored at distance all the time; online and robotic medical surgeries; and autonomous vehicles, as trains, cars, drones or Unmanned Aerial Vehicles (UAV).

CPS systems represent a new way of interaction based on the possibility of both full understanding of physical phenomena and environmental behaviors as well as exchanging of contextualized information between the computing world and the physical world, in the same way as people interact with each other at the internet (RAJKUMAR et al., 2010). In a previous scenario, computer components were bigger, more expensive and the communication (wireless or not) capacity were limited, whereas the physical world was only witnessed by the computing world. On the one hand, the computing world includes all types of computing platforms, able to process and provide information for people or other technological components; on the other hand, the physical world includes physical phenomena and processes that can be found in the environment.

From the computing world side, the following devices can be found: Unix-based computers; microcontrollers; microprocessors; embedded systems; Digital Signs Processors (DSP); Programmable Logic Controller (PLC); Field-Programmable Gate Arrays (FPGA); signal acquisition hardware; among others. From the physical world side, the following physical phenomena can be found: temperature; electrical current and voltage; atmospheric pressure; motion (velocity and direction); lighting; radio-frequency; sound; time; among others. Physical processes are a combination of some of these physical phenomena in a certain context, such as: room temperature, which changes over the time considering the number of people inside the room; airplane pressure, which changes according to the flight altitude; and the current provided by an electrical engine, which is proportional to its load.

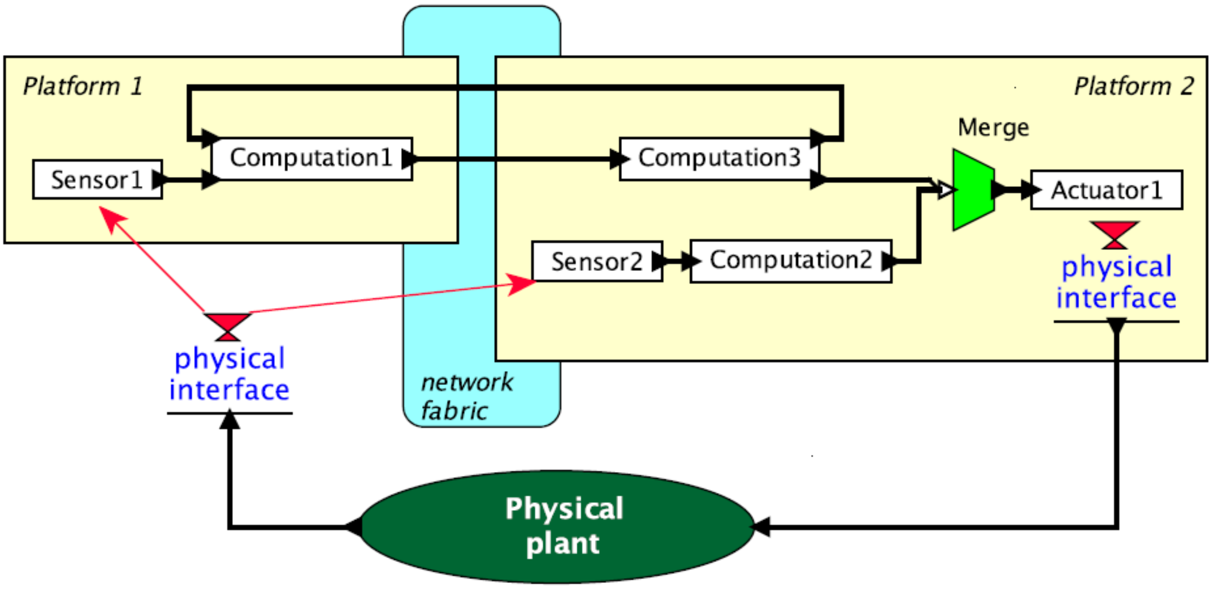
Aiming to bring together these two worlds allowing interaction, some intermediate elements are used, which are called sensors and actuators. Sensors may be any technological device capable of transforming a physical phenomenon into electrical signs or some other computer-readable sign. Actuators are specific technological devices able to generate electrical signs, sound, radio-frequency, indirect motion, or any other physical phenomena to stimulate elements in a physical process. The actuators can also stimulate sensors of other CPS systems (LEE; SESHIA, 2014). Thus, this interaction consists of computers interactively reading and controlling the physical world, through cycles of feedback reading and the control adaptation through computing for the next interaction (LEE, 2008).

Figure 1 presents an illustrative example of a generic CPS architecture, with three main elements: the physical plant, the platforms and the network fabric. The physical plant represents the physical world, including the physical phenomena and processes as previously described. Lee and Seshia (2014) add human operators also as part of physical processes. The platforms represent the computing world, including computers and operating systems as well as sensors and actuators as interfaces to the physical world. Finally, the network fabric represents the mechanisms for computers to communicate, such as wireless networks or industrial protocols and buses, and can be considered also part of the computing world.

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

In this context, issues related to reliability, safety, robustness, security and quality of services are highly relevant since wrong actuation or misinterpretation of signs in a physical world may cause accidents. Regarding these issues, there are still open technical challenges, as preventing cyberattacks in non-Unix systems (LEE, 2008; SHA et al., 2009; RAJKUMAR

Figure 1 – Illustrative example of a generic CPS architecture



Source: Lee and Seshia (2014)

et al., 2010). In order to properly address CPS systems, computing and networking abstractions need to be redesigned, seeing that, in the physical world, time can define the required computing approach, and concurrency is intrinsic (LEE, 2008). Moreover, network components should be remodeled to fit the new technologies of computing platforms (SHA et al., 2009). As many industrial CPS systems 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 systems, mobile device integrations as well as distributed sensors and actuators can be mentioned (SHA et al., 2009). On the other hand, in terms of methodological issues, items such as 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 systems, such as: advanced automotive systems, including autonomous vehicles; agriculture; avionics and airplanes; critical infrastructure control; defense systems; robotics; electric vehicles; energy harvesting; environmental control; health-care; instrumentation; intelligent buildings; medical devices and systems, including medical prostheses; mobile devices; power generation; real-time systems; space vehicles; traffic control; among others (LEE, 2008; SHA et al., 2009; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014). Moreover, some existing technological devices can acquire these CPS features, such as: cognitive radio,

Radio Frequency Identification (RFID); and other devices of asset tracking (LEE, 2008). According to Sha et al. (2009), three main areas can be cited as the biggest challenges to CPS systems: global warming; energy shortage; and health care services for chronic diseases.

Approaches related to CPS systems have been addressing concerns related to: *(i)* previous design with a detailed networked control system model to calculate communication delay, packet 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 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 different areas of professionals involved during the development and design of CPS systems (DERLER et al., 2013).

CPS systems 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 more powerful, allowing embedded systems to be present at many different applications. Nowadays, embedded systems are found in elements such as: vehicles; appliances; mobile devices; manufacturing industries; aircraft; among others. This means that the main challenges related to embedded systems is currently its environment and not its size or performance. Nevertheless, these attributes are frequently object of improvement, including the challenge of keeping a low power consumption (LEE; SESHIA, 2014).

Some specific embedded systems became conceptually similar to CPS systems, given that some areas of application of embedded systems started to demand more increased features and networked devices, besides the need for interaction with physical environment, found in CPS systems (LEE, 2008). Furthermore, features related to time processing and synchronous data exchange between different devices typify many embedded systems as real-time applications. Accordingly, specialized operating systems are currently called

Real Time Operating Systems (RTOS), which are usually embedded ones (LEE, 2008). The broad use of internet for communicating all kind of devices led to some similar to CPS concept of applications, called Internet of Things (IoT). The internet of things concept is the representation of the wide adoption of internet for connectivity among different technologies, as smartphones, TVs, domestic appliances and computers, through the internet, which is a data network well established. These kind of application are usually informative, but also interacts with physical world in some level. Sensors network is another approach that mixes CPS concepts, whereas the main goal is to get data of physical world and provide it to a computing system. In this kind of application, a network is develop aiming to enhance the coverage of sensors or to perform quality methods. Unlike internet of things, sensors network usually works with industrial protocols of communication and radio frequency. Considering industrial applications, there is another expression to describe computing systems interaction with physical processes: automation and control engineering. This can be considered an area of application very close to CPS concepts, once it mixes mechanical, electrical, programming and many other disciplines present in development of all these previously mentioned kind of systems, but generally is more used in industrial environment than CPS. For the last, a broadly used term to described many systems similar to CPS is System of Systems (SoS). This concept is not grounded on the interaction with physical world, but on the interaction and interdependence of different systems, assembled to accomplish the same goal.

For some experts, all the terms: CPS systems, embedded systems, automation and control systems and system of systems can be understood as the same. However, CPS systems have been recently more widely used, since it represents a wider context, including all previously applications and concepts, besides internet of things and sensors network trends. For this reason, the term CPS systems was the term chosen to be used in this work to represent the entire area of study.

2.2 Project management

A project is a temporary effort, to reach a specific goal (usually the creation of a product or service) taking into account some time, cost and requirements constraints. The goals 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 goals 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 means to apply knowledge, skills, tools and techniques over the development of a product or a service to assure the achievements of the project's requirements. Project management is also defined as a process of definition, planning, monitoring, controlling and delivering projects (APM, 2012). PMI keeps a base of knowledge called Project Management Body of Knowledge (PMBOK) that presents a set of best practices to be used in project management. Similarly, the Association for Project Management (APM) also keeps its set of project management best practices called APM Body of Knowledge. PMBOK is considered by this author as on of the most used worldwide,besides the fact that the practices are presented in a didactic way. Due to large adherence of project managers in industry and researchers of academia, its best practices are used as a basis for this work.

The main constraints that project management 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 changes, 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 or probability of the existing ones. According to Lester (2014), the project's goals must satisfy three fundamental criteria: timely completion; completion within budgeted cost; and compliance of quality requirements.

As well as the project management techniques, the project success criteria – also known as Critical Success Factors (CSF) – may vary according to the organization or project approach. The main or primary goals established for the project define which concerns or criteria must be satisfied for the project success criteria. All the goals proposed for the project must usually be satisfied so that a project can be considered completed. However, a project can be considered successful, if the at least the primary goals were achieved when the secondary goals are unfeasible. For example, a project in civil engineering must be finished in time for the inauguration day, even if there are paintings not finished yet. In this case, cost and a part of the scope had to be sacrificed to satisfy the time constraint, and these other goals may be satisfied later (LESTER, 2014). Another possible success factor, mainly in CPS projects, is related to safety, for which a system or application can only be used if does not provide any harm risky to the users. Security can also be part of the success factors in CPS projects, seeing that 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 adequately satisfied, it can be considered completed but not successful. In general terms, PMBOK defines project success criteria as completing the project within realistic and feasible constraints of scope, time, cost, quality, resources and risk.

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

Considering all these different variables that define success, project management practices may have its modified versions, for each specific CSF or project area of application. The advantage is to allow project team to focus on recurrent issues from the area, saving time and resources from unnecessary practices. Technical characteristics surrounding project team, environment, products or services involved also present an opportunity to use specific approaches, as many authors do.

Errihani, Elfezazi and Benhida (2015) suggest a model to apply PMBOK practices in public body, establishing fluxograms, sequences and data flow diagrams. The model follows the UML standard, which may be a guide for managers used with software engineering disciplines. Besides a public body context, the authors make it clear that the model is in Moroccan context and works better up to medium size projects (the authors does not specify the criteria for projects size classification). In a clinical research environment context, Pandi-Perumal et al. (2015) use the practices for stakeholders management described in PMBOK and creates a systematic model for planning, managing and implementing guidelines. The authors present real examples and explain how to manage stakeholders engagement understanding their motivation, power of influence and interests. In this context, the stakeholders management can deeply influence the project success since stakeholders are the main element of clinical research.

Golini and Landoni (2014) introduce practices for better management of International Development (ID) projects. According to the authors, there are characteristics found in ID projects that should be considered to manage them: lack of customer; high number of stakeholders; complex environment (politically and geographically); resource scarcity; difference of cultures; and intangible project outputs. Non Governmental Organizations (NGOs) are the focus of study and PM4DEV and PMDPro1 methods are presented as specifically for NGOs, complementing PMBOK. In a similar context, Deshpande, Beecham and Richardson (2013) address Global Software Development (GSD) management, proposing a communications management model, called GSD-COORD. The model mixes stakeholders and communications management processes presented in PMBOK, adding two new techniques: appoint communication agents (a person responsible for integrate communication among teams); and implement communication training (to standardize teams' understanding). Indian software organizations were used to started the validation, but the authors did not specified the global localization of developers. Still dealing with communication, McKay, Marshall and Grainger (2014) propose a reflection regarding new concerns in Information Technology (IT) developments. It adds that IT project team should be aware of the value creation concepts, mainly in the deliverables. Allied to this, the customers' customer satisfaction and needs are included in the context of the project. Although related to scope and stakeholders management, the authors use these concepts to rethink the communications management. It also include necessary project manager skills, such as: emotional intelligence; empathy by the team; confidence; and ability to engage with stakeholder; for proper communications management in IT projects.

Reusch (2015) presents an extension of PMBOK's processes, arguing that new concerns emerged over the last years, as project management methods became more mature. The first extension is regarding stakeholders management, adding information about project portfolio and responsible identification for identify stakeholders processes. The second extension is in quality management, regarding plan quality management process. It adds information of strategies and standards followed during the project execution. The last extension is a entire new knowledge area, called sustainable project management, including the awareness of reuse of project management practices for future projects. It is also related with quality standards and lessons learned application and collection.

2.2.1 Project management processes

The execution of project management practices in order to achieve project success, through determined success criteria, requires concrete and systematic processes. A process, in this context, can be defined as a set of activities performed to reach the specified stage of the project execution. It is characterized by its inputs, tools and techniques used, and the outputs resulted (PMI, 2013). The suggested processes may change according to each project or organizational environment. 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.

Some details of the activities performed according to each process group are presented as follow (PMI, 2013):

1. **Initiating**: this group includes 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 defined.

2. **Planning**: this group includes processes performed to establish the total scope, define and refine the goals and develop the course of action required to achieve those goals, including strategies and tactics to successfully complete the project or phase.
3. **Executing**: this group includes 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**: this group includes processes performed to track, review and orchestrate the progress and performance of the project, besides identifying any area in which changes to the plan are required to initiate the respective changes. This allows identifying areas requiring additional attention by the manager.
5. **Closing**: this group includes processes performed to conclude all activities started across the project. The following activities may be executed: obtaining acceptance of the project by the customer; documenting lessons learned; applying updates to organizational process assets; archiving all relevant project artifacts; closing out all procurement activities; performing team members' assessments; and releasing project resources.

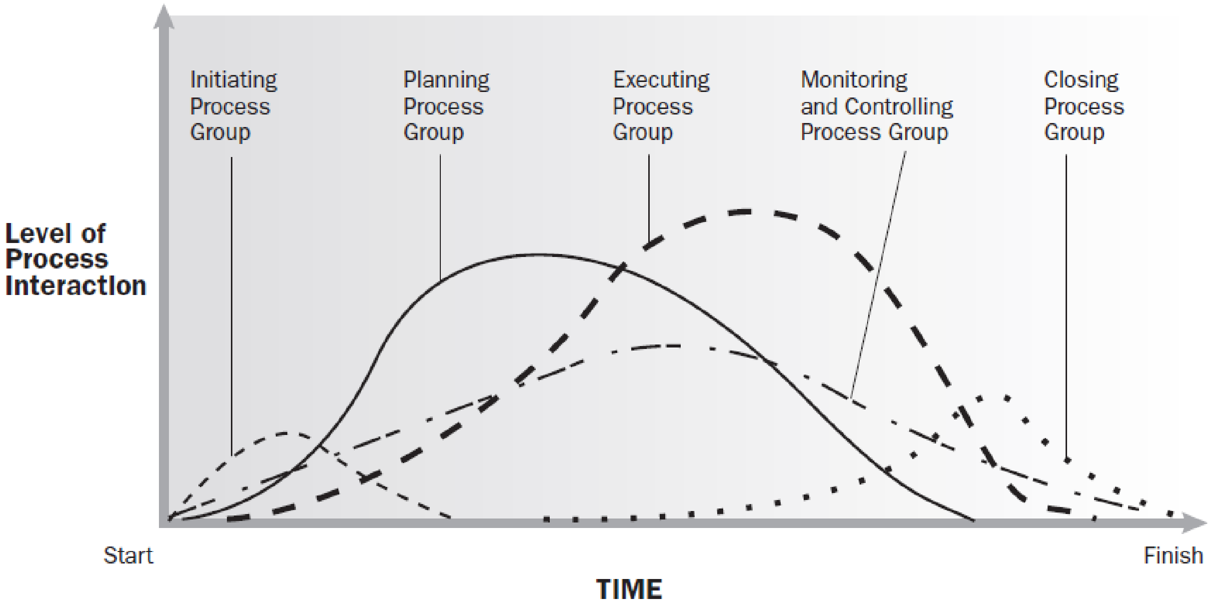
These five groups of processes are not mutually exclusive; in fact, there is a lot of intersection among them during the course of the project. Figure 2 shows a possible application of all processes groups during the accomplishment of a project and their overlaying.

2.2.2 Knowledge areas

For a complete and successful project management, it is necessary to deal with different dimensions of the organization administration, different professional fields and even different specialization areas (PMI, 2013). Accordingly, PMBOK splits its project management practices into the following ten knowledge areas: integration; scope; time; cost; quality; human resource; communications; risk; procurement; and stakeholders. Each knowledge area represents a set of concepts, terms, activities, tools and techniques that should be properly used to manage a project.

Each one of the project management process groups may involve one or more knowledge area depending on their features and needs as well as the life cycle phase of the

Figure 2 – Process groups interactions in a project or a project phase



Source: PMI (2013)

project (PMI, 2013). Although there are other project management strategic divisions, this work explores only this structure adopted by PMI (2013) (version 5), which are deeper presented as follows:

1. **Project integration management**: responsible for identifying, defining, combining and coordinating all the project management processes and activities. This knowledge area basically organizes and prepares all the processes of the other nine knowledge areas. It includes the use of a Project Management Information Systems (PMIS). It includes the change management planning and may also include configuration management practices. The main artifacts produced by this knowledge area are: *(1)* the project charter and *(2)* the project management plan. The involved processes are: *(1)* develop project charter; *(2)* develop the project management 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 successfully complete the project was predicted and is being executed. It defines what is and what is not included in the project, i.e., within the scope and out of scope. The main artifacts produced by this knowledge area are: *(1)* scope management plan; *(2)* requirements documentation; *(3)* scope baseline; and *(4)* accepted deliverables. The involved processes are: *(1)* plan scope management; *(2)* collect requirements;

(3) define scope; *(4)* create Work Breakdown Structure (WBS); *(5)* validate scope; and *(6)* control scope.

3. **Project time management**: responsible for managing the time of a project, which means ensuring that the project activities will be completed in the planned time and controlling the possible delays and advances in a way that the project still remains feasible. The planning and definition of the milestones, if used, are made in the context of this knowledge area. The main artifacts produced by this knowledge area are: *(1)* schedule management plan; *(2)* activity list; *(3)* activity attributes; *(4)* milestones list; *(5)* activity duration estimates; 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**: responsible for managing the approved or authorized budget to be executed. The amount of available funds depends on the origins of the project and the organizations involved. In order to conduct the project within the given budget, the costs of the project need to be properly managed, which consists of planning, estimating and controlling the costs as the activities are completed, the results are delivered, and, although rare, the approved budget changes. The main artifacts produced by this knowledge 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**: the quality of a project is directly related to the results delivered to its customers and the customers' satisfaction regarding the project. Quality is also related to overcoming the stakeholders' expectation about the overall project progress. This knowledge area includes the process that ensures that the project and product requirements are satisfied and validated, although the quality criteria may depend on organizational policies and the nature of the developed project. The main artifacts produced by this knowledge 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**: this knowledge area includes processes to organize, manage and lead the project team, which is comprised of all people

with assigned roles and responsibilities for completing activities during the project execution. The project team members may have varied skills, according to their roles in the project. The members' participation time also vary and may be either full-time or part-time. The inclusion of all team members in project planning and decision making is beneficial because this improves motivation and commitment, besides to add the experience of the team members in the planning process. The main artifacts produced by this knowledge area are: *(1)* human resource management plan; *(2)* project staff assignments; *(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**: this knowledge area is necessary to ensure that all the project information is properly shared with different stakeholders and stored. Its goal is to create effective communication methods so that the diverse stakeholders, including the project team members, may understand each other. The differences in terms of cultural, technical and organizational background are the primary sources of misunderstanding that can provide risks to the project progress and overall quality, and can be avoided by properly managing communication. The main artifacts produced by this knowledge 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 the project status and frustrate the project performance, quality, acceptance or results. The event can be unexpected or foreseen but controlled. Risks can be indeed positive events that improve indicators related to some result, cost or time or positively affect any other knowledge area. This knowledge area is related to plan, identify, analyze and control the project risks, aiming to increase the impact of positive events and decrease the impact of negative events. The main artifacts produced by this knowledge 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**: this knowledge area includes the processes required to purchase or acquire products, services, materials or any results needed from outside the project team. It involves legal treatment of official artifacts such as agreements, contracts and non-disclosure agreements. It also includes supplier management, aiming to provide a reliable relationship network among organizations. The main artifacts produced by this knowledge 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 stakeholders management**: the stakeholders represent all the parts interested in the project success or failure, including people, groups or organizations which could positively or negatively impact or be impacted by the project. This knowledge area includes processes required to identify the stakeholders, analyze their expectations and potential impacts on the project, and to develop appropriate management strategies for effectively engaging them. The engagement of the stakeholders in project decisions and execution is essential for their satisfactions, and this should be managed as one of the main goals of the project, through continuous communication and the understanding of their needs and expectations. The main artifacts produced by this knowledge area are: *(1)* stakeholders register; *(2)* stakeholders management plan; and *(3)* issue log. The involved processes are: *(1)* identify stakeholders; *(2)* plan stakeholders management; *(3)* manage stakeholders engagement; and *(4)* control stakeholders engagement.

2.3 Cyber-physical systems project management

The proper management of a project of any field may bring many benefits to this project, and, depending on the used approach, the manager is able to deal with issues of all areas involved in the project, as showed in the previous section. If the management approach is focused in a specific field, the project team can enhance their chances of success and improve its technical skills to solve future problems in similar projects (COOKE-DAVIES; ARZYMANOW, 2003). According to Lee (2008), the problems to be solved by the development of CPS systems are not entirely new, but they are problems solved by mixing many different fields.

CPS systems as a specific discipline enable both systematic research by the scientific community and investments in appropriate technologies by involved organizations. The CPS application domain contributes to creation of new types of issues, challenges, technological advancements and also a new type of users (RAJKUMAR et al., 2010). The CPS users include a mix of, for example, biologists, chemists or even lay users, which need to deal with systems and interact with something more complex than just computers. Similarly, CPS project team members comprise a mixed type of professionals, which need to form a single team able to work together during the project execution (RAJKUMAR et al., 2010).

Although CPS project management may prove challenging due to its novel aspect, some initiatives have been conducted to drive organizations and administrative practices involved in CPS projects. Furthermore, development methods have been adapted to fit in the dynamic nature of CPS projects. To widely explore this type of initiative as well as contribute to development of this work, a systematic literature review (or simply systematic review) was conducted aiming to evaluate the specific aspects of CPS project management. The main goals of the conducted systematic review were: finding initiatives of CPS project management and identifying the corresponding involved knowledge areas according to the PMI (2013) taxonomy; and analyzing the faced challenges and found workarounds. Still more important, it aimed to find the specific practices (in terms of techniques and tools) proposed to be applied in CPS project management when compared to the generic good practices present in PMBOK. Therefore, this systematic review was driven to find works related only to CPS project management issues, and not related to technical issues regardless of concerns related to project management. It includes embedded systems, internet of things, sensors network, automation and control engineering and system of systems project management studies, due to their similarity with CPS systems as described in Section 2.1. The protocol used to conduct the systematic review is presented in Chapter 3 as part of the method used to carry out this research work.

The results of the systematic review allowed to identify that certain knowledge areas have been object of study in the project management context for both CPS systems and other expressions related to CPS systems, as expected. In summary, the results shows that three from the ten knowledge areas were found more frequently: scope management, human resource management and stakeholders management. One can understand that the larger occurrence of these three knowledge areas is connected with: the dynamic aspect of CPS systems, besides multidisciplinary teams and technologies used.

According to the systematic review results, the following practices are suggested to address the project scope management: application of international standards; estimations based on use case points and hardware points; software and frameworks for requirements analysis; and specific modeling languages for requirements elicitation and system architecture visualization; requirements review through peer reviewing and Scrum boards; development of design models; specific development approaches; meetings with live demonstrations; analysis-driven design; lists of requirements; model-driven design; and new process models for scope management and project development (GREENE, 2004; JUN; RUI; YI-MIN, 2007; MADACHY; BOEHM; LANE, 2007; MADACHY, 2008; SILVA; LOUBACH; CUNHA, 2009; SHATIL; HAZZAN; DUBINSKY, 2010; BERGER; RUMPE, 2010; GARAY; KOFUJI, 2010; SAVIO; ANITHA; IYER, 2011; RONG et al., 2011; HELPS; MENSAH, 2012; HUANG; DARRIN; KNUTH, 2012; PENZENSTADLER; ECKHARDT, 2012; INSAURRALDE; PETILLOT, 2013; ZHU; MOSTAFAVI, 2014; PARKHOMENKO; GLADKOVA, 2014; YUE; ALI, 2014; SAPIENZA; CRNKOVIC; POTENA, 2014; FASCHANG et al., 2015; LATTMANN et al., 2015).

As far the project human resource, the following practices are suggested to address the management of this knowledge area: acquisition of a multidisciplinary and expert team; definition of specific key-roles usually needed for the team members; distribution of tasks considering the team members' profile and expertise; statistical estimation and classification of familiarity of team members, according their profiles and requirements; training in specific development methods, such as goal-driven, model-driven and extreme programming; and skill based human resource management (GREENE, 2004; MADACHY; BOEHM; LANE, 2007; MADACHY, 2008; CHEN; WEI, 2009; SHATIL; HAZZAN; DUBINSKY, 2010; WOLFF; GORROCHATEGUI; BÜCKER, 2011; RONG et al., 2011; HELPS; MENSAH, 2012; HUANG; DARRIN; KNUTH, 2012; ZHU; MOSTAFAVI, 2014; YUE; ALI, 2014; PARKHOMENKO; GLADKOVA, 2014).

Finally, considering the project stakeholders, the following practices are suggested to address the management of this knowledge area: identification of stakeholders and assignment of tasks following systematic algorithms and norms; assignment of stakeholders within the organization; involvement of stakeholders during the transition between development phases; face-to-face meetings; workshop meetings; and specific stakeholders management approaches such as the evolutionary development and the constructive SoS integration model (GREENE, 2004; MADACHY; BOEHM; LANE, 2007; MADACHY, 2008; SHATIL; HAZZAN; DUBINSKY, 2010; RONG et al., 2011; HUANG; DARRIN; KNUTH, 2012; PENZENSTADLER; ECKHARDT, 2012; SINGH, 2013; ZHU; MOSTAFAVI, 2014; YUE; ALI, 2014).

In addition to the practices mentioned above, the systematic review results also indicated some suggested practices shared among different knowledge areas, for example: all kind of meetings for scope and stakeholders management and development methods for scope and human resource. Moreover, there are some similar or equivalent practices that were suggested by different authors, such as: definition of specific roles for team members, aiming to empower them for decision-making; acquisition of a multidisciplinary team, mixing competences; and use of some practices related to agile development methods, such as Scrum boards and extreme programming for activity monitoring. Even if some practice apparently is part of a knowledge area, this practice was not considered for relevance score accounting if not related by the authors.

As a summary, tables 1 and 2 show the 25 primary studies selected according to the systematic review protocol. In addition, for each primary study, tables 3, 4, 5 and 6 show: the focus of the work in terms of terminology used (i.e., embedded systems, CPS or system of systems); the identified knowledge areas; a calculated relevance score for each knowledge area; and, finally, the suggested practices identified for each knowledge area. the classification of the focus were based observing the project described regarding area of application and technologies used, besides the explicit mention of term. In cases that the authors mention a specific term, but their project presents aspects of some other, both terms were used. The relevance scores were calculated in order to identify which knowledge areas are more relevant to CPS project management, according to the found primary studies. The relevance scores were calculated based on the number of times that a given primary study addressed keywords related to the corresponding knowledge area. These keywords, in turn, were determined observing those relevantly recurrent words on each work for the corresponding knowledge areas, besides the name of the knowledge area, if not representing too much ambiguity, which is the case of: integration (representing hardware integration), scope (of the paper) and time (all possibilities of time, unless of the project). The keywords used are presented in table 7.

Table 1 – Selected primary studies (Part 1)

ID	Authors(Year)	Title
1	Jun, Rui and Yi-min (2007)	Software Processes Improvement and Specifications for Embedded Systems.
2	Silva, Loubach and Cunha (2009)	An estimation model to measure computer systems development based on hardware and software.
3	Krikhaar et al. (2009)	Enabling system evolution through configuration management on the hardware/software boundary.
4	Chen and Wei (2009)	Multiagent approach to solve project team work allocation problems.
5	Shatil, Hazzan and Dubinsky (2010)	Agility in a large-scale system engineering project: A case-study of an advanced communication system project.
6	Berger and Rumpe (2010)	Supporting agile change management by scenario-based regression simulation.
7	Garay and Kofuji (2010)	Architecture for sensor networks in cyber-physical system.
8	Wolff, Gorrochategui and Bücker (2011)	Managing large HW/SW Codesign projects.
9	Rong et al. (2011)	Goal-Driven Development Method for Managing Embedded System Projects: An Industrial Experience Report.
10	Helps and Mensah (2012)	Comprehensive design of cyber physical systems.
11	Penzenstadler and Eckhardt (2012)	A Requirements Engineering content model for Cyber-Physical ystems.
12	Huang, Darrin and Knuth (2012)	Agile hardware and software system engineering for innovation.
13	Singh (2013)	Norms as a basis for governing sociotechnical systems.

Source: Elaborated by the author, 2016

Table 2 – Selected primary studies (Part 2)

ID	Authors(Year)	Title
14	Insaurralde and Petillot (2013)	Cyber-physical framework for early integration of autonomous maritime capabilities.
15	Yue and Ali (2014)	Applying search algorithms for optimizing stakeholders familiarity and balancing workload in requirements assignment.
16	Sapienza, Crnkovic and Potena (2014)	Architectural decisions for hw/sw partitioning based on multiple extra-functional properties.
17	Parkhomenko and Gladkova (2014)	Virtual tools and collaborative working environment in embedded system design.
18	Lattmann et al. (2015)	Towards an analysis-driven rapid design process for cyber-physical systems.
19	Faschang et al. (2015)	Requirements for real-time hardware integration into cyber-physical energy system simulation.
20	Zhu and Mostafavi (2014)	Towards a new paradigm for management of complex engineering projects: A system-of-systems framework.
21	Savio, Anitha and Iyer (2011)	Considerations for a requirements engineering process model for the development of systems of systems.
22	Madachy (2008)	Cost modeling of distributed team processes for global development and Software-Intensive Systems of Systems.
23	Madachy, Boehm and Lane (2007)	Assessing hybrid incremental processes for SISOS development.
24	Greene (2004)	Agile methods applied to embedded firmware development.
25	Cornford and Sarsfield (2004)	Quantitative methods for maturing and infusing advanced spacecraft technology.

Source: Elaborated by the author, 2016

Table 3 – Characteristics of the primary studies (Part 1)

ID	Focus	Knowledge area	Relevance score	Suggested practices
1	ES	Integration	9	Adaptation of CMMI practices for ES software development.
		Scope	25	Software processes management tool based on CMMI level 3.
2	ES	Scope	87	Use Case Points Technique / Hardware Points.
		Cost	9	Table of Hardware Relevant Factors. Hardware Points Technique.
		Procurement	1	Table of Hardware Relevant Factors.
3	ES	Integration	96	Set of practices by Software Release and Product Delivery. Product Data Management.
		Quality	4	Set of practices by Software Release and Product Delivery.
4	ES	Human Resource	90	Fuzzy Belief-Desire-Intention approach.
5	ES	Scope	6	Business day meeting performing live demos from last iteration.
		Time	11	Agile development method using daily and iteration metrics.
		Cost	2	Knowledge sharing.
		Quality	4	Business day meeting performing live demos from last iteration. Agile development method using daily and iteration metrics.
		Human Resource	120	Roles definition (Tracker, Process Engineer and Architect).
		Communications	7	Roles definition (Tracker, Process Engineer and Architect).
		Stakeholders	33	Proxy customer (system engineer) instead of the real one.
6	ES	Scope	13	Regression simulation for code production. Agile Development Method.
		Quality	17	Developers as customer for previous iteration. Agile Development Method.

Source: Elaborated by the author, 2016

Table 4 – Characteristics of the primary studies (Part 2)

ID	Focus	Knowledge area	Relevance score	Suggested practices
7	CPS	Scope	40	Architecture model for WSN (HW, nodes and network views).
				Framework for general WSN development.
8	ES	Time	28	Core team meetings with critical chain project management.
		Quality	6	Core team meetings.
		Human Resource	51	Self-planning and multidisciplinary sub-teams.
		Communications	5	Core team consisting of sub-project managers, lead engineers and overall project manager.
		Risk	4	Core team meetings with critical chain project management.
9	ES	Scope	11	Goal-driven development.
		Time	36	Weekly team meetings.
				Goal question metrics / Earned value management.
		Quality	33	Weekly team meetings.
				Software defect inject and removal technique.
		Human Resource	136	Goal owner assignment / GDD training.
		Communications	11	Weekly team meetings / Goal profile report.
		Stakeholders	25	Participation of each last launch phase / Goal profile report.
10	CPS/ES	Scope	10	Design Model based on project phases.
		Human Resource	10	Multidisciplinary team division.
		Risk	13	The iterative aspect of the created Method.
11	CPS	Scope	101	Content model for requirements elicitation of CPS.
				SysML and UML for modeling.
		Communications	19	Enterprise Architect with Model Driven Generation plug-in.
		Stakeholders	22	Artifact based model.
				Weekly conference for workshops.

Source: Elaborated by the author, 2016

Table 5 – Characteristics of the primary studies (Part 3)

ID	Focus	Knowledge area	Relevance score	Suggested practices
12	ES	Scope	18	Peer reviewing / Scrum board.
		Time	28	Non-linear process development flow / Scrum board.
		Cost	23	Non-linear process development flow.
		Quality	12	Early hw/sw test and integration / peer reviewing.
		Human Resource	24	Creation of small experienced team.
		Communications	12	Deputizing key team members and co-locating them. / Scrum board.
		Risk	9	Early hw/sw test and integration.
		Procurement	1	Evaluation of COTS options.
				Evaluation of vendor integration versus homemade low cost solutions.
		Stakeholders	18	Often face-to-face status meeting with the sponsor.
13	CPS	Stakeholders	34	Identification through application of norms.
14	CPS/ES	Scope	39	Hierarchic design using JAUS standard. / Framework for predetermined tasks division.
15	CPS	Scope	174	Requirements analysis for scoring.
		Human Resource	1	Team profile classification.
		Stakeholders	90	Optimization algorithm for best task assignment.
16	CPS	Scope	55	Extra functional requirements classification (lifecycle, runtime and business).
17	ES	Scope	29	ISO/IEC 12207:2008.
		Time	15	Atlassian JIRA.
		Cost	3	Hardware architecture analyses.
		Human Resource	5	Tasks distribution according to team members profile.
		Communications	11	Atlassian JIRA and Confluence.
18	CPS	Scope	55	Analysis-driven design aiming to identify multiple domains requirements.
		Quality	8	Parametric exploration models, test benches, probabilistic certificate of correctness and surrogate modeling to analyze the design robustness and quality of development.
19	CPS	Scope	24	List of ten requirements among communication simulation and lab/hardware set up.

Source: Elaborated by the author, 2016

Table 6 – Characteristics of the primary studies (Part 4)

ID	Focus	Knowledge area	RS	Suggested practices
20	SoS	Integration	40	Management approach based on dimensions named: levels, categories and classification.
		Scope	19	Emergent properties of systems as base requirements.
		Time	2	Autonomy given of constituents of the project.
		Cost	12	Bottom-up approach analyzing human agents and their behaviors in every subsystem.
		Quality	9	Interdependency assessing of constituents of the project.
		Human Resource	12	Human agent management, classifying in skill type, skill level and attention allocation.
		Communications	40	Levels domain approach (base, activity, process and project).
		Risk	11	Interdependency assessing of constituents of the project.
		Stakeholders	5	Evolutionary development approach.
21	SoS	Scope	21	Requirement engineering process model based on external, surface and internal views.
22	SoS	Scope	4	Model-driven requirements estimation.
		Time	15	Model-driven task assignment.
		Cost	52	Extension of Cost Xpert Group and USC-CSSE model for cost estimation.
		Quality	3	Incremental hybrid development process for distributed team.
		Human Resource	121	Model-driven task assignment.
		Communications	2	Distributed development model.
		Stakeholders	2	Constructive SoS Integration Model (COSOSIMO) from USC-CSSE.
23	SoS	Scope	13	Scalable spiral process model for requirements accomplishment.
		Time	31	COCOMO for construction schedule calculation.
		Cost	33	COCOMO for construction effort estimation.
		Human Resource	104	Process using three-team (plan-driven, verification and validation, and rebaseliners) cycle.
		Communications	8	Dynamic resource allocation.
		Risk	7	Risk-driven spiral model considering COTS products, legacy and external systems.
		Stakeholders	2	Stakeholders participation of upcoming increments negotiation and rebaselining.
24	ES	Scope	14	Scrum and extreme programming for constantly changing requirements
		Human Resource	64	Extreme programming concepts for collaboration and communication among team.
		Stakeholders	7	On site customer practice from extreme programming method.
25	CPS	Cost	59	Developmental Maturity Index and Key Engineering Performance Parameters.
		Risk	90	Developmental Maturity Index and Key Engineering Performance Parameters.

Source: Elaborated by the author, 2016

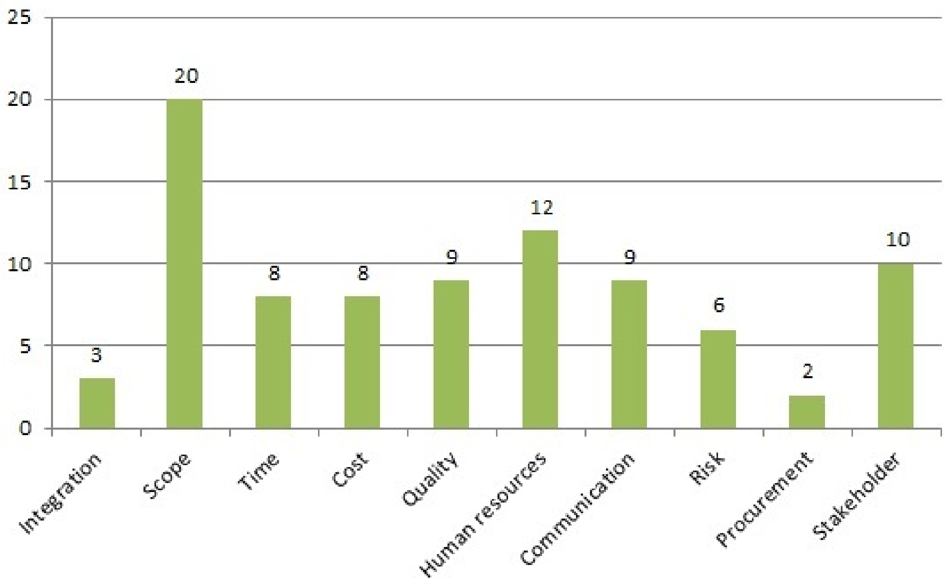
Table 7 – Knowledge areas and respective keywords for relevance score estimation

Knowledge area	Keywords
Integration	Configuration management, project management, 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.
Stakeholders	Stakeholder, sponsor, customer.

Source: Elaborated by the author, 2016

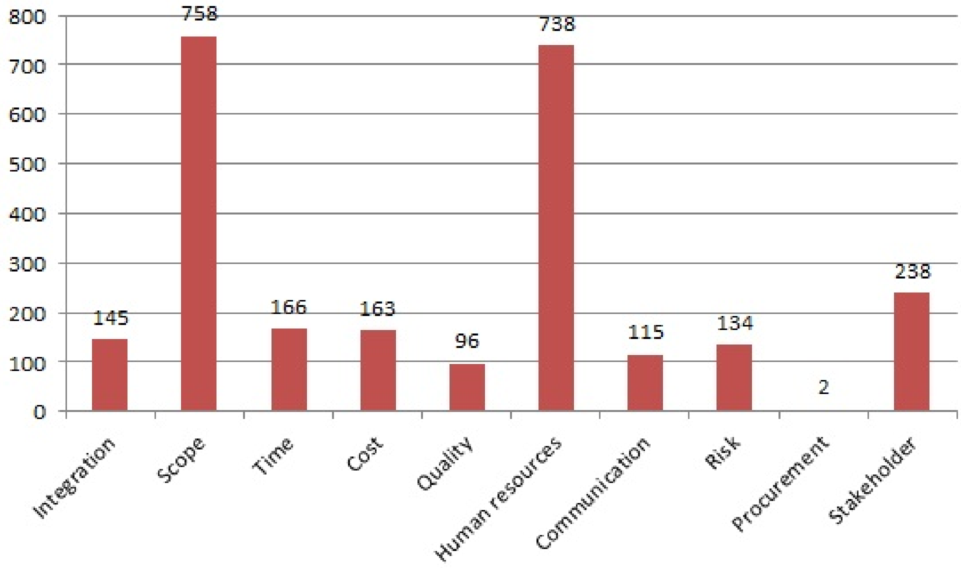
Finally, figures 3 and 4 summarize the main results obtained with the systematic review in terms of overall values, presenting, respectively, the number of studies in which each knowledge area is addressed (Figure 3) and the sum of the relevance scores obtained per knowledge area considering all the obtained primary studies (Figure 4).

Figure 3 – Number of studies found per knowledge area



Source: Elaborated by the author, 2016

Figure 4 – Sum of the relevance scores per knowledge area



Source: Elaborated by the author, 2016

2.4 Final remarks

Project management shows as a good method for controlling the progress and enhance the probability of success of a project, independently of its area (PMI, 2013; LESTER, 2014). CPS systems is an area of development which can be really boosted by good practices of project management due to its intrinsic innovative technologies and multidisciplinary professionals involved (BAHETI; GILL, 2011; RAJKUMAR, 2012). The scientific and industry communities are improving project management of CPS systems step by step, by their own ways: some times solving the dynamicity of requirements in an university-industry project; the constraints of time and cost in an R&D development; and the relationship of the very technically heterogeneous project team and stakeholders (SHA et al., 2009; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; RAJKUMAR, 2012).

To clarify the mains challenges faced on managing CPS development, by both scientific and industry communities, a systematic literature review was conducted connecting CPS systems and project management practices. Terms related to similar systems to CPS systems were included in the review, such as: embedded systems; internet of things; sensors network; automation and control engineering; and system of systems. Based on accounting of keywords which refers to each ten knowledge area described in PMBOK (PMI, 2013), the studies showed more concerns regarding: scope management, human resource management and stakeholders management.

3 Research method

This research is based on professional background of the author, who is a LabVIEW programmer and coordinator of an industrial automation team in a Brazilian R&D company. LabVIEW is a graphical programming language mainly used to communicate software with hardware. Nevertheless, this research also aims to review existing practices from project management area and theories from technological systems concepts. This characterizes this work as theoretical and empirical. Considering that the main purpose is to explore the management practice of CPS development and provide reflections regarding its problems and solutions, it is considered an exploratory research. As described in the following sections, it is used both quantitative and qualitative approaches, considering the systematic literature review conducted and exploratory analysis respectively. Although partially based on project management and CPS theories, it is intend of this research to get results that can be useful for industry which aims to improve their project management. It is also intends to contribute for further researches for academia, in the CPS project management context. For this reason, the nature of this work can be considered as applied research.

Both main areas involved in this project – CPS systems and project management – are intrinsically related to daily problems. The project management practices emerged to systematically solve business problems or to support challenge resolution. On the other hand, CPS systems are 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 method. This section describes the design science concept and its application in the context of this research as well as details of the systematic review conducted as part of the method.

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 satisfy 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).

Considering the project management challenges found in CPS development as the problem, this research aims to solve or minimize the impacts of these challenges, which consists of improving team communication, technical understanding, manage the dynamic scope, human resource and stakeholders expectation. These challenges are described in the following sections. Seeing that design science research is a method based on problem-solving, the practices obtained from this research aims to improve existent project management approaches and create new ones, focusing on CPS development.

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 an already known process, characterizing routine design. It is imperative the application of appropriate theories and methods to evaluate and develop the artifacts that rely on 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 processes. This cycle uses requirements from 'relevance cycle' and theories from 'rigor cycle'. In addition, for each iteration, it provides feedback for design improvement to the following iteration.

By applying design science in this project work, the first step was an exploratory study looking for project management works related with CPS systems, followed by a systematic review looking for the state of the art in this field. The exploratory study assured evidences of the relevance of the CPS project management as well as allowed to raise a conceptual background for this research work. It was possible to explore study cases describing technological projects which use different terms related to CPS systems including embedded systems and system of systems. The results of this exploratory study was the main responsible for defining the terms to be used in this research work. On the other hand, the systematic review was aligned with the 'relevance cycle' of the design science research and was aimed at searching for the main challenges and open issues related to CPS project management.

Based on the results of the systematic review and on the application of the strategies described in the 'rigor cycle', the following three PMBOK's knowledge areas were found as the most addressed in the literature related to CPS projects and considered as focus of this work: scope, human resource and stakeholders management. The decision of using the most addressed knowledge areas instead of less addressed, was made considering that: by managing the most problematic knowledge areas, the chances of success of a project may be enhanced. This not means that the remaining knowledge areas are not important, but it is expected that PMBOK may be enough to manage well even for CPS development. Following, the project management practices used on each found study related to at least one of these three knowledge areas were further analyzed and compared with practices existing in PMBOK. As a result, it was possible to find extra practices still not covered by PMBOK as well as specializations of some practices existing in PMBOK. The systematic review protocol is described in the following section.

Based on the 'design cycle', this research work aimed to propose a set of project management best practices specifically for CPS project management. These best practices were defined through the analysis of the found related works as well as based on the author's background. The main practices were those that were used by more than one author or intersect with some previous ideas of the author if this work. These best practices include classification models, standardized forms and organizational strategy approaches, which were evaluated by professionals in a R&D company. Some feedback from managers and developers turned into improvement of practices, changing the final presentation. Other feedback presented to be affordable in the next stage of this research. More details of CPS-PMBOK evaluation, including results and feedback are described in section 5.

Accordingly, in the CPS project management context, the artifacts evaluated are the project management practices as part of PMBOK but designed specifically for the CPS context. Whereas PMBOK describes generic constructs, models and methods, there are some specific cases that demonstrate their specializations (i.e., their instantiations) for the CPS context. This means that the artifacts produced as a result of this research work are specializations of the PMBOK practices for the CPS context, besides the novel practices based on author's technical background, systematic review and exploratory studies.

3.2 Systematic review protocol

In order to find works related to the context of CPS project management as well as the challenges and open issues described in such works, a systematic review was conducted following the guidelines and phases proposed by Brereton et al. (2007) in order to keep the review reproducibility. The main goal of this systematic review was to correlate the project management practices observed in CPS projects with the best practices present in

PMBOK. Thus, studies describing any type of concern related to project management in the context of development of CPS systems were analyzed. This systematic review also addressed the following different but similar terms related to CPS systems, as described in 2.1: embedded systems; internet of things; sensors network; automation and control engineering; and system of systems. These terms were used to broaden the coverage of studies analyzed, in order to represent similar projects to CPS development, since many projects contains at least one element of CPS, such as: sensors; physical phenomena studies; or computing platforms actuating in real world processes. In these cases, a focus on practices regarding these elements were given in the primary studies analysis stage.

The results of the conducted systematic review are presented in section 2.3. In this section, the protocol used to conduct the systematic review, as part of the method used to carry out this research work, is presented.

The planning phase of the systematic review aimed at developing a research protocol, which defines the purposes and procedures to be adopted during the systematic review conduction. In order to drive the goals, four research questions were elaborated. These research questions are responsible to lead the results to comprehensive conclusions and collaborations. The defined research questions are:

- **Research question 1**: are there evidences of practical application of project management practices during the development of CPS?
- **Research question 2**: which PMBOK's knowledge areas are addressed in the found approaches related to CPS project management?
- **Research question 3**: for each specific PMBOK's knowledge area found for CPS project management, which are the specific methods and tools addressed?
- **Research question 4**: are there challenges are open issues that are mentioned in the approaches found for CPS project managements?

These four research questions aimed at thoroughly answering the main research goal, indicating the PMBOK's knowledge areas addressed for CPS project management, the main methods and tools suggested for use, the results of their applications, and existing challenges and open issues. The research questions support the search for results and emphasize the contribution of the systematic review for this research work.

During the conducting phase, the first step was to define a search engine that might provide relevant studies. As an indexer of the main known and relevant databases, Scopus was selected, allowing directly obtaining papers from ACM Digital Library, IEEE Explore, Springer, among several others. Following, the search string was defined, which includes the main keywords used to search papers that might be consistent with the defined research questions. The keywords had to express both CPS systems (and similar terms) and project management fields. Variations over these words were used, resulting in the search string shown in 8. Related to CPS systems, it was decided to search project and management with a "logical or", embracing both papers describing projects without necessarily contain management. This was made due to CPS systems be the main focus of this research and the lower number of results found. For remaining similar systems, which returned lot more papers, the entire "project management" keyword was applied, enhancing assertiveness.

Table 8 – Basic search string

Search string
(("cyber-physical system*" OR "cyber physical system*" OR "cyberphysical system*") AND (project OR manag*)) OR (("embedded" OR "system of systems" OR "systems of systems" OR "sensor network" OR "sensor networks" OR "automation and control engineer*" OR "control and automation engineer*" OR "internet of things" OR IOT) AND ("project manag*"))

Source: Elaborated by the author, 2016

The complete version of search string was used, which include some exclusion criteria automatically and syntaxes elements for scopus engine application. The exclusion criteria related peer-reviewed and language was applied by choosing certain types of journals and publication vehicles, and excluding languages different from English. The specific search string is shown in table 9.

Moreover, two inclusion criteria and eight exclusion criteria were elaborated to be applied on the results obtained from the Scopus search engine in order to guarantee the relevance of the final set of studies. The criteria elaborated and used to define the studies are as follows:

- Inclusion Criteria (IC):
  - **IC-1**: The paper addresses CPS systems as main theme.
  - **IC-2**: The paper describes some experience in project management.
- Exclusion Criteria (EC):

Table 9 – Search string specific for Scopus

Search string
TITLE-ABS-KEY(((“cyber-physical system*” OR “cyber physical system*” OR “cyberphysical system*”) AND (project OR manag*)) OR ((“embedded” OR “system of systems” OR “systems of systems” OR “sensor network” OR “sensor networks” OR “automation and control engineer*” OR “control and automation engineer*” OR “internet of things” OR IOT) AND (“project manag*”))) AND (LIMIT-TO(SUBJAREA,“ENGI”) OR LIMIT-TO(SUBJAREA,“COMP”)) AND (LIMIT-TO(SRCTYPE,“p”) OR LIMIT-TO(SRCTYPE,“j”) OR LIMIT-TO(SRCTYPE,“k”) OR LIMIT-TO(SRCTYPE,“b”)) AND (LIMIT-TO(DOCTYPE, “cp”) OR LIMIT-TO(DOCTYPE,“ar”) OR LIMIT-TO(DOCTYPE,“re”) OR LIMIT-TO(DOCTYPE,“ch”) OR LIMIT-TO(DOCTYPE,“ip”)) AND (EXCLUDE(LANGUAGE,“Japanese”))

Source: Elaborated by the author, 2016

– **EC-1**: The paper addresses only technical details or challenges of the CPS domain with no type of contribution considering the project management perspective.
– **EC-2**: The paper aims at contributing with other areas than project management, 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 management – instead of project management.
– **EC-4**: The publication is not peer-reviewed.
– **EC-5**: The paper is not written in English.
– **EC-6**: The paper is not electronically available.
– **EC-7**: The paper is a secondary study, such as a systematic review or a survey.

Title and abstract section of each work obtained by the search in Scopus were read in order to apply these inclusion and exclusion criteria. When necessary, part of introduction and conclusion were also read. Once identified the selected papers, called primary studies (BRERETON et al., 2007), the entire paper was read aiming to summarize their main topics and to find information to answer the defined research questions. The results of this review are summarized in chapter 2.

4 The CPS-PMBOK approach

This chapter includes the detailed concepts related to the cyber-physical systems-project management body of knowledge (CPS-PMBOK) approach proposed in this work. CPS-PMBOK provides two types of extensions for the original PMBOK: an extra model to be used to characterize CPS projects and the specialization of some PMBOK's processes related to the following PMBOK's knowledge areas: project scope management; project human resource management; and project stakeholders management. Both extra characterization model and specializations of the three knowledge areas are oriented to the specific context of CPS projects.

The presentation of the proposed CPS-PMBOK approach in this chapter is organized in three sections: *(1)* the overview of the approach including some considerations about applicability; *(2)* the CPS characterization model being proposed; and *(3)* the specialization of the mentioned three PMBOK's knowledge areas.

4.1 CPS-PMBOK overview

CPS-PMBOK is proposed as an extension for the original set of best practices of PMBOK in order to address the specific features of CPS projects. For this end, CPS-PMBOK is basically composed of the following elements:

1. The whole original set of PMBOK best practices.
2. An extra model to be used to generically characterize CPS projects, called here "CPS characterization model" (as described in section 4.3).
3. The specialization of three PMBOK's knowledge areas – project scope management, project human resource management and project stakeholders management (as described in section 4.3).

First, this approach assumes that all the best practices originally provided by PMBOK are completely adherent to CPS projects and hence are part of CPS-PMBOK. Besides that, the agile methodologies for project management, that are consolidated in industry and academia are not used directly due to the massive use in software development. The purpose of this approach is to present new paradigms of project management which considers elements different of only software development, such as: physical phenomena;

hardware specialties; and heterogeneous background professionals. Given that, the agile methods influence many practices of CPS-PMBOK, but indirectly.

In terms of the proposed CPS characterization model, it is composed by two parts – “CPS environment” and “CPS complexity”. Both parts together allow to determine a set of possible technical characteristics and their influences for a given CPS project. Considering the reached formalization of the CPS system’s characteristics, the CPS characterization model allows a better understanding of the projects to be developed as well as a better estimation of the project size (DERLER; LEE; VINCENTELLI, 2012).

On the other hand, the specializations of the three knowledge areas aforementioned refer to adding new processes to them or else changing some of their existing processes. Such specialized knowledge areas provide a set of best practices particularly applicable to CPS projects. According to Cooke-Davies and Arzymanow (2003), focused project management practices can bring benefits such as innovation, adaptability and effective application of lessons learned.

4.2 CPS characterization model

A characterization model is a tool for brainstorming, attempting to normalize the familiarization of CPS systems. Developers, managers and stakeholders should provide hints about what the CPS system is or should be, based on their understandings. This CPS characterization model is proposed based on the most frequent technological characteristics found in CPS projects. Such characteristics were chosen considering three different sources of information: the professional background of the author of this work; exploratory studies; and the systematic review conducted as part of this research work. These common characteristics generically cover: *(i)* influences of the CPS system on the environment considering its way of use and *(ii)* different technologies that can be part of the CPS system. The CPS characterization model is systematically composed by two parts – “CPS environment” and “CPS complexity”.

Figure 5 shows an example of a proposed CPS characterization model whose parts “CPS environment” and “CPS complexity” are detailed as follows. This proposed model uses percentages to quantify the CPS environment and pre-established weights to quantify the CPS complexity. The resulting numbers can be used for project size estimation.

Figure 5 – CPS characterization model

CPS characterization model			
CPS environment requires:	Little	Med	Much
• Limited tasks			
• Communication with known group of devices			
• Interaction with known group of people			
• Following industrial standards or norms			
Complexity			
• Mechanical structures			
• Network			
• Sensors			
• Actuators			
• Data storage			
• User interaction			
• Legacy systems integration			
• Power energy system			

Source: Elaborated by the author, 2016

This work does not intend to propose a CPS characterization model with a closed set of characteristics, but indeed an open model that enables future expansion through adding different perspectives considering different specialists' experiences as well as technological improvements. Accordingly, new elements may be added to each one of the two proposed model parts or else new entire parts can be proposed.

The first part of the CPS characterization model – i.e., the "CPS environment" – 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 system are defined: "well-defined processes" and "dynamic", as stated below:

1. **Well-defined processes**: in application environments with well-defined processes, the CPS system performs limited tasks and interacts with a known group of people.

The physical infrastructure is usually standardized by industrial rules and the influence of the physical world is minimal. The low dynamism 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. An application environment with well-defined processes can usually be found, for example, in: *(i)* industrial applications, as automated tests (SCHWEIGHOFER; RAAB; BRASSEUR, 2003); *(ii)* construction, with structure for health monitoring (CHANG; FLATAU; LIU, 2003); and *(iii)* power supply, as smart grids (ZABALLOS; VALLEJO; SELGA, 2011; FANG et al., 2012).

2. **Dynamic**: in a dynamic application environment, the CPS system deals with unexpected situations and with unknown behavior of people. The processes which the CPS system is interacting with can be modeled, despite its complexity. CPS applications in this type of environment are usually located into hard access, mobile or hazardous structures. From the point of view of user, these applications are often intelligent, presenting 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 can be found in: autonomous vehicles (INSAURRALDE; PETILLOT, 2013); surgical interventions (BALLANTYNE, 2002; TAYLOR et al., 2008); and nuclear plant monitoring (FANTONI et al., 2002; LIN; WANG; SUN, 2004; MA; JIANG, 2011).

To characterize the CPS environment as “well-defined processes” or “dynamic”, four variables were chosen (see example in figure 5): limited tasks; communication with known group of devices; interaction with known group of people; and following industrial standards or norms. The purpose is to characterize all these variables using the following rates: little; medium; and much. The project team, in a brainstorming session, would appoint which rate each variable has, and the project manager or technical specialist would mediate the hints from all participants. As more “much” the model has, more well-defined is the CPS environment.

The second part of the CPS characterization model – i.e., the “CPS complexity” – is defined taking into account that, in order to make possible the interaction with the physical world, the development of CPS systems may need to deal with several different technologies as well as with some existing and running systems. Therefore, the complexity of a CPS system 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 system. Another point of view is the role played by the CPS systems, such as the role of systems which completely replace a human activity or 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 system is, it is also possible to find examples of CPS systems consisting by only one system but with a large number of sensors and actuators or of a high computing cost, which enhance its complexity. A set of common technological items able to be integrated to a CPS system is characterized as follows (as example shown in figure 5):

1. **Mechanical structure**: CPS systems must often be built over a mechanical structure or have a supporting mechanics. In this case, the mechanical structure is part of the CPS project and must be considered as part of the CPS system. Some examples of CPS systems which use mechanical structures are: robotic applications; drones; rescue vehicles; and 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 for which communication is a requirement, such as when wireless sensor networks and smart power grids are involved. The entire link can be part of the CPS project, including the antenna, the demodulation and the messages decoding.
3. **Sensors**: sensors represent the bridge between the physical and the computing worlds. Sensors mainly allow a CPS system to read the variables around it, providing information to adapt its processing or performance. Mostly, a CPS system 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 giving the feedback of sensors' readings, processed by computers. Actuators may appear in the way of switches, engines action or electrical signals. CPS systems may be not integrated with actuators, providing its responses to environment readings through a simple graphical user interface.
5. **Data storage**: many CPS systems 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 systems often require 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 systems are 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 systems. Mainly if the CPS system will be accessible to people, i.e., when users or operators can act in place of a CPS system or its operation depends on users' judgment.
7. **Legacy systems integration**: as CPS systems 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 application into some more complex. The integration between these unpredictable systems may represent the need of different management approaches, since the CPS systems developed may enhance productivity and allow transparency for the users of these legacy systems, in the way that was before.
8. **Power energy system**: many CPS systems are autonomous and formed by mobile systems, and some of them 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 the type of equipment involved and the application environment and may require specific professionals of power energy systems design.

In summary, the complexity of a CPS system being developed can be measured by verifying the existence of one or more of the previous eight technological items. The same rates are used for this part (as used for the "CPS environment"): little, medium or much. In the same way that the CPS environment was characterized, the CPS would be: the project team give hints for the rates for each item, and the project manager, supported by specialist, moderate the final characterization.

The proposed characterization model can be applied to support project size estimation. For this end, one could apply weights for each characteristic according to its influence, frequency or amount of use. For example: a CPS system characterized as much complex in power energy system, in a company where there is few resources with this profile, can lead to team increase or outsourcing solutions, depending on project manager's decision. Besides size, schedule, cost, team, among others estimations, the CPS characterization model supports a normalized understanding of the entire CPS project, from team members perspective.

4.3 Knowledge area specializations

The selection of the three knowledge areas (scope, human resource and stakeholders), from the ten original PMBOK's knowledge areas, was carried out considering the outcomes of the systematic review conducted as part of this research project (see section 2.3). As a result of such systematic review, it was possible to identify these knowledge areas as the three most addressed ones in specialized literature for the context of CPS projects. The identification of the most discussed knowledge areas was supported by a relevance score calculated based on the number of times that keywords related to the ten knowledge areas appeared in the selected primary studies. Only the knowledge areas with a number of references above the average was selected. Considering the average of studies of 9 times per knowledge area, the number of times that the chosen knowledge areas were found was: 20 times for "scope"; 12 times for "human resource"; and 10 times for "stakeholder". The average relevance score was 255 per knowledge area, and 758 for "scope", 738 for "human resource" and 238 for "stakeholder". Although stakeholder was below the average, it was one of the selected knowledge area due to number of studies be over average and a very close relevance score.

The project management processes related to the scope, human resource and stakeholders knowledge areas were specialized to satisfy the previously discussed specific characteristics of CPS systems. The specializations of these project management processes allow CPS-related project managers and developers to deal earlier with common challenges faced during the development of this type of project, such as continuously and sudden discovery of requirements, originated from an unexplored application as CPS systems; and lack of communication among team project and stakeholders, due to multidisciplinarity of technical subjects involved. The three specialized knowledge areas inside the CPS-PMBOK context are detailed 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 provide special challenges for CPS projects due to the innovative aspect of the application, as discussed previously (LEE, 2008; SHA et al., 2009; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014).

For this reason, a feature related to CPS-PMBOK is the dynamism of requirements. Considering the ordinary needs to use technologies previously unknown by the project team as well as to develop CPS systems to latest application domains (such as robotic medical surgery, autonomous vehicles and smart buildings), CPS projects tend to present innovative features (RAJKUMAR, 2012). In addition, the high complexity required to model the physical world and its physical phenomena is another source for innovation needs. Such innovative requirements result in ever-changing requirements mainly due to: realignment of the stakeholders' conception; understanding of further issues; rise of new technologies; adaptation of unstructured processes; and finding of new physical phenomena. In this innovative scenario, a late discovery of new requirements is inevitable mainly when considering an exploratory development method as required and adopted by many organizations (HUANG; DARRIN; KNUTH, 2012). CPS project managers should be able to constantly look for new requirements, bringing up changes in scope as soon as possible. Besides contributing to a proper system specification, a partnership-based approach, involving an outsourced organization, also allows to proper address ever-changing requirements when its participation is needed.

In this context, taking into account the features aforementioned, CPS-PMBOK proposes the following additional best practices, as detailed below: "review requirements process" and "pre-elaborated list of requirements".

4.3.1.1 Review requirements

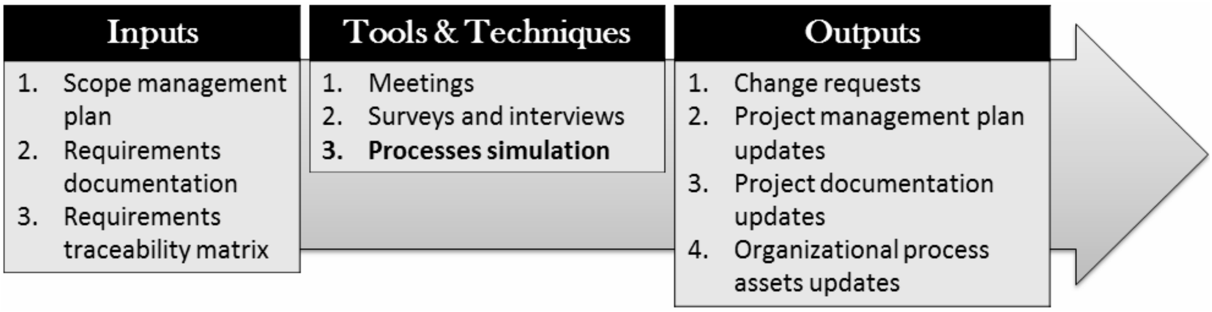
Due to the evolutionary characteristic of CPS projects and hence the constantly changing scope, a whole new process is proposed for the project scope management. The new process, named “review requirements”, is proposed as part of the monitoring and controlling process group. This additional process is proposed as new best practice based on the professional background of the author of this research work, observing the behavior of different customers, whom used to make reviews of their own project’s goals and definitions.

The review requirements process aims to advance such reviews, bringing up the changes as soon as possible, so it can be timely addressed. The review requirements process results in change requests similarly to performed by the control scope process, as described in PMBOK. The difference is that, in CPS-PMBOK, review requirements is a creation-focused process, considering less the already known requirements and revisiting the highest definitions of the project looking for new requirements whereas, in PMBOK, the control scope process focuses on ensuring the accomplishment of the defined scope and, when needed, the appropriate processing of changes are made.

Following the input/tools_techniques/outputs description pattern for PMBOK’s processes, 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)* surveys or interviews; and *(3)* process simulation (a new technique proposed). Finally, the outputs are: *(1)* change requests; *(2)* project management plan updates; *(3)* project documentation updates; *(4)* organizational process assets updates. The graphical pattern for presentation of PMBOK’s processes is also followed here to represent the proposed review requirements process, as show in figures 6 and 7.

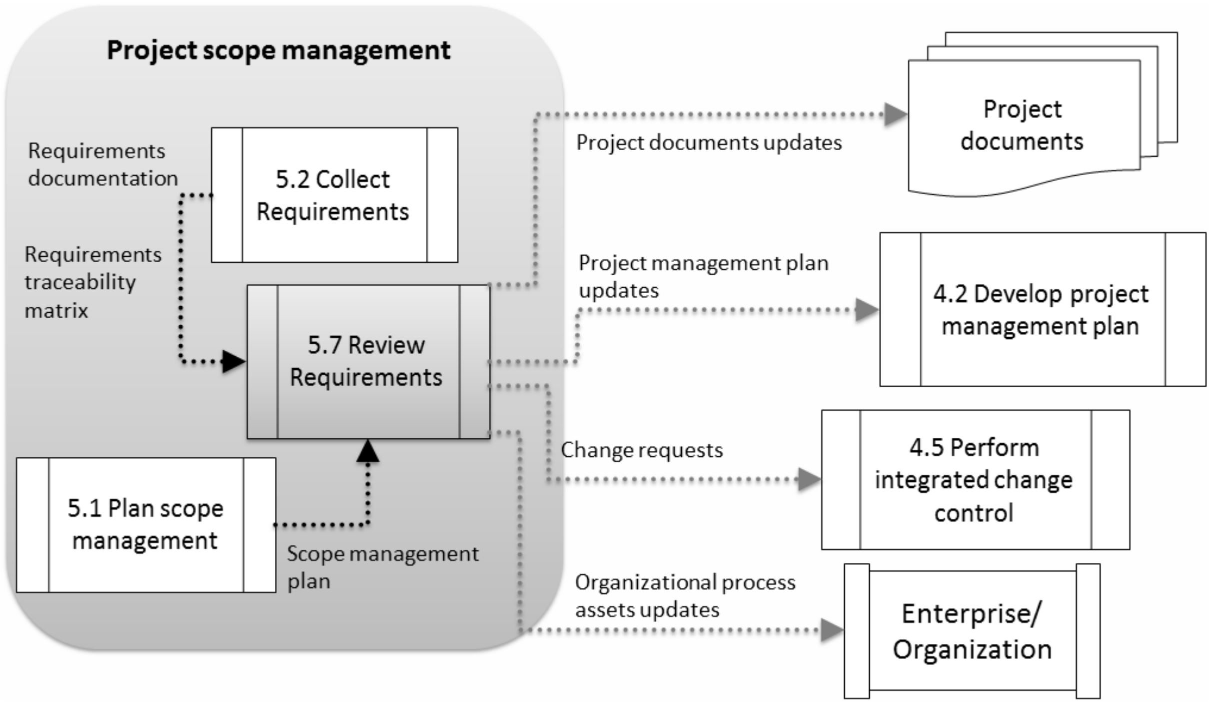
From three techniques showed in figure 6, two are described in PMBOK: meetings; and surveys and interviews. The remaining technique, called process simulation, is proposed as part of CPS-PMBOK approach. It is a set of diverse test, validation and verification techniques which can be used in many situations. Regarding to an industrial process automation context, process simulation refers to a step-by-step analysis of the process inputs and outputs, often using process modeling or mapping. The behavior of an installed CPS system is compared to the previously non automated process regarding the influences of

Figure 6 – Review requirements process: inputs, suggested tools and techniques, and outputs



Source: Adapted from PMI, 2013

Figure 7 – Data flow diagram for the review requirements process



Source: Filipe Palma, 2016

the industrial environment, i.e., other processes, systems and people. Trial or demo versions of the system, consisting of partially functional CPS systems are deployed to evaluate the requirements accomplishment and to stimulate the discovery of new requirements. The functionalities may be deployed in the environment according to requirements reviewing needs. Mechanical devices may be simulated with prototypes or 3D printed models. When working in a more dynamic process or environment, mathematical models may be applied to simulate its behavior. This mathematical modeling is developed through previously mapped variables which may change the CPS behavior accordingly, leading to the expected responses, as if CPS systems were deployed in the real environment. For embedded systems, a Hardware in the Loop (HIL) or Software in the Loop (SWIL) strategies are often adopted for process simulation, according to proportional progress of the CPS systems. The process simulation may indicate how many changes an environment or process may suffer after the CPS deployment, and which actions may be taken to minimize possible negative changes. Process simulation may support the validation of the current stage of development and the discovery of new requirements. Examples of the use of process simulation for CPS projects can be seen in Madachy, Boehm and Lane (2007), Lattmann et al. (2015) and Faschang et al. (2015).

4.3.1.2 Pre-elaborated requirements list

Aiming to additionally support the "collect requirements" process, as described in PMBOK, CPS-PMBOK proposes the use of a new technique/tool: pre-elaborated lists of requirements, based on the CPS complexity and environment attributes as described in the CPS characterization model proposed. The use of pre-elaborated lists may improve the detailing of requirements as well as the coverage of the scope definition. Furthermore, if constantly updated according to requirements changes, the pre-elaborated lists may enhance lessons learned, reducing the uncertainty of requirements for future similar projects.

A pre-elaborated list of hardware requirements were applied by Silva, Loubach and Cunha (2009) aiming to estimate the necessary effort for system development. The technique is called hardware points analysis, probably inspired by the function point analysis technique, and was used in an aerospace project context (SILVA; LOUBACH; CUNHA, 2009). The pre-elaborated list can be used for supporting the requirements elicitation from different point of views. Table 10 presents an example of the use of the hardware points technique, using pre-defined weights that mean the necessary effort assigned for every technical question.

Table 10 – Example of application of the hardware points analysis technique

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
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)

Additionally, Table 11 presents a proposal of a pre-elaborated list of software requirements for an initial collection of requirements. This list indicates a subject of high level of abstraction (on the "topic" column) and a corresponding technical question for each topic (on the "description" column).

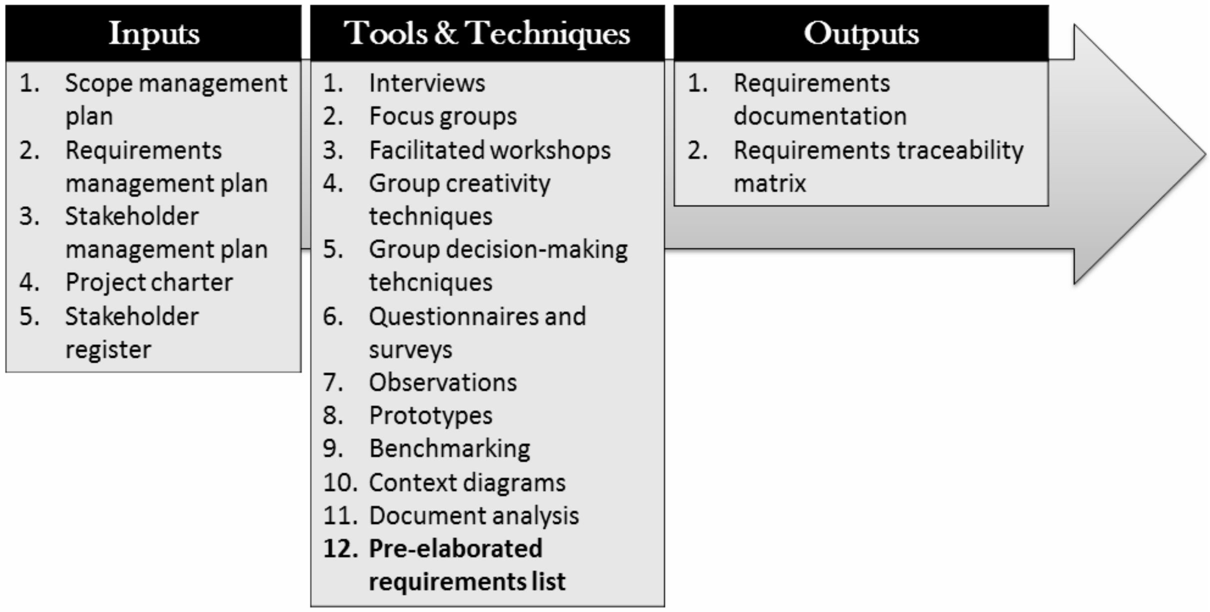
Table 11 – Example of application of the software points analysis technique

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?
Remote access	May it be necessary web visualization or operation?

Source: Filipe Palma, 2016

The graphical pattern for presentation of PMBOK's processes is also followed here to represent the proposed pre-elaborated requirements list technique, as shown in figure 8

Figure 8 – Collect requirements process: inputs, suggested tools and techniques, and outputs



Source: Adapted from PMI, 2013

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 projects, the human resource which may be part of a project team can be from very different areas of specialization, what increases the challenge of managing relationships and technical communication (WOLFF; GORROCHATEGUI; BÜCKER, 2011). In a practical example, a project to develop a smart power grid system may include professionals from electrical supply, hardware design, telecommunication and software development. Professionals from electrical supply and software may be not familiar with hardware technologies whereas telecommunication professionals and hardware designers come from a very different school, where software is usually not object of study. These different academic approaches applied in a same product or project may cause misunderstanding among team members, influencing requirements understanding and even task priorities.

Taking into account the features aforementioned, CPS-PMBOK proposes the following additional best practices, as detailed below: “cross training” and “specialized team divisions”.

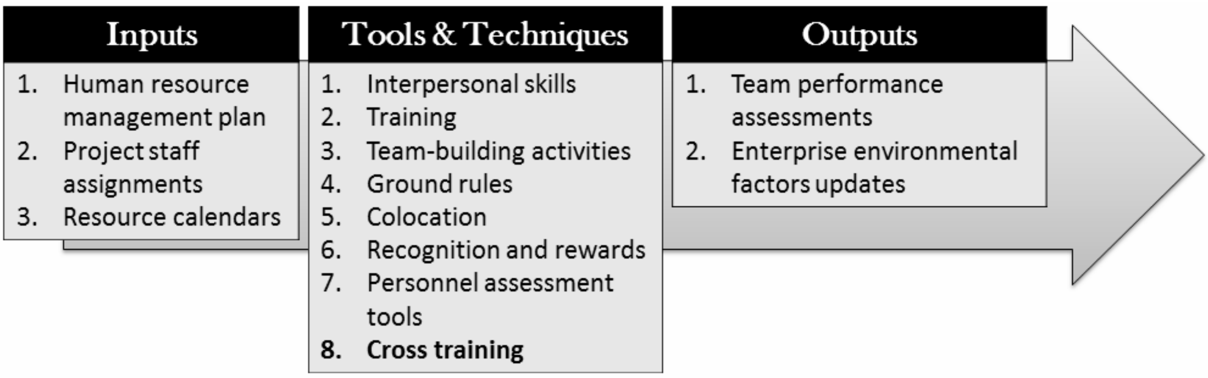
4.3.2.1 Cross training

To minimize misunderstandings and enhance the project execution performance, CPS-PMBOK proposes a specialization of the cross training of people, briefly cited in PMBOK as a preventive action for team member changes (PMI, 2013) as part of "develop project team" process described in PMBOK. Unlike only preventing changes, an intense cross training approach may improve communication, commitment and skills development.

A cross training is an allocation strategy which consists of a double assignment of tasks: one person, more experienced, should be the main responsible whereas a second person, not so familiarized in that area, should follow the task development, learning and even making some minor deliveries. In this approach, the second professional becomes 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. The drawback of such approach is that a resource keeps delivering less results than others, initially enlarging the budget of the project. On the other hand, some time can be saved when integrating all CPS parts.

The graphical pattern for presentation of PMBOK's processes is also followed here to represent the proposed cross training technique, as shown in figure 9.

Figure 9 – Develop project team process: inputs, suggested tools and techniques, and outputs



Source: Adapted from PMI, 2013

4.3.2.2 Specialized team divisions

Another best practice proposed by CPS-PMBOK is to pre-split the team into sub-teams, according to specialties commonly found in CPS systems, as an additional technique/tool to support the human resource management processes "plan human resource management" and "acquire project team", as 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), CPS-PMBOK is based on the CPS complexity of the characterization model, with more generic specializations, and it may be used to support to design organizational breakdown structures or resource breakdown structures. A specialized team division may include varied departments or even external organizations. This is an optional suggested technique/tool since depending on the project needs it may be unnecessary. Considering the main applications visualized by Rajkumar (2012), Sha et al. (2009) and Kim and Kumar (2012), and the CPS project complexity characterization model, specialized 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. The electric power requirements is also part of the work of this team.
4. **Network design team**: consisting of 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.

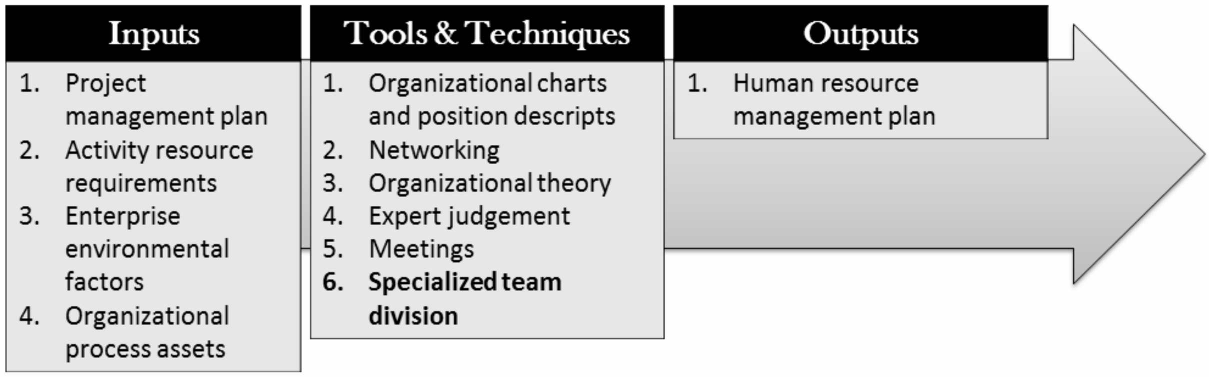
5. **Information system development team**: consisting of programmers, computer and software engineers, this team is responsible for software development, data storage architecture design and implementation, and graphical user interface development.

This team division is proposed in order to improve performance of CPS projects and avoid inappropriate assignment of responsibilities, and is based on general needs of CPS projects. However, it can be adapted according to specific project needs, based on the context of the system application. An alternative division is based on deliverables or partial results of the project, assigning a focused team for each logical deliverable part of the developed CPS system. Following the example of an autonomous weather information collector: a case of drone development, allied with weather sensoring and statistical software for forecasting, the deliverables would be:

- **Mechanical structure**: mixing mechanical and hardware design profiles, responsible for structure and engines design and development.
- **Flight system**: composed of mechanical and hardware design profiles and possibly a theorical flight expert. This team is responsible for designing and developing the propellers and orientation sensors.
- **Power energy system**: a team composed of electrical design profiles plus chemists for battery technologies experts.
- **Communications system**: it is the same network design team aforehand described, responsible to deliver the radio communication system for remote control and data collection.
- **Embedded software**: information systems development profiles, but with a focus on reliable embedded software design. It is the team responsible to deliver the main software of the drone, which controls the engines, read sensors, communicate with radios and also has some autonomous routines for emergencies.
- **Weather data system**: team composed by weather sensors and statistical experts, allied with some electrical and hardware design professionals. The specification of appropriate sensors to be used and interpretation of results is part of the deliverable of this team. If the statistical software will be developed, information systems profiles may be part of this team.

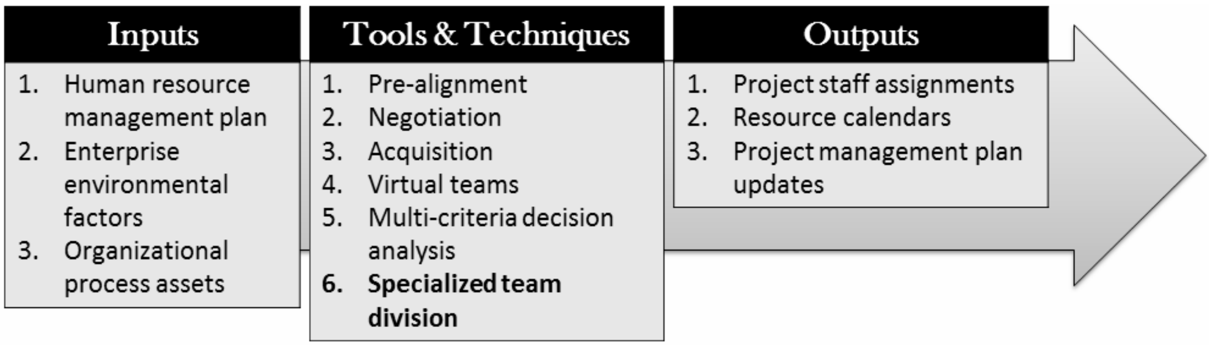
The graphical pattern for presentation of PMBOK's processes is also followed here to represent the proposed specialized team division technique, as shown in figures 10 and 11

Figure 10 – Plan human resource management process: inputs, suggested tools and techniques, and outputs



Source: Adapted from PMI, 2013

Figure 11 – Acquire project team process: inputs, suggested tools and techniques, and outputs



Source: Adapted from PMI, 2013

4.3.3 Project stakeholders management

PMBOK describes project stakeholders management as the control of expectation and engagement of all people who influence or is influenced by the project. Stakeholders engagement brings benefits for the project as mutual understanding of requirements, project quality and project performance. Project stakeholders in a context of CPS 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 researchers 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 (BAHETI; GILL, 2011; RAJKUMAR, 2012).

Taking into account the features aforementioned, CPS-PMBOK proposes the following additional best practices, as detailed below: “technical trust” and “dynamic follow-up strategies”.

4.3.3.1 Technical trust

PMBOK describes a practice of trust building for stakeholders engagement management, by showing that the company, project team and even the manager have competencies to accomplish project’s requirements in time and cost. In this context, CPS-PMBOK proposes a specialization of the trust building, adding the technical issue to this practice. It is a practice not related to one specific process, but a general stakeholder management practice.

Building technical trust, means to get close to the stakeholder, in situations in which they are very technical. This can be fulfilled by an expert team member or an external consultant participation on the project. This person has the role of translating technical stakeholders concerns and even clarifying specific issues in place of the real stakeholder. The main goal is to provide to stakeholders a technical neighbor which can represent their interests accordingly. The technical trust may improve stakeholders’ satisfaction due to their proximity and understanding of technical issues.

4.3.3.2 Dynamic follow-up strategies

As stakeholders management is closely related with communications, quality, human resource and scope management, the proposed practices may influence other processes of these knowledge areas. PMBOK mentions the communication methods described in communications management as a technique to manage stakeholders engagement, however, as observed in the outcomes of the systematic review conducted, this may be not enough to keep stakeholders properly updated.

Huang, Darrin and Knuth (2012) used face-to-face meetings to update the project status to stakeholders. Rong et al. (2011) included stakeholders’ participation in every last weekly follow-up meeting of development iterations. Penzenstadler and Eckhardt (2012) organized weekly workshops for system demonstrating, aiming to update stakeholders.

Considering the previous practices, CPS-PMBOK proposes a technique called: dynamic follow up strategies, aiming to support the process "manage stakeholder engagement" and "control stakeholder engagement", described in PMBOK. The dynamic follow up strategies technique is a combination of these meetings, according to project stage and stakeholders availability, as follows:

1. Regular face-to-face meetings during the understanding stage, in order to build stakeholders trust and improve the understanding of project needs, influencing the project scope management.
2. Sporadic participation of stakeholders in internal and technical meetings during the development stage, in order to build technical trust, provide feedback and analyze new requirements.
3. Project workshops with live demonstration of the developed CPS system during the consolidating stage, with stakeholders participation, occurring as soon as possible aiming to visualize the system.

The choice to use each aforehand strategy is done by observing the project status. The application of previous types of follow-up is not necessarily linked to a specific time or cycle of the project, but to a stage observed by the project manager. In this approach, if one or more of the following situations show up, an appropriate strategy should be used.

The following situations can be found during the understanding stage of project: requirements discovery; stakeholders discovery; specific area understanding; more resources availability; time flexibility; and more stakeholders engagement.

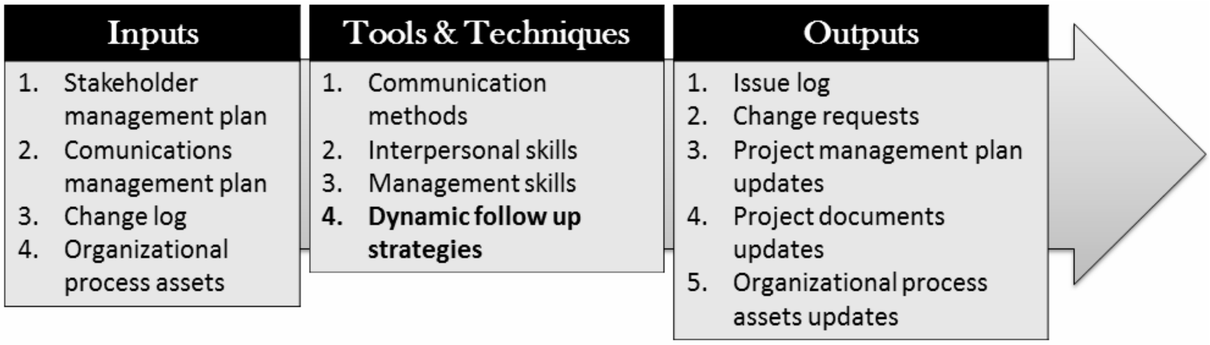
The following situations can be found during the development stage of project: requirements conflicts; technical demands by stakeholder; documentation and procedures alignment; and starting of requirements redefinition.

The following situations can be found during the consolidating stage of project: requirements redefinition (after the conflict, new definition of requirements were made); more execution demands by stakeholder; resources scarcity; time re-planning; stakeholders updating (Due to changing of people or the emergence of decisive profile); and less confidence and engagement of stakeholder.

These practices aim to enhance stakeholders' engagement and hence satisfaction, providing opportunities to improve project quality as unexpected requirements are discovered.

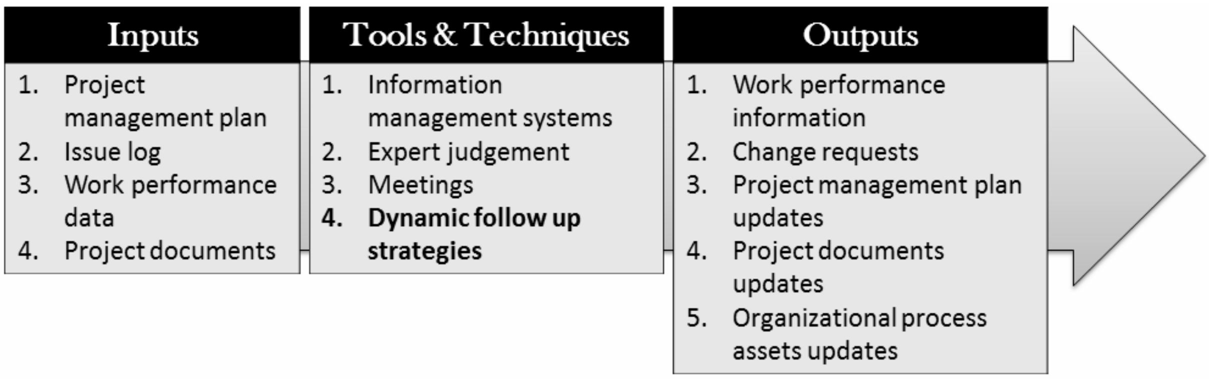
The graphical pattern for presentation of PMBOK's processes is also followed here to represent the proposed dynamic follow up strategies technique, as shown in figures 12 and 13

Figure 12 – Manage stakeholder process: inputs, suggested tools and techniques, and outputs



Source: Adapted from PMI, 2013

Figure 13 – Control stakeholder process: inputs, suggested tools and techniques, and outputs



Source: Adapted from PMI, 2013

4.4 Final remarks

According to results obtained in systematic review, the PMBOK practices for the remaining knowledge areas not addressed in CPS-PMBOK may be enough to manage it. However, there are some additional concerns regarding CPS projects that should be taken into account by project managers in addition to those addressed by the three specialized knowledge areas as proposed by CPS-PMBOK. Considering professional background and some examples of literature, this section aims to provide some reflections regarding communications management and procurement management. For remaining knowledge areas, more research for specific approaches considering CPS systems is necessary.

In terms of project communications management, CPS-PMBOK is primarily based on the multidisciplinarity of both subjects and team members, a very common aspect of CPS projects (LEE, 2008; SHA et al., 2009; RAJKUMAR et al., 2010; BAHETI; GILL, 2011; LEE; SESHIA, 2014). Multidisciplinarity means that the project team necessarily consists of professionals from different specialties due to the inherent integration of the computing world with the physical world, which need to communicate each other during the project development. As a result, the proper execution of CPS projects relies on breaking the communication boundaries among the organization's departments. Thus, project managers should be able to broadly facilitate communication. Although the original set of best practices for communications management provided by PMBOK also applies to CPS projects, a further concern may be required when considering the greater disparity on the specialties among the different involved professionals. Wolff, Gorrochategui and Bücker (2011) and Huang, Darrin and Knuth (2012), for example, used a team leader empowerment practice, assigning the explainer role to some senior professional who may also be responsible for updating the tasks progress, obtaining effective team communication and commitment.

In terms of project procurement management, depending on some organization features, external devices produced by other organizations may be necessary to be integrated to a given CPS system. Outsourcing may be useful for devices of a CPS system that are needed only sporadically or whose parts are very specialized, and hence is not cost effective to create a specific team to develop them. Some examples of this type of devices are: heavy industrial machining; dielectric packing; and simulations of antenna radiation, physical robustness and heat dispersion. Another advantage is the possibility of customization over project development, since many hardware development demand adjustments. 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 organizations, using non-disclosure contracts that provide some benefits for both sides. Although not specifically based on a partnership model, the project procurement management, described in PMBOK, addresses best practices for the appropriate outsourcing and hiring management. Examples of procurement management, including internal development and outsourcing solutions were given by Wolff, Gorrochategui and Bücker (2011) and Silva, Loubach and Cunha (2009).

5 Approach evaluation

In order to evaluate the proposed CPS-PMBOK approach, the developed best practices were presented to project managers at a private R&D organization. The goal was to evaluate the influence of CPS-PMBOK in the project execution from managers' and developers' viewpoints, based on previous experiences in the organization.

The involved departments currently develop projects in power energy distribution, industrial automation, autonomous vehicles, energy harvesting and cognitive systems areas. All project managers worked at least in one project considered a CPS system. Two of them are currently PMP (Project Management Professional) certified and one is in the process of. All of them are familiar to PMBOK practices and use it in their activities, although not required by the company. The results of evaluation may depend on individual identification and skills in applying CPS-PMBOK, even hypothetically. The skills, in turn, depend on technical background and social abilities. Davis (1989) studied the acceptance level of new technologies and created the technological acceptance model (TAM), which aims to better understand the acceptance level and behaviors that lead to individual different intentions to use. According to Davis (1989), two main factors lead to real intention to use a new technology: perceived usefulness and perceived ease to use. These two, allied to external factors – such as other people influence – may contribute to acceptance and consequent intention to use (VENKATESH; DAVIS, 2000).

It is possible to predict acceptance level or at least mapping causes of bad acceptance, by observing these factors and the environment which technology would be applied. This allows to improve the technology, before the delivery or to prepare an appropriate strategy of technology presentation to the group of users. Although TAM is often used to new information systems technologies acceptance, new processes and practices may also have its acceptance mapped. Umarji and Seaman (2005) adapted TAM to evaluate acceptance in software process improvement (SPI). Since the adoption of new processes may change users' activities at workplace, the same factors can be applied to predict their acceptance. To do that, some variables may be included: organizational issues, personal issues, SPI-related issues and social psychology issues (UMARJI; SEAMAN, 2005). As SPI is not a product or application itself – such as CPS-PMBOK, is a process or a set of tasks – this research used the approach proposed by Umarji and Seaman (2005) to develop precautions, preventing bad acceptance of CPS-PMBOK. The only type of issues not addressed was SPI-related issues, since this research focus on CPS systems. The main actions to soften the previous issues were:

- Make it clear that the participation is voluntary.
- Make it clear the confidentiality of data gathered.
- To assure project management office support.
- Let the managers decide how many and which projects will be considered.
- Let the managers decide which practices of CPS-PMBOK will be considered.
- Produce the most comprehensive CPS-PMBOK material as possible.

Organizational issues such as compatibility of work practices and organization's politics were not taken into account to enable the general application of CPS-PMBOK. To perform the evaluation, it was made an initial meeting with three managers, aligning the concepts of CPS systems and explaining CPS-PMBOK. All the academic research context was explained, including the systematic review and the motivations, to avoid comparisons with organization's issues.

After the initial meeting, it was asked the managers to apply CPS-PMBOK as possible in their current projects. Monthly follow-up meetings were made to align CPS-PMBOK concepts and gather feedback from managers. At the second meeting, it was decided that managers would not literally apply the practices due to the influence that could cause in the organizational practices. Instead of, the managers would do analyses of hypothetical CPS-PMBOK application according projects events. The follow up meetings was used to contribute to the updating of managers' opinion about CPS-PMBOK applicability. To enhance CPS-PMBOK evaluation, three more managers were added to the questionnaire application. It was made an explanation of CPS-PMBOK practices and CPS context alignment, such as in the first group of managers, but their opinions – which vary from systematic review methodology to the feasibility of the practices in a research and development-driven company – were gathered in a shorter time. There were managers who had the same impressions from some practices, such as the use of a template for CPS characterization model, in order to compare and normalize the hints. The feedback collected often are simply possible applications of practices observed by the managers, but which were not presented or imagined as new benefits. Examples of feedback are: success definition influencing CPS-PMBOK in a general way, given that for each project or situation, different variables means success, causing in different use strategies of the practices; and life risk as a factor in the CPS characterization model, due to the very near contact with people which CPS systems can have. In a general way, the managers could separate the troubles of the company from their professional opinions. A summary of all managers' feedback can be seen in the Table 12.

Table 12 – Feedback from managers

Practice	Feedback
General	The definition of success could influence more the practices.
CPS characterization model	The life risk factor should be added in the CPS environment.
CPS characterization model	The results can provide inputs for decisions like project sequence or appropriate time and cost initially planned.
CPS characterization model	The time, team and cost available can influence CPS characterization.
CPS characterization model	A template made by project manager and a specialist could be used to consider team CPS characterization
Pre-elaborated list of requirements	When in an exposed environment, a list should be made.
Cross training	Useful for parallel approaches when technologies are very unknown.
Specialized team division	The role of an architect is missing to integrate all other teams.
Dynamic follow up strategies	The workshop strategy can be useful to show what is accomplished, avoiding changes.
Both from scope	The review requirements process and pre-elaborated list of requirements could be more connected, like a tool from each other.
Build technical trust	Can be used to bring trust inside the team too.
CPS characterization model	Could be weighted depending on profile and specialty who originated of the hint.
Review requirement process	Should be closely related to risk management.
Build technical trust	Also can be useful to translate technical concerns and expressions to project team.
CPS characterization model	May inhibit creativity and innovation.
Dynamic follow up strategies	Should be closely related to scope management

Source: Filipe Palma, 2016

After the follow up meetings period – approximately five months – for the first three managers, and a week later the presentation for the three last managers, an on line questionnaire was applied to register managers' evaluation. The questionnaire responses were anonymous and the questions were related to practices presented and its influence for its respective area of knowledge management or purposes – in case of CPS characterization model –, considering the development of CPS systems. It was asked to consider the use of CPS-PMBOK compared to PMBOK practices, to identify the real relevance of the approach. The evaluators choose if they agree or disagree in a scale of one to five, being five totally agreement of practice benefits for its area of knowledge. Two more questions were made besides those related to PMBOK's knowledge: the influence of CPS-PMBOK in team communication and project activities understanding. These additional question were made due to the main characteristics of CPS systems, as discussed previously (cf. section 2.3): the multidisciplinary teams and very innovative scope. Lastly, a question requiring a free text answer was made. The Appendix A presents the applied questionnaire in English and Appendix C the responses in Portuguese (the questionnaire was made in Portuguese to avoid misunderstanding). Table 13 shows the summary of responses summarizing the points considered the level of agreement, the team communication improvement and activities comprehension.

Table 13 – Responses from managers

Practice	Points	Comm.	Act. Compr.
CPS characterization model	24	2	5
Review requirements process	24	5	5
Pre-elaborated list of requirements	26	1	4
Cross training	25	3	2
Specialized team divisions	26	3	1
Technical trust building	26	2	3
Dynamic follow-up strategies	25	5	4

Source: Filipe Palma, 2016

The viewpoint of developers about CPS-PMBOK were evaluated in a similar way: a presentation to four representatives of technical personnel – not necessarily involved in projects with managers participating of evaluation – was made, aligning CPS context understanding and explaining the approach. The profile chosen was more senior than junior, due to some project issues knowledge, such as stakeholders direct contact, often not experienced by junior professionals. There were representatives from multiple specialization areas: hardware engineering; software programming; and power energy. Although they represent the development side of project team, some of them had familiarity with project management concepts.

The feedbacks collected were similar to managers, such as the lack of an integrator role in specialized team division. Another missing issue was the representation of software development in CPS characterization model: it was suggested to add intelligence over data in the CPS complexity characterization, besides an "unknown" or "new technologies" variable for remaining issues. A very technical suggestion was sharing source code of developed software for stakeholder, so they can compile its own version, improving stakeholders expectation and engagement management. To improve the definition of levels in CPS characterization model, at least fourth level was suggested. Concerns about documentation showed up, which was not addressed in this approach due to the wide information provided by PMBOK. Regarding the creativity inhibition issue, there was some feedbacks from developers side too: the missing over time of requirements meaning was appointed as risky for different success context projects. It was suggested to use more than one list for these cases. Table 14 summarizes the feedback collected from developers.

Table 14 – Feedback from developers

Practice	Feedback
CPS characterization model	Define better the level: little, medium and much.
CPS characterization model	Add "intelligence over data" in the CPS complexity characterization
Build technical trust	Provide access to source code of developed software for technical stakeholder.
General stakeholders	Provide a wiki or any way of compile information about project, informally and shared.
CPS characterization model	Add hazardous environment or extend the industrial standards and norms to embrace it in CPS environment characterization.
Cross training	It works if all sub areas or teams of project do that.
Specialized team division	A role of an integration is missing. It is suggested that the leaders of each team be an integrator
General	Lack of documentation practices, mainly in changes of project
Pre-elaborated list of requirements	Too much risk for different project success context.
Dynamic follow up strategies	The workshop preparing can spend too much time in situations where no more resources or time are available
CPS characterization model	Add "unknown" in the CPS complexity characterization
Review requirement process	A more integrated process simulation should be considered
Pre-elaborated list of requirements	Should define the team of project when filled

Source: Filipe Palma, 2016

The questionnaire was developed in a similar way, but was not asked to compare CPS-PMBOK to PMBOK practices, due to the execution point of view of the evaluators. Instead, a brief description of each knowledge area was made, asking if the practices would contribute to reach the descriptions. The same questions regarding communication among teams and understanding of activities improvement were made. To finish, suggestions to enhance CPS-PMBOK applicability or general project management practices in CPS development were asked. The Appendix B presents the questionnaire applied to developers and Appendix D their responses. Table 15 shows the summary of project team responses.

Table 15 – Responses from developers

Practice	Points	Comm.	Act. Compr.
CPS characterization model	17	2	3
Review requirements process	18	0	3
Pre-elaborated list of requirements	15	3	2
Cross training	18	3	3
Specialized team divisions	17	3	3
Technical trust building	18	2	0
Dynamic follow-up strategies	15	1	0

Source: Filipe Palma, 2016

5.1 Discussion of results

All six managers answered the questionnaire and provided feedback personally. The results of managers' questionnaire shows the pre-elaborated list of requirements, specialized team division and technical trust building as the most relevant for its respective area of knowledge, with 4 answers of agree and 2 totally agree for two first and 2 answers of agree and 3 totally agree for the last. Although with no disagrees answers, the review requirements was the less chosen as influence to respective area of knowledge, counting with 2 neutral responses. The practices which more influence communication improvement were review requirements process and dynamic follow up strategies, both with 5 votes. The pre-elaborated list of requirements received only one for communication improvement. By the other hand, CPS characterization model and review requirements process were voted as more relevant for improving activities understanding, both with 5 votes. The less voted practice regarding activities understanding was specialized team division with 1 vote.

It was not expected the review requirements as more improver of team communication, but is comprehensible that managers conclude this, since it requires collective cooperation and interaction to process simulation technique and review requirements itself. It is possible to observe that the practices related to discuss requirements and system validation are more involved in activities understanding: CPS characterization model and review requirements process. This leads to conclude that in CPS development, practices which formalize, document and visually represent the technological variables are relevant to project success, although review requirements was less voted as relevant for its knowledge area. This could be happened due to the insecurity to lost control of project scope, since it can turn the scope something infinite if not managed well. In summary, the practice may helps to improve activity understanding but is not so proper for scope management, from the point of view of managers.

All four developers attended the questionnaire in time, besides providing the previously discussed feedbacks. The results of developers' questionnaire shows the review requirements, technical trust building and cross training as the most relevant for its respective area of knowledge, with 2 answers of agree and 2 totally agree for first two practices and 3 totally agree for the last. The pre-elaborated list of requirements was the less chosen as influence to respective area of knowledge, with 1 disagree response. The practices which more influence communication improvement are pre-elaborated list of requirements, cross training and specialized team division, all with 3 votes. The review requirement process received no votes for communication improvement. By the other hand, CPS characterization model, review requirements process, cross training and specialized team division were voted as more relevant for improving activities understanding, all with 3 votes. The less voted practices regarding activities understanding were technical trust building and dynamic follow up strategies,with no votes.

All these results leads to conclude that developers evaluation tend to agree more with human resource and scope practices than managers. Probably due to the less contact with stakeholder, considering it as the customer. Another point of view is the feeling of helpless when dealing with high challenging technologies and troubles for integrating all subsystems. The insecurity felt by managers does not appear for developers, due to the their vision of proper delivery of CPS systems be more important than stakeholders satisfaction. For managers, both are more connected: an impossible to reach scope, with the compromise of project team, certainly bring stakeholders dissatisfaction. There was no unanimity regarding team communication improvement, while for activities understanding the CPS characterization model and review requirements process seemed to be more relevant for both group of evaluators.

For the organization, the evaluation process itself showed to be useful for reconsidering its own organizational practices. It allowed to know technical team members skills and professional possibilities. Some legislative concerns showed up, not addressed in CPS-PMBOK, such as privacy and flight rules for drones, and metering regulation in power grid communication systems. The extinction of some professions in industry automation was also a point, whereas the same profile that validate solutions, can be replaced for machines, presenting a tread in stakeholders management. Particular human resource issues appeared in the discussions, which could depend on country and organization developing the CPS system, such as availability or suitability of professionals. Nevertheless, very specific profile resources could be a problem for every organization in every country, such as a physicist specialized in light propagation, for example.

Regarding the use of a template for comparison the CPS characterization model, a concern with the authenticity of project manager opinion shows up, since the template is known. To avoid this, the project manager could not hint in the same session of project team. Some opinions mixing the CPS characterization model and scope practices showed up, such as the inclusion of hazard or exposed environment information in some of practices. The appropriate approach would be to deal the issue in CPS characterization model if was not so frequent, so the team can analyze the issue further, depending on the characterization. The use of cross training for parallel development in very unknown subjects may be useful, but it goes against the purpose of this practice: the creation of a multidisciplinar competence and the improvement of communication among different teams. It only support team members lost, as described in PMBOK (PMI, 2013). One of the feedbacks regarding the dynamic follow up strategies suggested to use the workshops to explicit what is already finished, avoiding changes. Although this is in the wrong way of review requirements and all agile methods related, it can be useful to avoid superficial changes requests, in situations where changes could be disastrous. It have to be carefully used, to not inhibits innovation. The concern regarding inhibition of creativity is a relevant point of view, whereas a start to zero approach for requirements fro every project can bring new ideas. Nevertheless, the consequences of a forgotten requirements can be greater than the losses caused by inhibition of creativity, especially considering that CPS systems are innovative by its own.

One of the suggestions given by the developers group was to provide a way to keep every person involved in the project informed, by using a wiki for example. This technique can be aggregated to specialized team division, assigning the updating tasks to a specific project management support team. The role of an architect or integrator appeared twice in feedbacks: one from managers and other from developers group. But in the developers context, it was suggested that the leader for each team could do this role. Since the goal is to get together all information about current development in one person, this can create another need: an integrator of the leaders. The most wise strategy would be the assignment of the architect or integrator role to one person who gather skills of leadership, technical experience, impartiality and a good understanding of the project. If it was not possible to find this profile of professional, then the creation of an integration team may be necessary.

As predicted by Umarji and Seaman (2005), social issues seemed to influence the evaluation (UMARJI; SEAMAN, 2005): some managers showed more interest in participate of project, understanding the academic context involved, but others faced as a work evaluation, questioning the need to review their project management methods. This led to concerns with relevant subjects for CPS research, but are not the focus of this research, such as kinds of life cycle of projects, software development methods and financing strategies of projects. Since the organization is both industry and research-driven, issues related to final goals of projects showed up, such as a project to creating a product, methods or an art study for wider R&D projects. These issues indicate that particular modification of CPS-PMBOK or other approaches may be necessary according the final goal of the project, which connects to the success definition influence, cited by one of the managers. Although these also can be specific for each organization or country, it is relevant for CPS-PMBOK application, mainly in scope and human resource management – which some requirements and team members names can never change due to legal formalization of government funded R&D projects.

6 Conclusion

This master's dissertation aimed to set best project management practices for CPS development. The integration of the physical world and the computing world embrace developing very complex and unique systems, leading to innovative and multidisciplinary projects. These two factors may provide different challenges to project managers. To find out these challenges, we conducted a systematic review addressing CPS systems, its analogous systems and project management, correlating the studies with the widely used PMI body of knowledge, PMBOK. The results showed that three knowledge areas represent most efforts to manage CPS projects: scope management, human resource management and stakeholders management. Based on that, we created CPS-PMBOK, focusing on these three knowledge areas, specializing practices described in PMBOK and proposing new ones for managing CPS projects.

CPS-PMBOK presents a characterization model which supports project managers and project teams in: understanding the application domain; estimating cost, effort and time; mobilizing team; and elicitation of requirements. It works by scoring CPS environment – based on standards, workplace, procedures – and complexity – based on technologies composing the CPS system.

For scope management, CPS-PMBOK includes a new process, called review requirements. Aligned with agile method of software development, it aims to bring up requirements changing as soon as possible, considering that even the already accomplished requirements can change. Still in scope management, CPS-PMBOK present the pre-elaborated list of requirements, which is a tool to support scope definition and requirements collecting, minimizing missing technical specification.

In human resource management, we extend the cross training, which is a practice described in PMBOK for contingency action in case of team members leaving the project. In CPS-PMBOK, the cross training is incorporated as a human resource management practice, improving team skills, communication and commitment. Beside that, CPS-PMBOK presents a specialized team division to improve project's deliveries and assure appropriate manpower.

Stakeholders management requires stakeholders commitment, which requires mutual trust and PMBOK addresses it describing the building trust practice. In CPS-PMBOK there is the building technical trust, which is a practice to improve stakeholders commitment, whereas stakeholders are often very technical profiles, such as professors, specialists or seniors in their area. Another practice part of CPS-PMBOK are the dynamic follow-up strategies. It describes different ways of project meetings and presentations, for each set of situation which the project is, according to scope accomplishment, time or stakeholders satisfaction.

All these practices aim to support managers to face the challenges of such innovative and multidisciplinary teams projects. To evaluate its real contribution, CPS-PMBOK was analyzed by six project managers in a R&D organization. Follow up meetings to discuss concepts and collect feedback were made for five months. The managers compared CPS-PMBOK to current projects and analyzed what benefits the practices would bring, if applied. At the end of this period, they registered their opinion in an online questionnaire. To evaluate team members viewpoint of CPS-PMBOK, the approach was presented to four developers from different specialties and another questionnaire were applied to them.

CPS-PMBOK aroused the interest of all managers and developers involved, and although it was not an official process of project management improvement in the company, many attendants showed excited with the possibility of application of the practices. In a general way, the evaluators felt lack of discretization in some practices, mainly the CPS characterization model and the pre-elaborated list of requirements. This happened probably due to the main profile of evaluators be of engineering. Actually this can bring more accuracy to the practices. A positive side of the approach was to deal with hardware requirements, which showed to be unexpected for both managers and developers group of evaluators. Therefore, it is considered that CPS-PMBOK reached its purpose, properly representing the integration of systems and physical process in the context of project management. In more than one feedback from managers, the implicit agile methods in the approach seemed to be very audacious and innovative, mainly the review requirements process. In a general way, CPS-PMBOK met expectations from managers' side by showing a more close to CPS development set of best practices, being specific when PMBOK could not be. From developers' side, the approach enabled technical representation enough to enhance understanding of challenges and provide sharing-based knowledge to engineers, designers, programmers or any specialty found in CPS development.

The research showed that CPS systems can be the convergence of many other systems classification, such as system of systems, hybrid systems, embedded systems and internet of things. This could be observed during the systematic review and in the evaluation, which professionals with different background and specialization identified their projects with CPS systems. This reinforces the need of more researches in CPS field, regarding standardization of models, practices, processes, languages, among others, in order to provide organized communication, acceleration of development and technology enhancement. With appropriate project management approaches, the scientific community can focus on technical challenges, physical world understanding and knowledge frontiers expansion.

6.1 Future work

Many of feedback received are likely to implementation, its contribution would be small, regarding the already existent practices of project management. Considering the improvement of usefulness of CPS-PMBOK, the more significant and perceived by majority issues are subject of future work. As discussed in section 5, the perceived usefulness and perceived ease to use are the factor which lead to real intention to use some technology (DAVIS, 1989). Therefore, since this is a study mainly for organizational use, a very close to companies' reality approach should be done to maximize its feasibility.

For future work, the role of an architect will be considered for specialized team division, covering the lack of an integrator among the teams. A possibility of integration team division should be studied too, for more complex CPS systems. Regarding the review requirements, more specifically the process simulation technique, other technologies, tools and methods will be studied to provide an integrated technique of review requirements, or at least examples of that.

The main subject of future work will be the CPS characterization model, due to the potential observed in the feedback sessions. Aiming to enhance its power of representation of CPS systems, and approximate project manager, developers and physical world variables, it intends to do two extensions: the inclusion of parameters; and to define a methodology of use.

The inclusions would be: add intelligence over data in complexity characterization; and set discrete levels instead of little, medium and much. The first inclusion is aiming to represent the software variable and its complexity. The second is to provide numbers for decision making and also to avoid or minimize duplicity of levels' interpretation.

Considering a methodology of use, the first step would be to define a procedure to set a template for checking the characterization made with developers. This would deal with the noise caused by hints from non specialists. In a second step, a correlation of the characterization obtained, with the pre-elaborated lists of requirements should be done, potentiating the process of collecting requirements, acquire project team, estimate time and cost. The idea is to get the list of requirements among many others, which represents a profile of project, still inside a CPS context. This profile of project would contains a record gathered from previous projects with same profile, with: approximated cost; schedule; teams profiles; possible companies for outsourcing; risk analyses methodologies; quality standards; among other lessons learned based set of information.

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Appendix

APPENDIX A – Project management team questionnaire

Answer considering CPS-PMBOK, regarding project management in development of CPS systems and from the managerial point of view.

1. The use of the “CPS characterization model” is a practice which relevantly supports the familiarity of the project team regarding the unknown area (physical world) in development of CPS systems:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.
2. The inclusion of “review requirements” process is a practice which contributes relevantly to scope management in development of CPS projects, when compared to practices described in PMBOK:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.
3. The use of “pre-elaborated list of requirements” is a practice which contributes relevantly to scope management in development of CPS projects, when compared to practices described in PMBOK:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.
4. The use of “cross training” is a practice which contributes relevantly to human resource management in development of CPS projects, when compared to practices described in PMBOK:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.

5. The use of “Specialized team division” is a practice which contributes relevantly to human resource management in development of CPS projects, when compared to practices described in PMBOK:

   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.

6. The use of “Technical trust building” is a practice which contributes relevantly to stakeholders management in development of CPS projects, when compared to practices described in PMBOK:

   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.

7. The use of “dynamic follow up strategies” is a practice which contributes relevantly to stakeholders management in development of CPS projects, when compared to practices described in PMBOK:

   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.

8. In your opinion, the following practices contribute relevantly for improving communication among project team members:

   - ( ) CPS characterization model.
   - ( ) Review requirements process.
   - ( ) Pre-elaborated list of requirements.
   - ( ) Cross training.
   - ( ) Specialized team divisions.
   - ( ) Technical trust building.
   - ( ) Dynamic follow-up strategies.
   - ( ) None.

9. In your opinion, the following practices contribute relevantly for improving understanding of activities to be executed:

   - ( ) CPS characterization model.

- ( ) Review requirements process.
- ( ) Pre-elaborated list of requirements.
- ( ) Cross training.
- ( ) Specialized team divisions.
- ( ) Technical trust building.
- ( ) Dynamic follow-up strategies.
- ( ) None.

10. Leave your comments to improve CPS-PMBOK practices or considerations to improve project management regarding the CPS development:

APPENDIX B – Developers questionnaire

Answer considering CPS-PMBOK, regarding CPS development and from the technical / execution point of view.

1. The use of the “CPS characterization model” is a practice which relevantly supports the familiarity of the project team regarding the unknown area (physical world) in development of CPS systems:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.
2. The inclusion of “review requirements” process by the project manager is a practice which contributes relevantly to inclusion and control of activities or functionalities needed to accomplish the development of a CPS system successfully:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.
3. The use of “pre-elaborated list of requirements” by the project manager is a practice which contributes relevantly to inclusion and control of activities or functionalities needed to accomplish the development of a CPS system successfully:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.
4. The use of “cross training” by the project manager is a practice which contributes relevantly to organization, leadership and commitment of people with assigned tasks related to development of a CPS system:
   a) Totally disagree.
   b) Disagree.
   c) Neutral.
   d) Agree.
   e) Totally agree.

5.The use of “specialized team division” by the project manager is a practice which contributes relevantly to organization, leadership and commitment of people with assigned tasks related to development of a CPS system:

a)Totally disagree.
b)Disagree.
c)Neutral.
d)Agree.
e)Totally agree.

6.The use of “technical trust building” by the project manager is a practice which contributes relevantly to identifying, expectation analysis and engagement of people which can be impacted or impact the project of a CPS development:

a)Totally disagree.
b)Disagree.
c)Neutral.
d)Agree.
e)Totally agree.

7.The use of “dynamic follow up strategies” by the project manager is a practice which contributes relevantly to identifying, expectation analysis and engagement of people which can be impacted or impact the project of a CPS development:

a)Totally disagree.
b)Disagree.
c)Neutral.
d)Agree.
e)Totally agree.

8.In your opinion, the following practices contribute relevantly for improving communication among project team members:

- ( ) CPS characterization model.
- ( ) Review requirements process.
- ( ) Pre-elaborated list of requirements.
- ( ) Cross training.
- ( ) Specialized team divisions.
- ( ) Technical trust building.
- ( ) Dynamic follow-up strategies.
- ( ) None.

9.In your opinion, the following practices contribute relevantly for improving understanding of activities to be executed:

- ( ) CPS characterization model.

- ( ) Review requirements process.
- ( ) Pre-elaborated list of requirements.
- ( ) Cross training.
- ( ) Specialized team divisions.
- ( ) Technical trust building.
- ( ) Dynamic follow-up strategies.
- ( ) None.

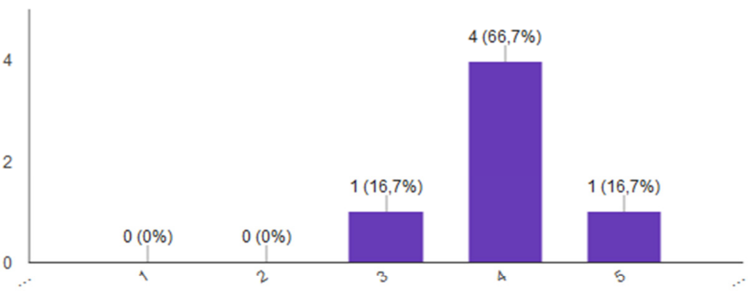
10. Leave your comments to improve CPS-PMBOK practices or considerations to improve project management regarding the CPS development:

APPENDIX C – Questionnaire responses from managers

The questionnaire was applied using the Google Forms, an online tool which assure anonymity. The following report is generated automatically.

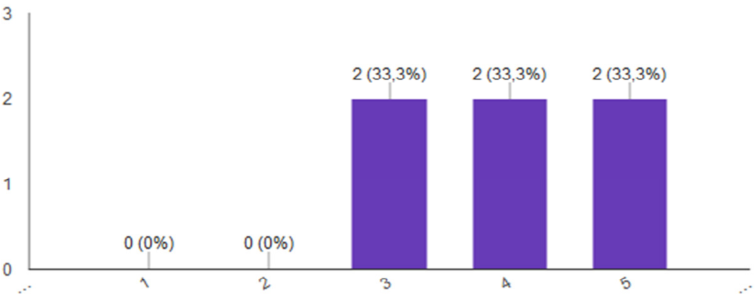
1) O uso do "Modelo de caracterização de sistemas ciberfísicos"(SLIDE 8) é uma prática que auxilia relevantemente na familiaridade da equipe do projeto em relação à área desconhecida (mundo físico) no desenvolvimento de um sistema ciberfísico:

(6 respostas)



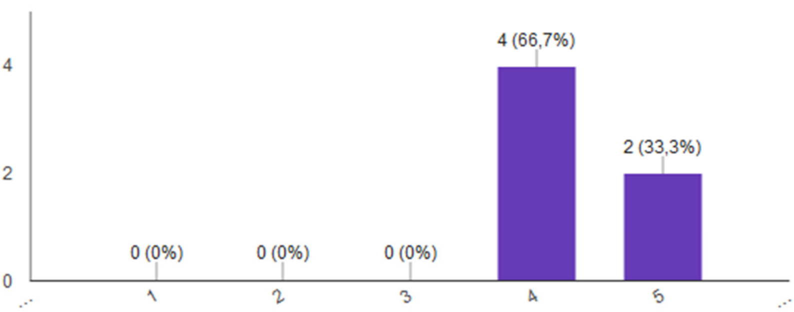
2) A inclusão do processo "revisar requisitos"(SLIDE 9-12) é uma prática que contribui relevantemente para a gestão de escopo no desenvolvimento de projetos ciberfísicos, quando comparada às práticas descritas no PMBOK:

(6 respostas)



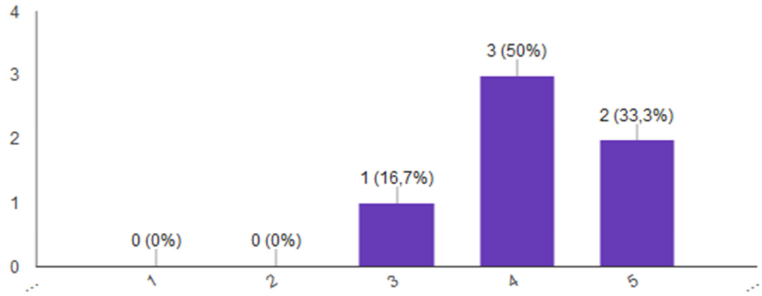
3) O uso das "Listas pré-elaboradas de requisitos"(SLIDE 13-15) é uma prática que contribui relevantemente para a gestão de escopo no desenvolvimeto de projetos ciberfísicos, quando comparada às práticas descritas no PMBOK:

(6 respostas)



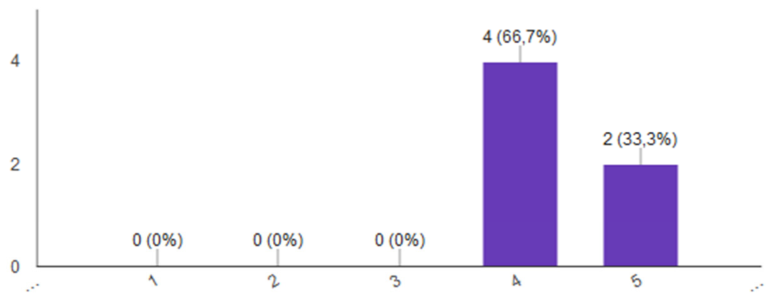
4) O uso do "Treinamento cruzado"(SLIDE 16) é uma prática que contribui relevantemente para a gestão de recursos humanos no desenvolvimento de projetos ciberfísicos quando comparada às práticas descritas no PMBOK:

(6 respostas)



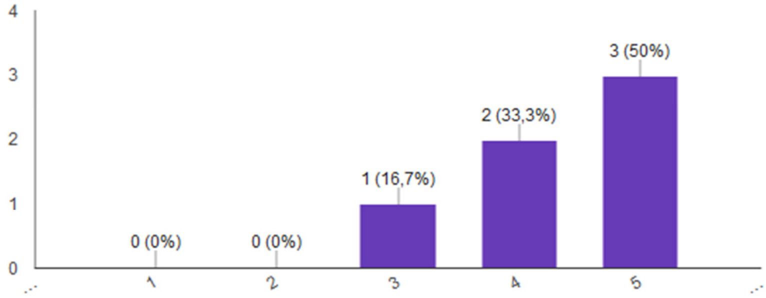
5) O uso da "Divisão de equipes especializadas"(SLIDE 17-18) é uma prática que contribui relevantemente para a gestão de recursos humanos no desenvolvimento de projetos ciberfísicos quando comparada às práticas descritas no PMBOK:

(6 respostas)



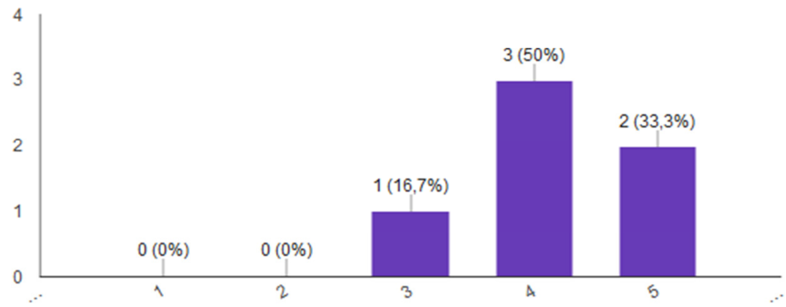
6) O uso da "Construção de confiança técnica"(SLIDE 19) é uma prática que contribui relevantemente para a gestão de partes interessadas no desenvolvimento de projetos ciberfísicos quando comparada às práticas descritas no PMBOK:

(6 respostas)



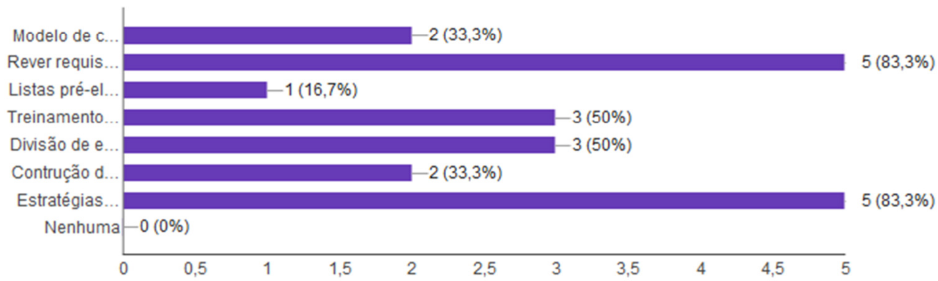
7) O uso das "Estratégias dinâmicas de acompanhamento"(SLIDE 20-23) é uma prática que contribui relevantemente para a gestão de partes interessadas no desenvolvimento de projetos ciberfísicos quando comparada às práticas descritas no PMBOK:

(6 respostas)



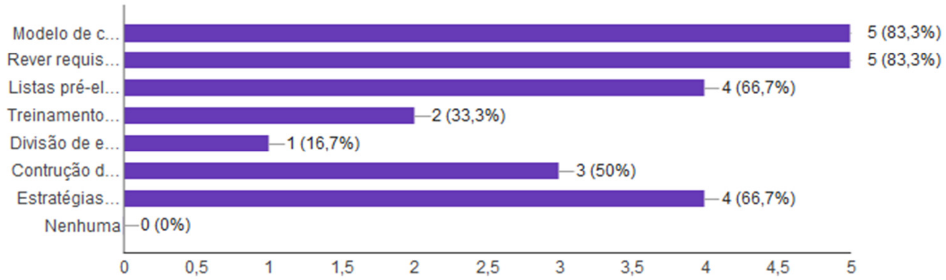
8) Em sua opinião, as seguintes práticas contribuem relevantemente para a melhoria da comunicação entre os membros da equipe do projeto:

(6 respostas)



9) Em sua opinião, as seguintes práticas contribuem relevantemente para a melhoria da compreensão das atividades a serem desenvolvidas:

(6 respostas)



10) Deixe seus comentários para o aperfeiçoamento da abordagem CPS-PMBOK ou considerações para melhorar a gestão de projetos em relação ao desenvolvimento de sistemas ciberfísicos:

(4 respostas)

Caracterizar melhor no trabalho ou apresentação quais particularidades os sistemas ciberfísicos têm de diferente dos outros projetos e como suas técnicas sugeridas podem ajuda-las. Caso contrário, as técnicas acabam sendo úteis para quaisquer tipos de projetos.

Achei a abordagem muito interessante, e no meu entendimento seria muito útil a sistemas onde o caráter de inovação se sobrepõe, pois algumas das práticas propostas - por ex, de revisão de requisitos - pode ajudar muito na construção de sistemas onde os requisitos estão constantemente sendo avaliados, tanto pela equipe, como pelo cliente, no sentido de descobrir e construir o melhor caminho que atenda a todos, considerando prazo e custo

O Controle do escopo em áreas que evoluem muito raptadamente é sempre um desafio muito grande. Muitas vezes, para alcançar o resultado esperado, é necessário se adaptar às mudanças de percepção de produto e de mercado no meio do projeto. Neste sentido, é realmente importante definir alguns marcos de revisão de escopo, associadas às ferramentas de controle de custos, adequando o projeto para concretizar as metas contratadas.

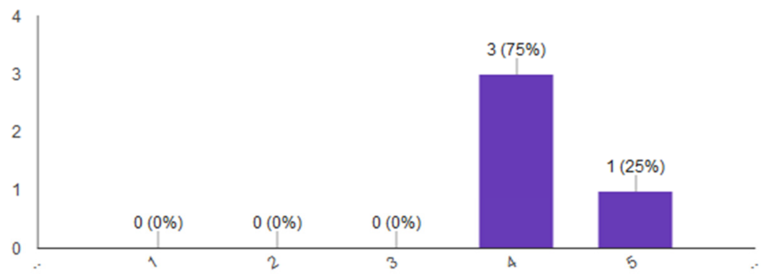
Especialmente com relação a questão 4, o treinamento cruzado acarreta em aumento do custo de desenvolvimento (o que pode não ser muito bem visto no projeto...), contudo acredito ser uma prática importantíssima para a coesão da equipe e disseminação do conhecimento.

APPENDIX D – Questionnaire responses from developers

The questionnaire was applied using the Google Forms, an online tool which assure anonymity. The following report is generated automatically.

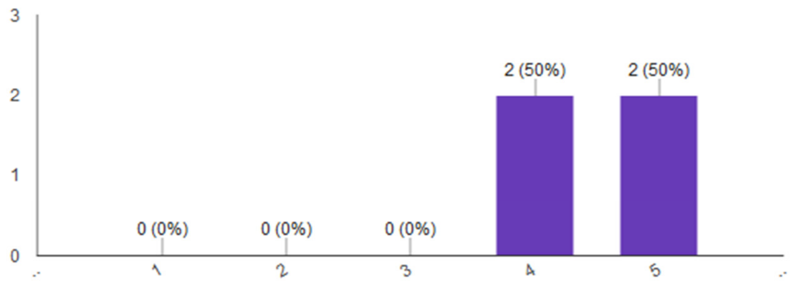
1) O uso do "Modelo de caracterização de sistemas ciberfísicos"(SLIDE 8) é uma prática que auxilia relevantemente na familiaridade da equipe do projeto em relação à área desconhecida (mundo físico) no desenvolvimento e um sistema ciberfísico:

(4 respostas)



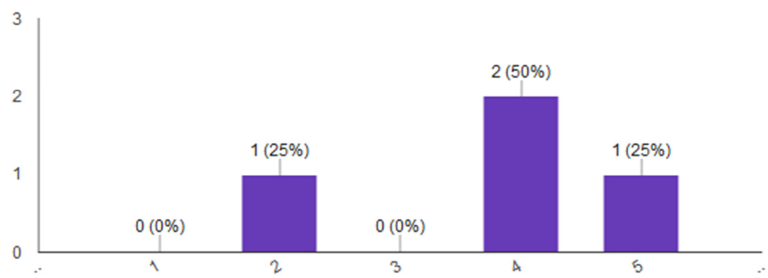
2) A inclusão do processo "rever requisitos"(SLIDE 9-12) pelo gerente de projeto, é uma prática que contribui relevantemente para a inclusão e controle das atividades ou funcionalidades necessárias para cumprir o desenvolvimento de um sistema ciberfísico com sucesso:

(4 respostas)



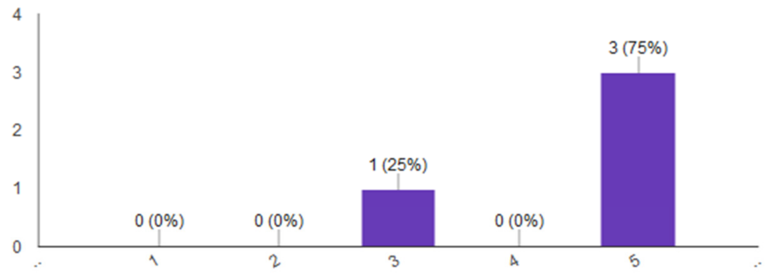
3) O uso das "Listas pré-elaboradas de requisitos"(SLIDE 13-15) pelo gerente de projeto, é uma prática que contribui relevantemente para a inclusão e controle das atividades ou funcionalidades necessárias para cumprir o desenvolvimento de um sistema ciberfísico com sucesso:

(4 respostas)



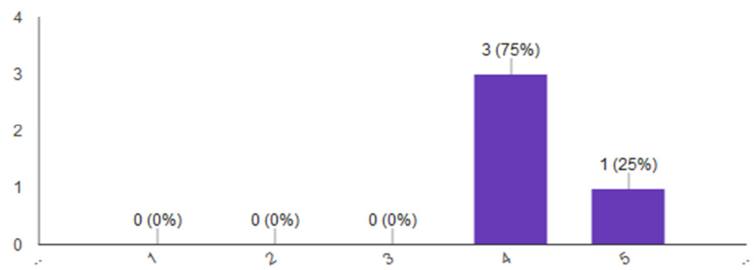
4) O uso do "Treinamento cruzado"(SLIDE 16) pelo gerente de projeto, é uma prática que contribui relevantemente para a organização, liderança e comprometimento das pessoas que possuem atribuições em tarefas relacionadas ao desenvolvimento de um sistema ciberfísico:

(4 respostas)



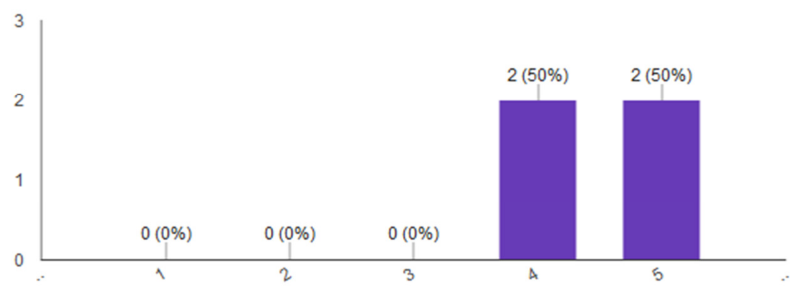
5) O uso da "Divisão de equipes especializadas"(SLIDE 17-18) pelo gerente de projeto, é uma prática que contribui relevantemente para a organização, liderança e comprometimento das pessoas que possuem atribuições em tarefas relacionadas ao desenvolvimento de um sistema ciberfísico:

(4 respostas)



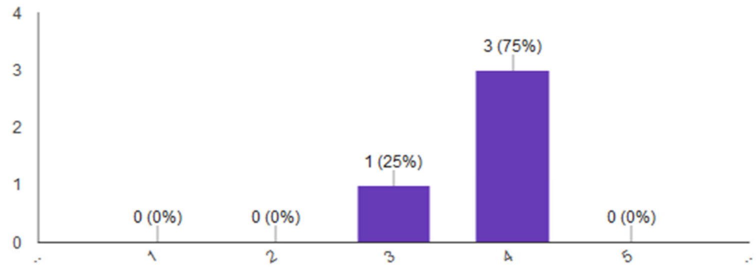
6) O uso da "Construção de confiança técnica"(SLIDE 19) pelo gerente de projeto, é uma prática que contribui relevantemente para a identificação, análise de expectativas e engajamento de pessoas que possam ser impactadas ou impactar o projeto de desenvolvimento de um sistema ciberfísico:

(4 respostas)



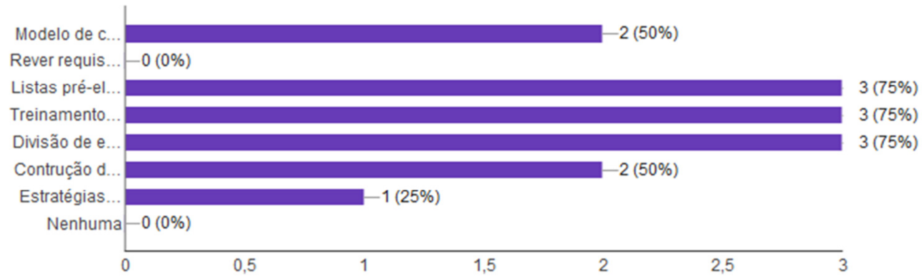
7) O uso das "Estratégias dinâmicas de acompanhamento"(SLIDE 20-23) pelo gerente de projeto, é uma prática que contribui relevantemente para a identificação, análise de expectativas e engajamento de pessoas que possam ser impactadas ou impactar o projeto de desenvolvimento de um sistema ciberfísico:

(4 respostas)



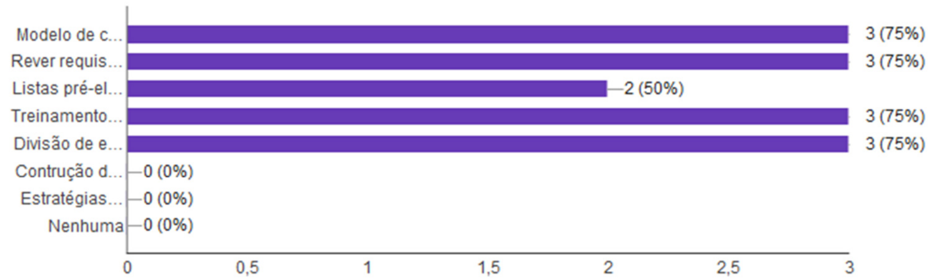
8) Em sua opinião, as seguintes práticas contribuem relevantemente para a melhoria da comunicação entre os membros da equipe do projeto:

(4 respostas)



9) Em sua opinião, as seguintes práticas contribuem relevantemente para a melhoria da compreensão das atividades a serem desenvolvidas:

(4 respostas)



10) Deixe seus comentários para o aperfeiçoamento da abordagem CPS-PMBOK ou considerações para melhorar a gestão de projetos em relação ao desenvolvimento de sistemas ciberfísicos:

(2 respostas)

Sugestões dadas em reunião presencial. Abs.

Acho que a pré-lista de requisitos é um risco para engessar muito o projeto.

APPENDIX E – Paper applied to the HICSS-50

As presented in chapters 2 and 3 of this work, the systematic literature review conducted to obtain the most studied knowledge areas in development of CPS projects, resulted in a paper which was applied to the Hawaii International Conference on System Sciences 2017 (HICSS-50). The paper, entitled "Project management practices in cyber-physical systems development: a systematic literature review" is presented entirely in this appendix.

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 with and understand the physical world. The CPS concept includes embedded systems, system of systems and internet of things applications, as well as many other technological disciplines aiming to support the physical phenomena interpretation. To lead the development of these kinds of projects to success, project management methodologies may be used, enhancing the understanding and controlling of internal and external variables. In this paper, a systematic literature review was conducted aiming to explore the challenges faced by the scientific community while managing CPS projects. The challenges found were classified into knowledge areas, established by PMBOK. All knowledge areas presented at least one management-related practice, however, three areas showed to be more widely approached: scope, human resources and stakeholder. The systematic literature review showed that there are many specific area-focused practices in development, besides large use of agile methods in CPS management.

1. Introduction

There is a growing need to understand physical phenomena, as this may be useful to improve quality of life or develop new technologies [1]. To meet this need, some specific computing systems that interact with the physical world are developed, which are called Cyber-Physical Systems (CPS) [2]. The development of CPS requires a multidisciplinary team, and may involve professionals from varied areas, such as computing, chemistry, physics or biology [3].

Project management is a practice that allows a project manager to control and measure the progress of the project development. It includes planning and monitoring the individuals involved in the project [4]. The Project Management Institute (PMI) keeps a body of knowledge called PMBOK (Project Management Body of Knowledge) [5], compiling a set of best practices and guidelines for project management in a general purpose. It describes ten knowledge areas representing specific professional fields inside the project management activity. They are: integration, scope, time, cost, quality, human resource, communications, risk, procurement and stakeholder management. Project management may improve potential factors of success, which leads the project to satisfactory results. Just like 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, 10]. A focused method of project management 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 research area is [11]. Many other approaches of technological systems have similar characteristics to those found in CPS. Examples include: embedded systems, system of systems, automation and control, internet of things, and wireless sensor networks. System of systems is conceptually the most similar with CPS approach. The difference is in the emphasis on real world's physical processes interaction in CPS. The remaining approaches represent practical application of CPS concepts. Other approaches similar to CPS are: test and measurement [12], test and monitoring [13], virtual instrumentation [14] and measurement and control [15], although these are industrial names for automation projects developed for manufacturing industries. The CPS concept has a wider scope and is more open to the application and collaboration between disciplines than previous approaches. 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 here on, this paper refers CPS and other similar systems approaches as only CPS, unless otherwise stated.

In this paper, a systematic literature review is conducted to find the challenges being faced in CPS project managing, as well as the solutions used and possible trends of improvement in some specific knowledge area approaches. The remainder of this paper addresses: related works regarding CPS and project management; the method used in the conduction of the systematic literature review; he results and a discussion; and its conclusion.

2. Related work

In order to investigate the current state of systematic researches regarding CPS and project management, works containing these keywords were searched. The expressions "cyber-physical systems" and "project management" were used with possible combinations of "systematic literature review". The data base used was Scopus [20] and there were no results returned. Thus, separated searches were made, investigating systematic researches of CPS and project management 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 embedded systems development [23].

Regarding systematic literature reviews related to project management, 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 project management issues – more precisely, scope management – dealing with the user requirements transformation in model analysis [26].

3. Review method

The purpose of conducting a systematic literature review (or simply a "systematic review") is to evaluate some specific aspects of an area, technology, methodology or phenomena – being natural or social – providing information for future research. This information can be used as motivation, reference or simply a summary of these specific topics [27]. In the area of software engineering, the systematic review conduction may prove more difficult in regards to separating evidence and identifying external factors that threaten its reliability, because the experiments are more likely to manipulate results, as software development is an iterative activity [28]. The investigated works of a systematic review are called primary studies, which can be works containing: a detailed description of developing systems, technique analysis or method 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. Systematic literature review is a form of secondary study [27].

To provide a reliable systematic review, the guidelines described by Kitchenham [27] were followed. In these guidelines, some general steps are proposed to conduct a systematic review, 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 systematic review; *(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 systematic literature review. As seen in the Section 2, no systematic review regarding CPS correlating to project management was found. All reviews found are dealing with some technical issue of systems development regarding to CPS, ES or similar systems. In the general project management area, the authors focused in only one or two knowledge areas. 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 systematic review can provide an unbiased vision of the state of the art regarding CPS project management. A well conducted systematic review helps to summarize the main used CPS definitions and concepts, as well as evaluates real application and challenges faced of project management practices.

3.1.2. 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 systematic review 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 systematic review is to identify studies that relate CPS with project management, 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 project management practices in development of CPS?* This is the primary research question, aiming to elucidate if the community of project management 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 project management of these kinds of projects.

RQ2: *Which PMBOK's knowledge areas and project management practices are addressed?* The purpose of this question is to identify which knowledge areas are explored when a CPS project is managed, and which knowledge areas 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 knowledge area through this question as well, enabling researchers to judge the rate of use and its influence to project management. 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 project management practices?* This question complements RQ2, specifying whether 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 RQ3.

RQ4: *Are there challenges and 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 project management practices, helping to identify another kind of issue, motivating future research in CPS development.

3.1.3. The research protocol. The protocol of a systematic review is a set of information that allows any other researcher to conduct this same systematic review, 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 presented in Section 3.1.2 may be part of the protocol [28] and the next steps are: *(a)* data source definition; *(b)* studies selection; *(c)* information extraction; and *(d)* summary results. The step *(c)* is described in this section but its execution is detailed in Section 3.2. The step *(d)* is addressed in Section 4.

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 computating and project management, among other areas. The primary keywords chosen were "cyber-physical system" and "project management", with many possible variations combined. 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 project management 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 1.

Table 1. Search string

TITLE-ABS-KEY((("embedded" OR "system of systems" OR "systems of systems" OR "sensor network" OR "sensor networks" OR "automation and control engineer*" OR "control and automation engineer*" OR "internet of things" OR IOT) AND ("project manag*")) OR (("cyber-physical system*" OR "cyber physical system*" OR "cyberphysical system*") AND (project OR manag*))) AND (LIMIT-TO(SUBJAREA,"ENGI") OR LIMIT-TO(SUBJAREA ,"COMP")) AND (LIMIT-TO(SRCTYPE,"p") OR LIMIT-TO(SRCTYPE,"j") OR LIMIT-TO(SRCTYPE,"k") OR LIMIT-TO(SRCTYPE,"b")) AND (LIMIT-TO(DOCTYPE, "cp") OR LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"re") OR LIMIT-TO(DOCTYPE,"ch") OR LIMIT-TO(DOCTYPE,"ip")) AND (EXCLUDE(LANGUAGE,"Japanese"))

After a preliminary analysis of the results, more keywords were included in the search, aiming to reach works that describe similar applications to CPS, as discussed in the Section 1. 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 project management of CPS as possible.

As strategy of studies selection, Inclusion Criteria (IC) and Exclusion Criteria (EC) were established, so that only those really related to this systematic review 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:

- **IC1** The paper addresses CPS as main theme.
- **IC2** The paper describes some experience in project management.

- **EC1** The paper addresses only technical details and challenges of the CPS application area with no type of contribution from the project management perspective.
- **EC2** The paper aims to contribute with other areas than project management, such as education, medicine, construction or logistics.
- **EC3** The term "management" is used in the context of technical resources management, i.e., performance, security, reliability, robustness and autonomy.
- **EC4** The publication was not peer-reviewed.
- **EC5** The paper is not written in English.
- **EC6** The paper is not electronically available.
- **EC7** The paper is a secondary study, such as a review or a survey of other studies.

The information extraction strategy consists of reading the title and the abstract sections by identifying the primary studies, applying the inclusion and exclusion criteria. In the cases where these sections aren't enough to identify the real contribution of the study, the introduction and conclusion sections are read. Once defined as primary study, the entire paper is read, highlighting the project management practices used. A summary or brief comments were 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) [35] was used to support the organization of studies.

3.2. Conduction

This section aims to describe all steps needed for conducting this systematic review. It presents the progress of primary studies identification and details the information extraction. Two basic activities were executed: defining primary studies and extracting the information.

3.2.1. Defining primary studies. 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 exclusion criterion EC2 and the date filter according to exclusion criteria EC4 and EC5 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 inclusion criteria and remainder exclusion criteria (EC1, EC3, EC7 and EC8) 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 the inclusion and exclusion criteria, 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 exclusion criteria. At the end, 17 studies are part of the primary studies, considering the CPS and ES keywords searches, except the duplicates.

3.2.2. Extracting the information. 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 research question RQ1 is answered by the application of inclusion criteria, showing evidence of practical applications of project management in CPS projects. To evaluate which knowledge areas 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. If one knowledge area showed less relevant than other, a weaker correlation with the study was considered. Aiming to express this correlation, a relevance score was created, using as criterion the number of times that a set of keywords was mentioned and the focused given by the authors for each knowledge area. The keywords were defined for each knowledge area, based on the previous analyses of exploratory review. Table 2 shows the possible knowledge area, 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; or computational tools supporting decisions, registering information and generating previews of project progress. It was possible to find new and already consolidated practices.

Table 2. PMBOK's Knowledge Areas

Knowledge area	Keywords
Integration	Configuration management, project management, 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.

4. Results

This section presents the outcome of the primary studies analysis. The studies #3, #4, #6, #7, #8 and #9 describe, in addition to project management practices, some development methodologies [36, 37, 38, 39, 40, 41]. Development methodologies are practices used to plan, organize and execute the software development. It can be used to manage teams, since the division of tasks and attribution of responsibilities depends on method adopted, as well as the following up of development progress [21]. In the cases where only a method or design technique was explored, the exclusion criterion EC1 was applied. Some studies focus on a specific sub-area of CPS, such as #2 for autonomous maritime vehicles [38], #3 for space bus applications [37], #4 for mobile phone design [43] or #17 for wireless sensor network development [44]. This does not invalidate the inclusion of these studies, since the main goal of this systematic review is to identify all kinds of project management challenges. Table 3 shows all primary studies, its respective knowledge area and the relevance score over each knowledge area. Some studies mix more than one method and even created a new one.

Only a few studies demonstrate the use of commercial or developed computational tools. The authors of paper #1 [45] use IBM Rational Requisite Pro to improve the Scope management registering the requirements. To manage communication, the authors use 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 yime and cost by observing the progress of the assigned tasks to the team. Although not specifically named, the authors of the study #2 [42] manage the scope and requirements using CAD models to analyze and illustrate the discussions in the peer-review sessions. Paper #11 [46] describes the development of a tool to support the team members' allocation along the project development, based on technical and personal profiles and behaviors. The authors in #12 [47] 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 is used by the authors of paper #16 [48] 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, #15 and #18 use many project management practices and explore some adaptations for CPS in a general way, such as team divisions, project conceptual analyses and stakeholder management [43, 49, 46, 50, 51, 52, 55].

By applying the inclusion and exclusion criteria, 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, 110 results were found. The search resulted in 146 articles regarding construction, describing from construction project management to embedded systems for building simulation, data acquisition for structure health among other applications. Regarding cyber security and network communication improvements, we found 122 papers describing practices, algorithms or techniques.

5. Discussion of results

By the numbers presented in the Section 3.2, it is possible to answer the research question RQ1: "Are there evidences of practical application of project management practices in development of CPS?"

Table 3 answers the research question RQ2: "Which PMBOK's knowledge areas and project management practices are addressed?" It can be seen that most studies were concerned with more than one knowledge area and some of them used more than one approach to deal with specific knowledge area. Most of the studies also described the practices used as useful for more than one knowledge area management, mainly those that described development methodologies [36, 37, 38, 39, 40]. Three studies [42, 36, 49] developed their own methodologies based entirely or partially on existing approaches. The study #2 [42] in addition explores an approach specific for a narrow field of application: maritime vehicles. The studies #4 [37] and #5 [43] used traditional approaches but for specific applications: cellphone processors development and spatial bus and satellites design. In total, eight studies presented new approaches, including: software tools, frameworks for project comprehension, models for requirements elicitation

Table 3. Primary studies

#	Primary study	Int	Sco	Tim	Cost	Qua	HR	Com	Risk	Pro	Stk
1	Virtual tools and collaborative working environment in embedded system design [45]	-	29	15	3	-	5	11	-	-	-
2	Cyber-physical framework for early integration of autonomous maritime capabilities [42]	-	39	-	-	-	-	-	-	-	-
3	Comprehensive design of cyber physical systems [36]	-	10	-	-	-	10	-	13	-	-
4	Agile hardware and software system engineering for innovation [37]	-	18	28	23	12	24	12	9	1	18
5	Managing large HW/SW Codesign projects [43]	-	-	28	-	6	51	5	4	-	-
6	Goal-Driven Development Method for Managing Embedded System Projects: An Industrial Experience Report [38]	-	11	36	-	33	136	11	-	-	25
7	Agility in a large-scale system engineering project: A case-study of an advanced communication system project [39]	-	6	11	2	4	120	7	-	-	33
8	Supporting agile change management by scenario-based regression simulation [40]	-	13	-	-	17	-	-	-	-	-
9	An estimation model to measure computer systems development based on hardware and software [41]	-	87	-	9	-	-	-	-	1	-
10	Enabling system evolution through configuration management on the hardware/software boundary [49]	96	-	-	-	4	-	-	-	-	-
11	Multiagent approach to solve project team work allocation problems [46]	-	-	-	-	-	90	-	-	-	-
12	Software Processes Improvement and Specifications for Embedded Systems [47]	9	25	-	-	-	-	-	-	-	-
13	Applying search algorithms for optimizing stakeholders familiarity and balancing workload in requirements assignment [50]	-	174	-	-	-	1	-	-	-	90
14	Architectural decisions for HW/SW partitioning based on multiple extra-functional properties [51]	-	55	-	-	-	-	-	-	-	-
15	Norms as a basis for governing sociotechnical systems [52]	-	-	-	-	-	-	-	-	-	34
16	A Requirements Engineering content model for Cyber-Physical Systems [48]	-	101	-	-	-	-	19	-	-	22
17	Architecture for sensor networks in cyber-physical system [44]	-	40	-	-	-	-	-	-	-	-
18	Towards an analysis-driven rapid design process for cyber-physical systems [53]	-	55	-	-	8	-	-	-	-	-
19	Requirements for real-time hardware integration into cyber-physical energy system simulation [54]	-	24	-	-	-	-	-	-	-	-
20	Towards a new paradigm for management of complex engineering projects: A system-of-systems framework [55]	40	19	2	12	9	12	40	11	-	5
21	Considerations for a requirements engineering process model for the development of systems of systems [56]	-	21	-	-	-	-	-	-	-	-
22	Cost modeling of distributed team processes for global development and software-intensive systems of systems [57]	-	4	15	52	3	121	2	-	-	2
23	Assessing hybrid incremental processes for SISOS development [58]	-	13	31	33	-	104	8	7	-	2
24	Agile methods applied to embedded firmware development [59]	-	14	-	-	-	64	-	-	-	7
25	Quantitative methods for maturing and infusing advanced spacecraft technology [60]	-	-	-	59	-	-	-	90	-	-

and formal representations for CPS management [42, 36, 41, 46, 47, 51, 52, 44]. This leads to the belief that already used methodologies can be used or briefly adapted for new kinds of problems and challenges, but authors tend to develop focused approaches for highly complex and non-conventional systems.

Almost all knowledge areas showed up more than once as a concern point of the studies, leaving only procurement management with only one mention. A possible explanation is that procurement management has a strong dependency on company politics, resulting in minor emphasis in the academic community. A particular study focused on cost management, and it addresses systems of systems, which generally has less hardware technologies involved [57]. This means that human resources spending may be as meaning as hardware investments, as presented by study #25 [60], which assess spacecraft technology project costs. Figures 1 and 2 show the distribution of studies per knowledge area regarding quantity and relevance score. It is possible to observe that the community has the awareness of the project management 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. Examples of that are: study #19 which describes requirements for hardware integration for energy simulations; and study #21 which dedicated to propose a process model for requirements engineering [54, 56]. The first shows that even one of the first fields explored by CPS concept, can still lacking for scope management research.

The answer to the research question 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. Some studies are part of a bigger project and the success of project was the next stage enabling. The real effectiveness of project management practices shall be verified aftermost [37, 51]. The authors of study #5, described a transparent planning which resulted in high commitment level by the team [43]. Cultural issues could be softened by the authors of study #7, allowing better use of practices of almost all knowledge areas described [39].

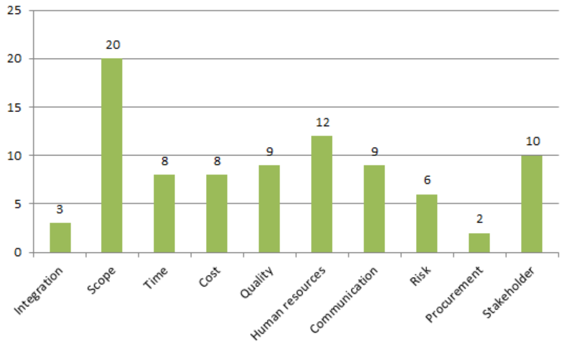


Figure 1. knowledge areas per mentions

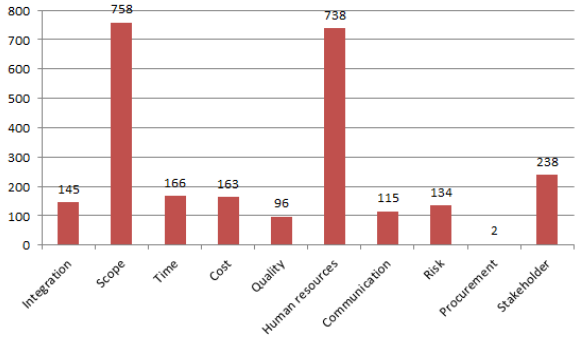


Figure 2. knowledge areas per relevance score

There was no clear answer to the research question 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. Examples of these unexpected challenges are: team members’ adaptation of proposed practices [43, 38], prior analysis of team profiles [50] and project planning complexity increase [52].

A great number of practices are common for ordinary software development context, and there were some papers mentioning agile approaches as methodologies [37, 39, 40, 59] following the trend of the computer science community [61]. A physical and computational approach is observed as an integration of hardware and software in many papers, reflecting the industrial changes seen nowadays, for example: creation of specialized teams [36, 37, 43] and architecture models for hardware representations [41, 48, 44]. Entirely new processes for CPS development could be observed, indicating a new mind set for project management [53, 58]. Another evidence of this adaptation of the scientific community is the adoption of CPS technologies by the most diverse areas, including construction, education and telecommunication as seen in Section 4.

Regarding the new challenges of project management in CPS, it may be included in the 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 Section 4, few tools are used to manage a CPS project. This could mean a lack of specific tools for project management of these kinds of projects an open source software adoption trend, but we believe that 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 project management practices [5] and CPS [1, 2] development projects, a systematic literature review was conducted including ES [11, 34] development projects, due to its similarity with CPS.

The main findings show that all knowledge areas described in the Project Management Institute's PMBOK [5] were objects of study for at least one paper. Human resource, scope and stakeholder were the knowledge area that most authors worked on, wherein some briefly adapted traditional techniques and methodologies were used 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, 61] 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 discussion of Section 4, some authors focused on the development of particular approaches for a specific filed of application also, such as maritime autonomous vehicles [42] or mobile phone processors 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 deficiency. The benefits of understanding the physical world and interacting with it have driven companies and academia to develop and research CPS even more efficiently, making project management practices even more relevant.

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APPENDIX F – Paper published at IX WTDSI

As mentioned in chapter 1 of this work, a short paper of this work was published and presented at the "IX Theses and Dissertations Workshop on Information Systems (WTDSI)" at "XII Brazilian Information Systems Symposium (SBSI)". The paper, entitled "Project management best practices for cyber-physical system development" is presented entirely in this appendix.

Project management best practices for cyber-physical system development

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ABSTRACT

Cyber-Physical Systems (CPS) represent the convergence of physical processes and computational platforms into technological solutions composed by sensors, actuators and software. Such as for other types of projects, Project Management (PM) practices can benefit a CPS development project. Due to some particularities of CPS, such as multidisciplinary team (the development of a CPS depends on the cooperation of many professionals of very different areas) and high innovation aspect (mixing different areas with computing requires most new technologies), generic PM practices may not be enough to enhance project success. Therefore, specific practices are proposed for better managing CPS projects, called CPS-PMBOK approach. CPS-PMBOK is based on the Project Management Institute's PMBOK body of knowledge. It is focused on the scope, human resources and stakeholder management areas; which were chosen considering a systematic literature review conducted to identify the main CPS challenges.

Categories and Subject Descriptors

C.3 [**Special Purpose and Application-Based Systems**]: Real-time and embedded systems; K.6.1 [**Management of Computing and Information Systems**]: Project and People Management—*Management Techniques*

General Terms

Management

Keywords

Project management; Cyber-physical systems; PMBOK

1. INTRODUCTION

Computing systems aiming to reproduce and understand the real world led to a new technological system field, called Cyber-Physical Systems (CPS) [12, 13]. Merging areas from embedded systems, mechanical engineering, software, among others [7], CPS gained remarkable advances in science, such as medical surgery, autonomous vehicles, energy harvesting and smart buildings [11]. CPS are composed of: sensors, which read environmental signs such as light, electrical current, humidity, etc.; computing platforms, which process the sensors' information according to environment needs; and actuators, which send processed information to other sensors and stimulate the environment [6]. Many CPS present network elements, since several computing platforms may communicate reliably itself, often far apart.

CPS projects tend to be large, complex and groundbreaking, with innovative algorithms and technologies [2, 12, 13]. An important CPS feature is multidisciplinarity since CPS merge computing and physic world concepts. A CPS project may be considered software engineering, civil engineering, experimental physics or natural sciences projects [2, 7].

Project Management practices aim to enhance the probability of success during a product or service development [8]. The Project Management Institute (PMI) gathers best practices in a body of knowledge – called PMBOK [10], which presents tools and techniques for a better management. PMBOK also presents concepts for the project organization through "process groups" and "knowledge areas".

Although PMBOK is a general purpose guide, specific areas may benefit from adapted or focused project management practices, better driving project activities and preventing common weaknesses [8]. Assaf and Al-Hejji [1] and Pandi-Perumal et al. [9] propose new techniques for stakeholder management, respectively, for construction projects and for clinical research environments. For globally distributed projects, Deshpande, Beecham and Richardson [3] and Golini and Landoni [4] address concerns on, respectively, stakeholders, scope and human resources, and communications.

2. PROBLEM STATEMENT

CPS projects presents two main characteristics: multidisciplinary team working together and technically innovative. According to Baheti and Gill [2], for instance, heterogeneous teams may face communication difficulties, requiring abstracted models for software and hardware development. The innovative aspect offers some challenges due the uncertainty of new technologies used, such as computational platforms, programming languages and even novel natural effects that can be recently discovered. In order to evidence CPS-related project management challenges, a systematic literature review was conducted to search research

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papers describing project management practices adopted in CPS projects. For this review, we considered the number of times that specific keywords related to each knowledge area have been used as an importance degree of each area, resulting in a relevance score. The review results indicated that three knowledge areas are major concerns for authors: scope (score: 608), human resources (score: 437) and stakeholder (score: 222). Therefore, we concluded that these three knowledge areas may represent the biggest part of the CPS challenges, although most authors described solutions only for their own issues.

The results showed that many authors use agile methodologies, formalisms and project management practices not necessarily related to PMBOK. Moreover, most of the issues found were solved with specific solutions, mainly related to technology, localization and culture. Many challenges related to technical comprehension and communication were found, which resulted in abstracted models and techniques for indicator traceability. All issues found are aligned with the raised CPS features: innovation and multidisciplinarity.

3. PROPOSED SOLUTION

Based on practices found in general literature, results from the systematic review, PMBOK experience, and professional skills, a set of best practices to manage CPS projects is being created – called CPS-PMBOK. This approach is split in two main views: characterization model, and knowledge areas adaptation. Both views may be used for project managers and aim to benefit the whole project team.

3.1 Characterization model

The characterization model aims to enhance comprehension of the project, application field, necessary technologies and involved environment. The model is split in two characterizations: environment and complexity (see Figure 1).

The environment characterization defines how much the CPS environment is surrounded by formalized processes; or how chaotic and unpredictable is the environment. Four situations are given to help this definition, considering that CPS environment requires: limited tasks; communication with known group of devices; interaction with known group of people; and following industrial standards or norms. The manager may choose among:“little”, “medium” and “much”. The more “much“ points, more well-defined the CPS environment is.

CPS characterization model			
CPS environment requires:	Little	Med	Much
• Limited tasks			
• Communication with known group of devices			
• Interaction with known group of people			
• Following industrial standards or norms			
Complexity			
• Mechanical structures			
• Network			
• Sensors			
• Actuators			
• Data storage			
• User interaction			
• Legacy systems integration			
• Power energy system			

Figure 1: CPS projects’ characterization model

The complexity characterization is an evaluation of the technologies usually found in CPS. It classifies the relevant integration of CPS with elements in eight areas: mechanical structures; network; sensors; actuators; data storage; user interaction; legacy systems integration; and power energy system. Supported by experts in each area, managers may define among “few”, “average” and “many” for each area.

3.2 Knowledge areas adaptations

Focused on the three most addressed knowledge areas, according to the systematic review conducted, the CPS-PMBOK adapts some practices found in PMBOK and adds new techniques, based on authors’ experience. Such adaptations are described in this subsection. The best practices described in PMBOK may be enough for managing the remaining knowledge areas, even in a CPS context.

3.2.1 Scope management

The innovative aspect of CPS demands many revisions and redefinitions of scope [5]. Since this is an usual practice in CPS projects, an additional process is proposed for scope management, aiming to reduce the impacts of requirements constant changing. This new process is called “review requirements”. Following principles of agile methodologies, its purpose is to predict requirements changes.

Moreover, in order to support requirements gathering, “pre-elaborated lists” should be applied [14]. The purpose of such lists is to create reusable assets through gathering common requirements found in CPS projects. It should aid to estimate project size and avoid missing requirements.

3.2.2 Human resources management

Due to many different areas involved in a CPS project, different specialists, with rather different technical background may be part of the same team. As a consequence, two additional techniques are proposed in CPS-PMBOK for human resources management: “cross training” and “team split”.

Cross training is a technique already briefly quoted in PMBOK, proposed to reduce impacts when a team member leaves the project. Specifically for CPS projects, a cross training should be always used to enable team members to act as a communication bridge for different sub-teams.

The “team split” technique is included in CPS-PMBOK in order to improve the development performance and avoid inappropriate assignment of tasks. According to this technique, the project team should be split in sub-teams considering different application areas or project deliverables, such as: mechanical design team, information system development team, and power bank development team.

3.2.3 Stakeholder management

CPS projects tend to involve academic researchers as well as specialists, who are technical stakeholders with comprehension of the application area and engineering. As a consequence, an additional technique is proposed in CPS-PMBOK for stakeholder management: “establish technical trust”. According to this technique, an internal specialist or an external consultant should be put in charge of following up the project manager activities. This action is necessary to allow stakeholders be more comfortable with the project progress.

Based on the different levels of demand and satisfaction of stakeholders, “follow-up strategies” should be added in CPS-PMBOK. For the project’s initiating stage, regular face-to-face meetings should be adopted. For the subsequent stages (planning, executing, and monitoring and controlling), sporadic participations of stakeholders should included during planning and technical meetings. For the project's closing stage, the stakeholders should be able to follow up the final results through workshops with live CPS demonstrations.

4. EVALUATION

A research and development organization accepted to collaborate with the CPS-PMBOK evaluation, through the participation of three project managers. The planned evaluation is to have such project managers using CPS-PMBOK in real projects. However, whereas projects are in different development stages, the project managers may find limitations to apply some of the proposed practices. For example, a team split cannot be carried out for a project at final stages. For such projects, the evaluation of the proposed practices should be carried out in view of previous experiences.

The managers should evaluate if the proposed practices are feasible and would bring benefits to a CPS project. They should be also encouraged to contribute with improvements based on their organization's practices and their own professional opinions. A questionnaire should be applied at the end of the five-month evaluation time. So far, CPS-PMBOK was presented and explained to the project managers and two follow-up meetings took place. The follow-up meetings were requested by the managers, who believe to be more useful to present feedbacks rather than only answering a questionnaire at the evaluation end.

5. CONDUCTED ACTIVITIES

This research project was presented in a qualifying exam on September 2015, with an examining board composed of the advisor and two other professors (one internal and one external to the graduate program). The remarks made by the board have been addressed during the last five months and research project is currently at the evaluation stage. In terms of the approach evaluation, an initial presentation of CPS-PMBOK was made, followed by two meetings to help project choice and additional explanation. The first project managers' feedbacks were already received and registered, and an additional follow-up meeting is planned before the questionnaire application. Moreover, the research project was presented at the "2nd workshop of master dissertations in information systems" at the University of Sao Paulo on October 2015. Finally, the results of the systematic review conducted to define research priorities was submitted to the ACM Computing Surveys journal on January of 2016. The research project is expected to be finished on June 2016.

6. CONCLUSIONS

The CPS field is in constant change raising a research challenge. Different terms are used to define very similar systems converged with the CPS context, such as: "system of systems", "hybrid systems", "embedded Systems" and "internet of things". The occurrence of several similar terms brings difficulties to find similar and relevant works. On the another hand, project management has been focused on traditional software development, neglecting other application areas. Therefore, there is a demand for upgrading PMBOK's best practices to current types of systems such as CPS.

The CPS-PMBOK approach has already been revealed useful for project managers, mainly for allowing them to: rethink their own concepts in terms of current projects; improve comprehension of team member capacities; and review the organization's project management best practices. The feedbacks collected so far from the project managers show insights regarding the dependency on the: project's life cycle adoption; development methodologies; project goals (e.g. new product, new service, new technology, proof of concept, preliminary study, etc.); and organizational policies.

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