Managing Scope, Stakeholders and Human Resources in 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 practices can benefit a CPS development project. Due to some particularities of CPS, such as multidisciplinary team and high innovative aspect, generic project management 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 integration, scope, human resource and stakeholder knowledge areas; which were chosen considering a systematic literature review conducted to identify the main CPS challenges. Managers and developers of a R&D organization evaluated the approach. According to the practitioners consulted, the proposed practices can improve several aspects related to CPS projects.

1 INTRODUCTION

Cyber-physical Systems (CPS) are computational systems that interact with the physical world (Rajkumar et al., 2010; Sha et al., 2009). CPS gained remarkable advances in science, such as autonomous vehicles, medical surgery, smart buildings and energy harvesting. A CPS is composed of a computing platform, the physical world, sensors and actuators (Rajkumar et al., 2010; Sha et al., 2009). CPS merge areas from embedded systems, mechanical engineering, software etc. (Lee and Seshia, 2017).

CPS development projects tend to be large, complex and groundbreaking, with innovative technologies (Rajkumar et al., 2010; Sha et al., 2009; Baheti and Gill, 2011). They are often related to proofs of concept, to test a new technology. These projects are usually related to research due to the natural complexity of its interaction environment. A usual feature is multidisciplinary, which requires good team communication skills, since CPS development merges computing and physical world concepts.

A recurring issue in CPS projects is the misunderstanding caused by the large number of concepts involved. Collaboration among practitioners from different areas (such as software engineering, civil engineering, experimental physics or natural sciences) is needed to accomplish CPS developments (Lee and Seshia, 2017; Baheti and Gill, 2011).

Project management practices aim to enhance the probability of success in a product or service development (Lester, 2014). The success depends on organization, application area and project goals, but priorities may vary, including: finishing within planned time, meeting agreed scope, reaching satisfactory quality or finishing in determined budget. Managing a project consists of controlling the development and providing all resources necessary for project execution; which is a responsibility usually assigned to a project manager. Project management is useful for diverse areas, such as: medicine, civil engineering, software development, advertising campaigns etc.

The Project Management Institute gathers best practices in the so called Project Management Body of Knowledge (PMBOK) (PMI, 2013), which presents tools and techniques for a better management considering experts' knowledge. PMBOK organizes the best practices via five process groups (initiating, planning, executing, monitoring and controlling, and closing) and ten orthogonal knowledge areas (integration, scope, time, cost, quality, human resource, communications, risk, procurement, and stakeholder).

Considering the particularities of CPS projects and the need to manage them to reach their goals ac-

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cording to the success factors established, this paper presents specific practices for better managing CPS projects. A preliminary version of the proposed practices was presented (Palma et al., 2018), but still with no evaluation results. These practices are proposed as a PMBOK extension, called CPS-PMBOK. CPS-PMBOK is focused on the integration, scope, human resource and stakeholder knowledge areas. They were chosen considering a systematic literature review conducted to identify the main CPS challenges. Thus, we expect to improve both team communication skills and understanding of the project activities. The proposed practices rely on approaches previously presented in literature as well as the authors' background. We consider that a well-managed CPS project may increase physical world comprehension, modeling and interaction, enhancing the technological advances.

The remainder of this paper presents: background, related work, research method, the proposed approach and its evaluation and the paper conclusion.

2 CYBER-PHYSICAL SYSTEMS

Cyber-Physical Systems (CPS) describe a new generation of engineered systems capable of high performance in information, computing, communication and control. Examples are: online and robotic medical surgeries; smart power grids, in which the power line health and consumption can be monitored at distance all the time; and autonomous vehicles, as trains, cars, drones or Unmanned Aerial Vehicles (UAV).

CPS are 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, as people interact with each other at the internet (Rajkumar et al., 2010). 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 side, some devices can be found: Unix-based computers, microcontrollers, microprocessors, signal acquisition hardware, embedded systems, digital signs processors, programmable logic controller, field-programmable gate arrays etc. From the physical side, some physical phenomena can be found: temperature, atmospheric pressure, electrical current and voltage, lighting, radio-frequency, motion (velocity/direction), sound, time etc. Physical processes are phenomena combined in a certain context, such as: room temperature, changing over the time considering the number of people in it; airplane pressure, changing considering the flight altitude; and the current provided by an electrical engine, proportional to its load.

Sensors and actuators enable the union of the two worlds. Sensors may be any technological device capable of transforming a physical phenomenon into electrical signs or 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. Actuators can also stimulate sensors of other CPS (Lee and Seshia, 2017). This interaction consists of computers reading and controlling the physical world, via cycles of feedback reading, and the control adaptation via computing for the next interaction (Lee, 2008).

CPS are addressable via 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 and biology (Lee, 2008; Sha et al., 2009; Rajkumar et al., 2010; Baheti and Gill, 2011; Lee and Seshia, 2017).

3 RELATED WORK AND RESEARCH METHOD

Specific areas, including CPS projects, may benefit from adapted or focused project management practices, which can better drive project activities and prevent common weaknesses (Lester, 2014). Some authors proposed new techniques for stakeholder management in civil engineering projects and in clinical research environments (Shen et al., 2015; Pandi-Perumal et al., 2015). Taking differences on organizational structures, some works are concerned on stakeholders, scope, human resources and communications for globally distributed projects (Deshpande et al., 2013; Golini and Landoni, 2014). Others propose entire revisions of PMBOK processes, knowledge areas or other project management approach adaptations, but in a general way. One example extends the knowledge areas creating the new 'project sustainability management', dealing with reuse of lessons learned and standardization of project management practices within an organization (Reusch, 2015).

To propose our PMBOK extension, we used results from a systematic literature review, conducted to link PMBOK's knowledge areas and the CPS development. We looked for works addressing specific CPS project management issues. We used various technical CPS-related terms to embrace as many primary studies as possible, such as: embedded systems, system of systems, sensors network, IoT, and automation and control. These terms are used for different levels of interactions but useful for our purpose.

The primary studies were analyzed to find which knowledge areas were subject of study. A relevance score was applied based on the number of times that keywords related to each area were mentioned. The outcomes are that scope, human resource and stakeholder were the areas with more issues studied. These results do not mean that the remaining knowledge areas are not relevant, but that the current project management practices are probably enough to properly manage them in the CPS context. Considering the outcomes of this systematic review, our work proposes project management practices, focused on the CPS context for the scope, human resource and stakeholder knowledge areas. We also propose a generic practice related to the integration area.

The following practices are suggested to manage scope in CPS projects: software and frameworks for requirements analysis; application of international standards; estimations based on use case points and hardware points; specific modeling languages for requirements elicitation and system architecture visualization; requirements review via peer reviewing and Scrum boards; development of design models; specific development approaches; meetings with live demonstrations; analysis-driven design; requirements lists; model-driven design; and new process models for scope management (Greene, 2004; Jun et al., 2007; Madachy et al., 2007; Madachy, 2008; Silva et al., 2009; Shatil et al., 2010; Berger and Rumpe, 2010; Garay and Kofuji, 2010; Savio et al., 2011; Rong et al., 2011; Helps and Mensah, 2012; Huang et al., 2012; Penzenstadler and Eckhardt, 2012; Insaurralde and Petillot, 2013; Zhu and Mostafavi, 2014; Parkhomenko and Gladkova, 2014; Yue and Ali, 2014; Sapienza et al., 2014; Faschang et al., 2015; Lattmann et al., 2015).

For human resource, these practices are suggested to CPS projects: distribution of tasks considering the team members' profile and expertise as well as statistical estimation and classification of familiarity of team members, according to their profiles and requirements; definition of specific key-roles needed for the team; use of an expert and multidisciplinary team; training in specific development methods, such as goal- and model-driven and extreme programming; and skill-based human resource management (Greene, 2004; Madachy et al., 2007; Madachy, 2008; Chen and Wei, 2009; Shatil et al., 2010; Wolff et al., 2011; Rong et al., 2011; Helps and Mensah, 2012; Huang et al., 2012; Zhu and Mostafavi, 2014; Yue and Ali, 2014; Parkhomenko and Gladkova, 2014).

Finally, considering the project stakeholders, the following practices are suggested to address this knowledge area in CPS projects: 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 et al., 2007; Madachy, 2008; Shatil et al., 2010; Rong et al., 2011; Huang et al., 2012; Penzenstadler and Eckhardt, 2012; Zhu and Mostafavi, 2014; Yue and Ali, 2014; Singh, 2013).

As part of the method to propose CPS-PMBOK, we analyzed all the practices related to scope, human resource and stakeholder found in the primary studies identified. We compared them with the best practices existing in PMBOK. As a result, we found both practices still not covered by PMBOK and practices covered but with suggested specializations. Following an empirical approach, we refined this list of practices considering the authors' practical experience in CPS projects. The final practices chosen are those most frequently found in the primary studies as well as aligned with the primary insights of the authors of this work. Finally, such chosen practices were also evaluated by experts in a CPS-related R&D company, including managers and developers, who presented some final suggestions to produced the last list of chosen practices to compose CPS-PMBOK.

4 THE CPS-PMBOK APPROACH

Given the growing demand on CPS projects and consequent need for proper management, this approach propose appropriate practices for managing CPS projects. Our main goal is improving both team communication skills and understanding of the project activities when addressing CPS projects. The Cyber-Physical Systems – Project Management Body of Knowledge (CPS-PMBOK) approach proposes practices based on Project Management Institute's PMBOK, but oriented to the specific context of CPS projects. Agile methods indirectly influence the practices since agile practices are also commonly related to the issues addressed here. One of the main characteristics of CPS-PMBOK is the adequate treatment of concerns with hardware beyond software as well as teams composed of very different technical profiles.

CPS-PMBOK is composed of the original set of PMBOK best practices, extending it for CPS projects. The specialization address four PMBOK's areas. For each, one or more practices are proposed: *(a)* integration – characterization model (artifact); *(b)* scope – pre-elaborated requirements lists (technique), review requirements (process), process simulation (technique); *(c)* human resource – specialized team division (technique), cross-training (technique); *(d)* stakeholder – build technical trust (technique), dynamic follow-up strategies (technique).

From the 47 processes suggested by PMBOK (v.5), seven of them received some enhancement suggestion, including: the addition of a new process output, the addition of a new process tool/technique, or the addition of a new whole process.

4.1 Integration Management

First proposed practice, the characterization model should be used a brainstorm driving, to equalize the comprehension and familiarization with the system to be developed. This artifact is proposed to be produced as an output of the develop project chart process, which is part of the initiating process group. Fig. 1 presents the proposed characterization model output artifact, highlighted in **bold**, within the develop project charter process, following the graphic pattern used in PMBOK to present its processes. This output should be used as input by all processes that use the project charter also as input, i.e.: plan scope management, collect requirements, define scope, plan schedule management, plan cost management, plan risk management, and plan stakeholder management.

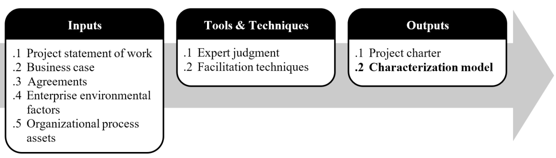

Figure 1: Characterization model ("develop project charter" process).

Fig. 2 illustrate a characterization model. For each proposed characteristic, the participants of the brainstorming fill the characterization model choosing between low, moderate and high. This may provide estimates regarding project size, complexity and technical challenges besides to discussions among the team members. These characteristics are divided in two sections: CPS environment and CPS complexity. Our example of CPS characterization model presents some characteristics usually found in CPS projects.

CPS characterization model			
CPS environment	**Low**	**Moderate**	**High**
• Limited tasks			
• Communication with known group of devices			
• Interaction with known group of people			
• Following industrial standards or norms			
CPS complexity	**Low**	**Moderate**	**High**
• Mechanical structures			
• Network			
• Sensors			
• Actuators			
• Data storage			
• User interaction			
• Integration with legacy systems			
• Power energy system			

Figure 2: CPS projects' characterization model (example).

The CPS environment represents the variables present in the CPS to be developed, such as how much: limited tasks are required, communication with known group of devices, interaction with known group of people, and industrial standards or norms should be followed. The higher the score assigned for each characteristic, the better defined and surrounded by formalized processes is the CPS environment. The opposite means that the CPS environment can be chaotic and unpredictable, which might define project management strategies, adequate teams to work on the project or budget adjustments.

The CPS complexity is based on specific technological areas: mechanical structures, network, sensors, actuators, data storage, user interaction, legacy systems integration, and power energy system. The complexity characterization is made by choosing how relevant is the integration of the CPS being developed with each of these technologies. For each one, a specific technical team may be required to estimate such complexity. Like the environment characterization, different project management decisions may be taken depending on the CPS complexity.

We do not intend to define a fixed characterization model, with fixed characteristics. Fig. 2 proposes a basic example that may be adapted for each organization or team, based on lessons learned, project goals or application area, considering CPS concepts. Moreover, we expect that the list of characteristics evolves considering the team's experience on past projects.

4.2 Scope Management

As for scope, some processes show special challenges for CPS projects due to highly innovative and dynamic aspects (Lee, 2008; Sha et al., 2009; Baheti and

Gill, 2011; Lee and Seshia, 2017). The high complexity of modeling the physical world and its phenomena is another challenge source. Innovation and complexity 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 et al., 2012). CPS project managers and team 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. As a result, two practices are proposed to the scope management: pre-elaborated requirements lists and review requirements.

4.2.1 Pre-elaborated Requirements Lists Technique

To support requirements gathering, CPM-PMBOK includes a technique called pre-elaborated requirements lists. Their purpose is to create reusable assets by gathering common requirements in CPS projects. This technique is proposed to be used within the collect requirements process, which is part of the planning process group. Fig. 3 presents the proposed pre-elaborated requirements lists technique, highlighted in **bold**, within the collect requirements process. Pre-elaborated requirements lists help collect requirements which should be used to estimate project size and avoid missing requirements. It contains topics of possible requirements so the project manager or team can fill with weights, points or simple tags signaling the existence of some requirement, such as a checklist. These topics may be divided in domains related to technical areas (cf. Fig. 2). Fig. 4 shows an example of a pre-elaborated list of software requirements for an initial collection of CPS requirements. It indicates a subject of high level of abstraction (on the 'Requirements topic' column) and a corresponding technical question for each topic (on the 'Technical issue' column) to be answered as a support for collecting requirements. It is based on the hardware points technique, proposed to estimate hardware assembly and development cost (Silva et al., 2009).

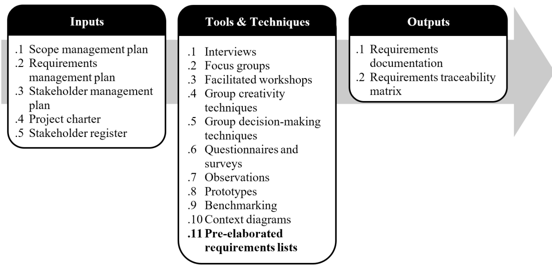

Figure 3: Pre-elaborated requirements lists ("collect requirements" process).

CPS software requirements checking	
Requirements topic	**Technical issues**
• Automation level	How much human intervention is required?
• Processing load	How complex is the processing of data collected?
• Data storage	What is the size of the data type addressed? Which technology is used to store results?
• Graphical interface	How should the graphical interface look like?
• Running time	How long should the system remain in operation?
• Parameters insertion	Should it be possible to register new parameters?
• Remote access	Should it be necessary to provide web visualization or operation?

Figure 4: Example of a pre-elaborated requirements list.

4.2.2 Review Requirements Process

CPS development may lead to unexpected results and hence dynamic requirements (Huang et al., 2012). Thus, the innovative aspect of CPS demands many scope revisions and redefinition. By understanding that such scope revisions and redefinitions are highly common in CPS projects, one of our specific practices is proposing an additional process to the scope knowledge area – review requirements – as part of the monitoring and controlling process group. Fig. 5 presents the proposed review requirements process, including its inputs, tools/techniques and outputs. Review requirements aims to advance requirements reviews, bringing up the changes as soon as possible, so it can be timely addressed. Review requirements 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 known requirements and revisiting the highest definitions of the project looking for new requirements. 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. This new process follows principles of agile methodologies. Its purpose is to predict requirements changes enabling the team to react in real time and according to the resources available. Moreover, this additional process aims to reduce the impacts of requirements constantly changing. In this new process, techniques to collect requirements already described in PMBOK are used, as meetings, surveys and interviews. CPS-PMBOK additionally includes the process simulation technique in support of review requirements. It consists of tests and validation of the various stages of development, according to the features becoming ready to use. Simulation tools to predict environment or conditions such as mechanical simulation, radiation diagrams and thermal dissipation are useful in review requirements and are part of process simulation. Other tools to isolate part of the CPS, to validate models or equipment, such as hardware or software in the loop may also be used.

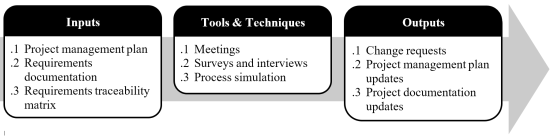

Figure 5: Review requirements process, with process simulation.

4.3 Human Resource Management

Considering multidisciplinary, human resources can be from different specialization areas, what increases the challenge of managing relationships and technical communication (Wolff et al., 2011). A project to develop a smart power grid system, for instance, may include professionals from electrical supply, hardware design, telecommunication and software development. Those from electrical and software areas may be not familiar with hardware technologies whereas from telecomm and hardware areas come from a very different school, where software is usually not object of study. These different academic approaches applied in a same project may cause misunderstanding among team members, influencing requirements understanding and even task priorities. As a result, two additional techniques are proposed in CPS-PMBOK for human resource management: specialized team division and cross-training.

4.3.1 Specialized Team Division Technique

specialized team division is included in CPS-PMBOK to improve the development performance and avoid inappropriate assignment of tasks. The team should be split into subteams taking different application areas or project deliverables. Some works found in literature were used as a basis to propose it, including: the application of team division based on academic profiles, such as electrical engineering, computer engineering and information technology (Helps and Mensah, 2012; Sha et al., 2009). This technique is proposed to be used within two processes: the plan human resource management process, which is part of the planning process group; and the acquire team process, which is part of the executing process group. Figures 6 and 7 present the proposed specialized team division technique, highlighted in **bold**, within both the plan human resource management process and the acquire team process, respectively. We propose an initial suggestion for a specialized team division considering the context of CPS projects and taking into account the proposed characterization model in terms of CPS complexity. According to our suggestion, the sub-teams for a CPS projects could be: *(a)* mechanical design team – responsible for physical structures and mechanical packing; *(b)* hardware design team – responsible for processing platforms, sensors and actuators specification; *(c)* electrical design team – responsible for electrical project and drawings, besides power energy design; *(d)* network design team – responsible for communication protocols and technologies specification; *(e)* information system development team – responsible for software development; *(f)* other specialized teams – power bank development team, human-computer interface team, antenna design team, specific sensors team etc. Other options for specialized team division can be used 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. As an example, considering an autonomous meteorological information collector, which involves drone development allied with weather sensing and statistical software for forecasting, a specialized team division based on deliverables could be: *(a)* mechanical structure – mixing mechanical and hardware design profiles, responsible for structure and engines design and development; *(b)* flight system – composed of mechanical and hardware design profiles and possibly a theorical flight expert, responsible for designing and developing the propellers and orientation sensors; *(c)* power energy system: composed of electrical design profiles plus chemists for battery technologies experts; *(d)* communications system – delivering the radio communication system for remote control and data collection; *(e)* embedded software – composed by software engineers with a focus on reliable embedded software design and development, responsible for delivering the main drone software, which controls the engines, reads sensors, communicates with radios and also has some autonomous routines for emergencies; *(f)* weather data system – composed by statistical experts on weather sensors allied with some electrical and hardware design professionals, responsible for specifying appropriate sensors to be used and for interpreting their results. A specialized team division may be used to support organizational or resource breakdown structures. A specialized team division may include varied departments or even external organizations.

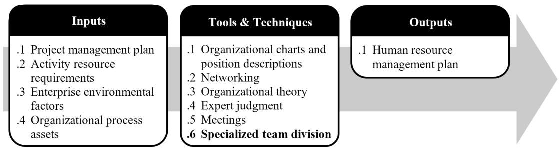

Figure 6: Specialized team division ("plan human resource management" process).

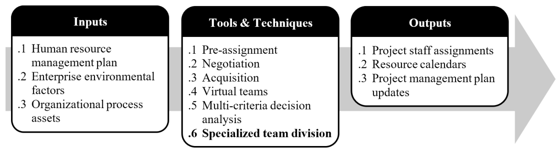

Figure 7: Specialized team division ("acquire team" process).

4.3.2 Cross-training Technique

cross-training is a practice briefly depicted in PMBOK, proposed to reduce impact when a team member leaves the project. It consists in allocating more than one resource to a task execution. For CPS projects, we propose that the cross-training should be always used to enable some team members acting as a communication bridge between different sub-teams by allocating a team member from a given area to perform a task of some other area. This technique is proposed to be used within the develop team process, which is part of the planning process group. Fig. 8 presents the proposed cross-training technique, highlighted in **bold**, within the develop team process. Considering cross-training, a software engineer may sporadically follow a mechanical engineer's work with the purposed of understanding and even positively contributing with potential ideas and insights emerged from another outlook. Cross-training can be used as a facilitator in the identification and development of multidisciplinary practitioners.

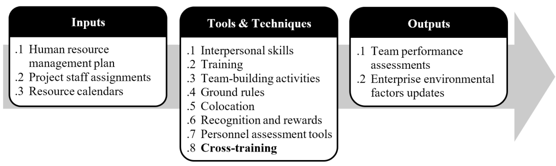

Figure 8: Cross-training ("develop team" process).

4.4 Stakeholder Management

Project stakeholders in CPS projects are usually highly technical or very close to the system's final users. This occurs mainly in joint projects of research with universities, where the stakeholders are researchers and students. Also in industrial projects to improve production performance, where many stakeholders are production leaders experts in many technologies of the area (Baheti and Gill, 2011). Due to the diverse and complex nature of CPS project stakeholders, we understand that specific techniques should be applied to properly address this stakeholder profile to guarantee that the best results are achieved. Consequently, two additional techniques are proposed in CPS-PMBOK for stakeholder management: build technical trust and dynamic follow-up strategies.

4.4.1 Build Technical Trust Technique

CPS projects tend to involve academic researchers or experts to support the development of CPS physical elements. They may represent technical stakeholders who understand both the application and engineering areas. PMBOK describes a practice of trust building for stakeholder engagement management, showing that the company, team and even the manager have competencies to accomplish project's requirements in time and cost. Accordingly, an relevant necessity when involving stakeholders in CPS projects is to build technical trust between them and the team. In this context, CPS-PMBOK proposes a specialization of the trust building, adding the technical aspect to this practice. Build technical trust is proposed to be used within the manage stakeholder engagement process, which is part of the executing process group. Fig. 9 presents the proposed build technical trust technique, highlighted in **bold**, within the manage stakeholder engagement process. Build technical trust means to pass technical confidence regarding project accomplishment conditions, considering the team and project manager. Accordingly, the team should get close to the stakeholders, mainly in situations in which the stakeholders are highly technical. For CPS-PMBOK, an internal expert or an external consultant should be put in charge of following up the project management activities allowing more technical stakeholders to be more comfortable with the project progress. This person has the role of translating technical stakeholders concerns. The technical trust may improve stakeholders' satisfaction due to their proximity and understanding of technical issues. Besides that, the developers may feel more comfortable as well, due to the understanding of terms and concerns provided by a expert or consultant.

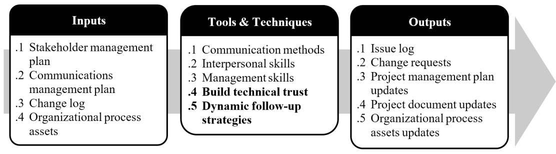

Figure 9: Build technical trust and dynamic follow-up strategies ("manage stakeholder engagement" process).

4.4.2 Dynamic Follow-up Strategies Technique

as observed in the outcomes of the systematic review that embased this project, some authors identified that the proposed practices for communication with stakeholders may be not enough to keep stakeholders properly updated in a CPS project. Some approaches found to improve communication with CPS projects' stakeholders are: face-to-face meetings to update the project status to stakeholders (Huang et al., 2012), stakeholders' participation in every last weekly follow-up meeting of development iterations (Rong et al., 2011), and weekly workshops for system demonstrating – to update stakeholders (Penzenstadler and Eckhardt, 2012). Most of these approaches are based on agile methods, which has the communication with stakeholders as one of their most relevant concerns. To meet the different levels of demand and satisfaction of stakeholders, we propose dynamic follow-up strategies as part of CPS-PMBOK. The proposed technique is based on practices found in literature with this purpose. This technique is proposed to be used within two processes: the manage stakeholder engagement process, which is part of the executing process group; and the control stakeholder engagement process, which is part of the monitoring and controlling process group. Figures 9 and 10 present the proposed dynamic follow-up strategies technique, highlighted in **bold**, within both the manage stakeholder engagement process and the control stakeholder engagement process, respectively. According to different aspects of a given specific CPS project, the project manager should adapt the follow-up strategy to enhance stakeholder engagement and reach their expectations. The following suggested strategies are proposed: *(i)* during the project initiation and planning stages, which involve, for example, discovering of requirements and stakeholders, understanding of highly engaged stakeholders, and understanding of stakeholders' application area – regular face-to-face meetings should be adopted as follow-up strategy; *(ii)* during the project execution and monitoring stages, which involve, for example, resolution of requirements conflicts and alignment between technical demands from stakeholders and project documents – only sporadic participation of stakeholders could be included during planning and technical meetings; and *(iii)* during the closing stage, which involves, resource scarcity, time re-planning and stakeholder staff updating – the stakeholders should be able to follow up on the final results via workshops with live CPS demonstrations.

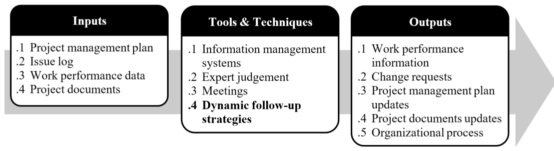

Figure 10: Dynamic follow-up strategies ("control stakeholder engagement" process).

5 EVALUATION

To evaluate CPS-PMBOK, we conducted a qualitative empirical analysis taking the experience of practitioners working in an R&D organization. This organization was chosen because it develops CPS projects and one of the researchers authoring this paper works there. We consulted six managers and four developers. The evaluation was split into an in-person interview and an online survey.

5.1 In-person Interviews

For the in-person interviews, we firstly presented to these practitioners the proposed practices. For each practitioner type, we presented a specific description of our approach. For managers, we explained that CPS-PMBOK is a PMBOK-based approach that aims to enhance CPS project success likelihood via project management concepts focused on CPS development. For developers, we emphasized that CPS-PMBOK should be applied by project managers with the collaborative presence of technical personnel, to provide better conditions for the CPS project. During the approach presentation, we discussed, with the practitioners, issues raised in CPS projects that they have previously experienced, now considering the practices proposed in CPS-PMBOK. Our purpose with this evaluation phase was to raise critical analysis regarding the CPS-PMBOK benefits and feasibility. We conducted this evaluation individually, i.e., a practitioner at a time. We were not able to conduct a group evaluation due to the non-availability of common hours by the involved practitioners, especially from those at managerial level. Nevertheless, we developed a non-structured roadmap to increase the chances of spontaneous feedback.

From the in-person interviews, we collected feedback from the practitioners, which allowed us to align the understanding of CPS project concepts. However, while we asked the practitioners to evaluate the proposed approach in a generic way, some feedback seems to be strictly related to the organization where the evaluation was conducted. Moreover, some developers showed knowledge about project management and hence some of their opinions are more related to managerial rather than technical aspects.

Table 1 summarizes the most relevant opinions. Different types were recorded, including praises, criticisms and suggestions. In some cases, we concluded that CPS-PBMOK and the proposed practices have not been properly presented since the raised criticism or suggestions refer to items indeed addressed by our approach. A large part of the suggestions is related to possible extensions of the proposed models. Such extensions or adaptations are in fact what is expected to be done by practitioners with specific needs.

5.2 Online Survey

We used a structured questionnaire to gather the practitioners' opinions on the potential effectiveness and relevance of each proposed practice. The practitioners were expected to consider the corresponding knowledge area to inform their opinions. We elaborated the questions and possible responses considering a five-points Likert-type scale. We chose standard five-level responses to represent the perceived effectiveness of each practice to its corresponding knowledge area. The used responses are: totally disagree, partially disagree, neutral, partially agree, and totally disagree. Moreover, the practitioners were asked to inform if they perceived each practice as relevant to two specific needs: *(i)* team communication and *(ii)* project understanding. These two additional questions were included to evaluate the proposed approach to our main goals when proposing such practices. Lastly, we also used a question with free-response style to allow the practitioners to present general comments about CPS-PMBOK and the practices.

Table 2 shows the results of the online survey applied to managers and developers. Although not statistically valid, sequential integers were assigned to the categorical responses to allow the calculation of a mean among the responses and obtain an overview of the practitioners' opinions, representing an average response. The following weights were used: totally disagree (1), partially disagree (2), neutral (3), partially agree (4) and totally agree (5). For contribution to the team communication and activities' understanding needs, the answers were 'yes' or 'no'.

Regarding effectiveness, both managers and developers reported a general perception with high rates. For both groups, the practices together received an average of 4.2, indicating a general response slightly higher than 'partially agree'. There were only some small differences between both groups. For example, managers' general opinions vary from 4.0 to 4.3 while developers' general opinions vary from 3.8 to 4.5. Both groups reported build technical trust with the highest effectiveness. On the other hand, managers reported review requirements with the lowest effectiveness while developers reported it with the highest effectiveness. Either way, the rating differences attributed to them are very small.

Regarding contribution to team communication and activities' understanding, both groups also reported a common general perception but with lower values. For almost all cases, an average of 50% of the practices were reported as contributing to both specific needs. Specifically for activities' understanding, managers reported the contribution of an average of 60% of the practices. Some notable differences are identified within each group: some practices contribute more to team communication than to activities' understanding (as the specialized team division, according to managers) while for some other practices the opposite is noticed (as review requirements, according to developers). Other notable differences are identified between both groups: managers reported that dynamic follow-up strategies highly contributes to both team communication and activities' understanding whereas developers reported it with a low contribution to both specific needs. The opposite was reported for the specialized team division. On the other hand, both groups agree that cross-training presents a good contribution for both.

5.3 Discussion of Results

We could observe some convergences and divergences between the managers' and developers' opinions. We analyzed some divergences to understand their motivations.

The managers perceived review requirements as one of the most contributors to team communication, which was not expected by us (considering the online survey, cf. Table 2). Although not initially expected, managers should have taken into account that reviewing requirements requires collective cooperation, mainly considering the proposed process simulation technique. Review requirements was also considered as one of the most contributors to activities' understanding, which is naturally understandable. Nevertheless, review requirements is contradictorily one of the two worst rated by managers in terms of gen-

Table 1: Feedback regarding the proposed management practices (Man – Manager / Dev – Developer).

	Area / Feedback	From
	Project Integration Management	
1	Life-threatening should be added as a characteristic in the model's environment section.	Man
2	The characterization model can support project planning activities such as estimating time or cost.	Man
3	Available time, team and budget may influence the characterization model.	Man
4	Something similar to the characterization model could be proposed to characterize the team.	Man
5	The model's characteristics could be weighted considering the proposers' profile and expertise.	Man
6	This practice may inhibit creativity and innovation.	Man
7	Levels 'low', 'moderate', 'high' should be better defined.	Dev
8	'Intelligence over data' should be added as a characteristic in the model's complexity section.	Dev
9	'Hazardousness' and related industrial standards should be added as a characteristic in the environment section.	Dev
10	'Unknown' should complement low/moderate/high levels.	Dev
	Project Scope Management	
1	Pre-elaborated requirements lists should be provided when considering an exposed environment.	Man
2	Pre-elaborated requirements lists and reviewing requirements should better connect with each other.	Man
3	Reviewing requirements should be associated to risk management since they are closely related.	Man
4	For pre-elaborated requirements lists, fixed requirements is very risky due to different contexts of success.	Dev
5	Process simulation, proposed for review requirements, should better integrate with other processes.	Dev
6	Pre-elaborated requirements lists should guide team definition.	Dev
	Project Human Resource Management	
1	Cross-training can be very useful as a parallel approach when the technologies involved are still quite unknown.	Man
2	An architect role should be considered in a specialized team division to integrate all sub-teams involved.	Man
3	Cross-training only works if all subteams practice it.	Dev
4	An integration role is missing in the specialized team division; all sub-team leaders should act as integrators.	Dev
	Project Stakeholder Management	
1	Dynamic follow-up strategies may be useful to show what is being achieved and avoid the need for changes.	Man
2	Build technical trust can be useful to bring confidence also to the team, not only to the stakeholders.	Man
3	Build technical trust can be also useful to translate technical concerns and terms to the team.	Man
4	Dynamic follow-up strategies should also be suggested as a technique to the scope management processes.	Man
5	Build technical trust can be enriched by providing access to the team's source code for technical stakeholders.	Dev
6	Preparing for a follow-up workshop may be very costly considering its potential results as return.	Dev

Table 2: Online survey responses (Eff – Effectiveness [1-5] / TC – Team Communication / AU – Activities' Understading).

Area	Proposed practice	Managers			Developers		
		Eff.	TC	AU	Eff.	TC	AU
Integration	Characterization model	4.0	33%	83%	4.3	50%	75%
Scope	Review requirements	4.0	83%	83%	4.5	0%	75%
	Pre-elaborated requirements lists	4.3	17%	67%	3.8	75%	50%
Human Resources	Cross-training	4.2	50%	50%	4.5	75%	75%
	Specialized team division	4.3	50%	17%	4.3	75%	75%
Stakeholder	Build technical trust	4.3	33%	50%	4.5	50%	0%
	Dynamic follow-up strategy	4.2	83%	67%	3.8	25%	0%
Average		4.2	50%	60%	4.2	50%	50%

eral effectiveness. This contradiction probably occurs due to the risk of losing the project control seeing that, if not properly managed, the requirements review can make the project scope infinite. This conclusion is corroborated by one of the managers' feedbacks (cf. Table 1) that states: 'Review requirements should be formally associated to the risk management area since both are closely related'.

The developers did not perceive any contribution of review requirements for team communication, exactly the opposite of the managers (considering the online survey, cf. Table 2). In fact, there is no feedback from developers considering the in-person interviews (cf. Table 1), which indicates they really do not see any importance for this practice. Another divergence, taking the online survey, is for the activities' understanding aspect, for which the managers saw an relevant contribution of dynamic follow-up strategies whereas the developers did not perceive any contribution of it for this aspect. Moreover, the developers raised some cost issues related to his technique, considering the in-person interviews (cf. Table 1). On the another hand, developers indicated more importance for the practices suggested to the human resource management when comparing to the managers' opinions about these practices.

There is no consensus as to what suggested practices may contribute most to team communication. For managers, review requirements and dynamic follow-up strategies can do it, whereas, for developers, pre-elaborated requirements lists, cross-training and specialized team division can. The other two practices (characterization model and build technical trust) were not well rated for both sides. In terms of contribution to activities' understanding, there were some convergences between managers and developers. For example, both groups consider that characterization model and review requirements are the most relevant for this aspect, although they diverge in terms of importance for the other practices.

For the organization where the evaluation was conducted, the evaluation process allowed to reconsider its own organizational practices. The evaluation 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 highlighted. Specific human resource issues appeared in the discussions, which may depend on country and organization developing the CPS system, such as availability or suitability of professionals. Nevertheless, dispite the differences among countries, very specific profile resources may be a problem for every organization in any country, such as a physicist specialized in light propagation, for example.

One of the suggestions from developers was to provide a way to keep every person involved in the project, by using a wiki, for example. This technique can be aggregated to specialized team division, assigning the updating tasks to a specific support team. The role of an architect or integrator appeared twice in feedbacks: one from managers and other from developers. 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: a leader integrator. 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 professional profile, then the creation of an integration team may be needed.

As stated by other authors, social issues seemed to influence the evaluation: some managers showed more interest in taking part of this research project, understanding the academic context involved, whereas others faced it as a work evaluation, questioning the need to review their project management methods. Some raised issues leed to concerns related to relevant subjects for CPS research, wich are not the focus of this research, such as: types of project lifecycles, software development methods, and project funding strategies. Since the organization in case is both industry and research-driven, issues related to project final goals showed up, such as any project to creating a product, methods or an art study for wider R&D projects. These issues indicate that particular refinements of CPS-PMBOK or other approaches may be necessary according to the final project goal, which connects to the success definition, as cited by one of the managers. Although these points can also be specific for each organization or country, it is relevant for the CPS-PMBOK application, mainly in scope and human resource management, since some requirements and team members can never change due to legal requirements in case of R&D projects funded by the government, for example.

6 CONCLUSION

This work proposed project management practices driven to CPS projects. The approach is based on PMI's PMBOK best practices and focused on integration, scope, human resource and stakeholder. CPS-PMBOK relies on the following requirements for CPS projects: multidisciplinary teams, high level of innovation and unpredictable requirements. The approach was presented to managers and developers to evaluate its potential benefits, feasibility and effectiveness and collect feedback. Both groups were excited about applying it to their organization and found it particularly audacious and innovative, mainly considering some characteristics imported from agile methods.

The feedback allows us to improve CPS-PMBOK considering a series of opportunities. Our challenge is to be able to evolve the proposed practices, including proposing new ones, considering two needs that can be seen as antagonistic ones: for one hand, being specific to the CPS project domain; but, for the other hand, being not too specific to allow adjustments as required for specific contexts and organizations.

REFERENCES

Baheti, R. and Gill, H. (2011). Cyber-physical systems. *The Impact of Control Tech.*, 12:161–166.

Berger, C. and Rumpe, B. (2010). Supporting agile change management by scenario-based regression simulation. *IEEE Trans. on Intel. Transp. Syst.*, 11(2):504–509.

Chen, Y. M. and Wei, C.-W. (2009). Multiagent approach to solve project team work allocation problems. *Int. J. of Prod. Res.*, 47(13):3453–3470.

Deshpande, S., Beecham, S., and Richardson, I. (2013). Using the PMBOK guide to frame GSD coordination strategies. In *8th Int. Conf. on Glob. Soft. Eng.*, pages 188–196.

Faschang, M., Kupzog, F., Widl, E., Rohjans, S., and Lehnhoff, S. (2015). Requirements for real-time hardware integration into cyber-physical energy system simulation. In *Work. on Mod. and Sim. of Cyb.-Phys. Energy Sys.*, pages 1–6.

Garay, J. R. B. and Kofuji, S. T. (2010). Architecture for sensor networks in cyber-physical system. In *Latin-Amer. Conf. on Commun.*, pages 1–6.

Golini, R. and Landoni, P. (2014). Int. development projects by non-governmental organizations: An evaluation of the need for specific project management and appraisal tools. *Impact Asses. and Proj. Appr.*, 32(2):121–135.

Greene, B. (2004). Agile methods applied to embedded firmware development. In *Agi. Dev. Conf.*, pages 71–77.

Helps, R. and Mensah, F. N. (2012). Comprehensive design of cyber physical systems. In *13th Ann. Conf. on Inf. Tech. Educ.*, pages 233–238.

Huang, P. M., Darrin, A. G., and Knuth, A. (2012). Agile hardware and software system engineering for innovation. In *Aeros. Conf.*, pages 1–10.

Insaurralde, C. C. and Petillot, Y. R. (2013). Cyber-physical framework for early integration of autonomous maritime capabilities. In *Int. Sys. Conf.*, pages 559–566.

Jun, D., Rui, L., and Yi-min, H. (2007). Software processes improvementement and specifications for embedded systems. In *5th ACIS Int. Conf. on Soft. Eng. Res., Man. & Appl.*, pages 13–18.

Lattmann, Z., Klingler, J., Meijer, P., Scott, J., Neema, S., Bapty, T., and Karsai, G. (2015). Towards an analysis-driven rapid design process for cyber-physical systems. In *Int. Symp. on Rapid Sys. Prot.*, pages 90–96.

Lee, E. A. (2008). Cyber physical systems: Design challenges. In *11th Int. Symp. on Obj. Ori. Real-Time Distr. Comp.*, pages 363–369.

Lee, E. A. and Seshia, S. A. (2017). *Introduction to Embedded Systems: A cyber-physical Systems Approach*. Lee & Seshia, 2nd edition.

Lester, A. (2014). *Project Management, Planning and Control: Managing Engineering, Construction and Manufacturing Projects to PMI, APM and BSI Standards*. Butterworth-Heinemann, 6th edition.

Madachy, R., Boehm, B., and Lane, J. A. (2007). Assessing hybrid incremental processes for SISOS development. *Soft. Proc.: Imp. and Prac.*, 12(5):461–473.

Madachy, R. J. (2008). Cost modeling of distributed team processes for global development and software-intensive systems of systems. *Soft. Proc.: Imp. and Prac.*, 13(1):51–61.

Palma, F., Fantinato, M., Rafferty, L., and Hung, P. (2018). Enhancing project management for cyber-physical systems development. In *Fed. Conf. on Comp. Sci. and Inf. Sys.*, pages 747–750.

Pandi-Perumal, S. R., Akhter, S., Zizi, F., Jean-Louis, G., Ramasubramanian, C., Freeman, R. E., and Narasimhan, M. (2015). Project stakeholder management in the clinical research environment: How to do it right. *Front. in Psyc.*, 6:71.1–71.18.

Parkhomenko, A. V. and Gladkova, O. N. (2014). Virtual tools and collaborative working environment in embedded system design. In *11th Int. Conf. on Remote Eng. and Virt. Inst.*, pages 90–93.

Penzenstadler, B. and Eckhardt, J. (2012). A requirements engineering content model for cyber-physical systems. In *2nd Work. on Req. Engi. for Sys., Serv. and Sys.of-Sys.*, pages 20–29.

PMI (2013). *Guide to the Project Management Body of Knowledge*. Project Management Institute.

Rajkumar, R. R., Lee, I., Sha, L., and Stankovic, J. (2010). Cyber-physical systems: The next computing revolution. In *47th Des. Autom. Conf.*, pages 731–736.

Reusch, P. J. A. (2015). Extending project management processes. In *8th Int. Conf. on Int. Data Acq. and Adv. Comp. Sys.: Tech. and Appl.*, pages 511–514.

Rong, G., Shao, D., Zhang, H., and Li, J. (2011). Goal-driven development method for managing embedded system projects: An industrial experience report. In *Int. Symp. on Emp. Soft. Eng. and Meas.*, pages 414–423.

Sapienza, G., Crnkovic, I., and Potena, P. (2014). Architectural decisions for hw/sw partitioning based on multiple extra-functional properties. In *IEEE/IFIP Conf. on Softw. Archit.*, pages 175–184.

Savio, D., Anitha, P. C., and Iyer, P. P. (2011). Considerations for a requirements engineering process model for the development of systems of systems. In *1st Work. on Req. Engin. for Sys., Serv. and Sys.-of-Sys.*, pages 74–76.

Sha, L., Gopalakrishnan, S., Liu, X., and Wang, Q. (2009). Cyber-physical systems: A new frontier. In Tsai, J. J. P. and Yu, P. S., editors, *Machine Learning in Cyber Trust: Security, Privacy, and Reliability*, pages 3–13.

Shatil, A., Hazzan, O., and Dubinsky, Y. (2010). Agility in a large-scale system engineering project: A case-study of an advanced communication system project. In *Int. Conf. on Soft. Sci., Tech. and Eng.*, pages 47–54.

Shen, Y., Tuuli, M. M., Xia, B., Koh, T. Y., and Rowlinson, S. (2015). Toward a model for forming psychological safety climate in construction project management. *Int. J. of Proj. Man.*, 33(1):223–235.

Silva, C. M. B. d., Loubach, D. S., and Cunha, A. M. d. (2009). An estimation model to measure computer systems development based on hardware and software. In *28th Dig. Avi.Sys. Conf.*, pages 6C2.1–6C2.12.

Singh, M. P. (2013). Norms as a basis for governing sociotechnical systems. *ACM Trans. on Int. Sys. and Tech.*, 5(1):21.

Wolff, C., Gorrochategui, I., and Bücker, M. (2011). Managing large HW/SW codesign projects. In *6th Int. Conf. on Int. Data Acq. and Adv. Comp. Sys.*, pages 919–922.

Yue, T. and Ali, S. (2014). Applying search algorithms for optimizing stakeholders familiarity and balancing workload in requirements assignment. In *Conf. on Gen. and Evol. Comp.*, pages 1295–1302.

Zhu, J. and Mostafavi, A. (2014). Towards a new paradigm for management of complex engineering projects: A system-of-systems framework. In *8th Ann. IEEE Sys. Conf.*, pages 213–219.